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Influence of the decoupling degree on the estimation of canopy stomatal conductance for two broadleaf tree species

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ABSTRACT

Canopy stomatal conductance (G_S) estimation is a critical aspect of evapotranspiration research. Selecting an appropriate model for scaling-up is necessary to study plant water regulation. Two monoculture plantations of broadleaf tree species, *Eucalyptus urophylla* and *Schima superba*, were selected to study G_S via a widely recognized equation simplified by Köstner (G_{S1}) and an inverse Penman–Monteith equation (G_{S2}). The decoupling coefficient (Ω) was estimated to quantify the decoupling extent of stomata from the atmosphere. We found that both species were well coupled with environmental conditions (0.1 ± 0.06 and 0.22 ± 0.09 for *E. urophylla* and *S. superba*). Ω increased exponentially with canopy conductance (G_C) and was depressed by the increase of G_a, which implied that there was a combined climatic and physiological regulation on Ω. G_{S1} for both species (63.7 ± 33.9 mmol m^{-2} s^{-1} and 48.4 ± 18.1 mmol m^{-2} s^{-1} for *E. urophylla* and *S. superba*, respectively) was underestimated with the simplified equation compared to G_{S2} (77.0 ± 52.4 mmol m^{-2} s^{-1}and 112.0 ± 52.5 mmol m^{-2} s^{-1} for *E. urophylla* and *S. superba*, respectively). The ratio of G_{S1}/G_{S2} linearly decreased with Ω by a slope of -1.92 and -1.31 for *E. urophylla* and *S. superba*, respectively. The increase of the LAI tended to increase the decoupling extent, which further reduced the accuracy of the estimation of G_{S1}. According to our results, the ratio of G_{S1}/G_{S2} had a mean of 0.94 for 85.3% and 0.6 for 37.6% of all of the data for *E. urophylla* and *S. superba*, respectively, implying a better estimation of G_{S1} for the stand that had a lower LAI. Based on the relationship between the LAI and the ratios of G_{S1}/G_{S2} (ratio = $1.0759 \times 0.02547^{(0.053\mathrm{LAI} + 0.054)} - 0.0078$), we can shed some light on the prediction error of stomatal conductance derived from the simplified equation in different forest types.

1. Introduction

As one of the most important functional processes of forests for maintaining the water balance of catchments and regions, transpiration provides vital ecological services for social and economic activities (Huber et al., 2008; Little et al., 2009). Environmental changes will likely change this balance and force forests to make adjustments, resulting in corresponding variations in carbon assimilation. The environmental control of canopy transpiration can be characterized in terms of the response of canopy conductance to environmental factors (Kumagai et al., 2004, 2008; Barradas et al., 2005). Based on this, many studies relating canopy conductance to environmental factors have been conducted to explore the underlying mechanisms of such responses (Morris et al., 2006; Blanken and Black, 2004).

In 2013, the State Forestry Administration (SFA) reported that the forest area in China was 2.08 hundred million ha, covering 21.63% of the total land. Of this amount, planted forests consisted of 33.17% of the total forest area (6.9 million hectare), which is the largest area of plantations in the world (http://www.forestry.gov.cn/main/58/content-660036.html). *Eucalyptus urophylla*, one of the most common species introduced for afforestation in South China, has experienced rapid expansion over the past two decades and covered 1.65×10^6 ha in Guangxi (Forest Department of Guangxi

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Zhuang Autonomous Region, 2010, http://www.gxly.cn:8888/pub/cms/1/3545/3559/3566/88981.html). Because high productivity is often related with high rates of water use, there have been concerns that Eucalyptus planting will adversely affect water resources by reducing water yields from water-supply catchments (Whitehead and Beadle, 2004; Engel et al., 2005). With a large planting area and high water consumption, *E. urophylla* has been found to exert a significant impact on the regional hydrology and carbon assimilation (Lane et al., 2004). *Schima superb* is a native pioneer species in subtropical evergreen broad-leaf forests in South China, commonly used for reforestation in degraded hilly lands. Peng (1996) proposed a succession pathway from pioneer coniferous trees to shade intolerant broadleaf trees (such as *S. superba*) to shade tolerant broadleaf trees, based on field studies over several decades. Gao et al. (2003) argued that the fitness of a species for a particular succession stage at a particular location can be measured by stomatal behavior and biochemical assimilation capacity under local climate and soil conditions. Hence stomatal conductance response of *S. superba* to environmental changes played a vital role in forest succession.

Quantifying the environmental regulation of the transpiration of planted *E. urophylla* and *S. superba* forests is necessary and meaningful due to the significant environmental variability in subtropical South China, which is dominated by the monsoon climate. The application of sap flow techniques enabled the accurate estimation of tree transpiration and analyses on its interaction with abiotic factors at both individual and stand levels. According to Köstner et al. (1992), canopy conductance can be derived from sap flow measurements if the sap flow through the xylem changes as a consequence of the stomatal response to environmental variables. Thus, up-scaled sap flux may provide a convenient way to evaluate the effect of the environmental variability on stomatal conductance. The mean canopy stomatal conductance (G_S) can be estimated using sap flux measurements in representative trees in various forest stands. As proposed by Köstner et al. (1992):

$$G_S = (G_V T_a \rho E_L)/D \quad (1)$$

However, this approach is only valid when the following requirements are met: (1) water stored in the plant contributes little to transpiration compared to water uptake from soil; (2) there is no vertical pattern of D within the canopy; and (3) the leaf boundary layer conductance is much higher than the stomatal conductance (Aphalo and Jarvis, 1991), meaning that a canopy is considered to be well coupled to the atmosphere.

As noted by Schäfer et al. (2000), this method is justified for well-coupled tree species, such as conifers, whose leaf character and crown structure meet the above requirements. However, the application of this method in broadleaf forests is still limited by the leaf and canopy properties (Motzer et al., 2005; Zhao et al., 2006), primarily by large leaf sizes, which create a thick boundary layer around the surface of the leaves and forest canopy. As reported by Zhao et al. (2011) for *Acacia mangium*, the relatively broader leaves tended to be buffered from the ambient air by the boundary layer produced by transpiration, resulting in a gradual decrease of aerodynamic conductance. The contribution of stored water in the xylem to transpiration was also significant, accounting for 8–10% of the total daily transpiration. The lag between the basal sap flow and canopy transpiration in *A. mangium* was ~2 h in the dry season, suggesting a non-negligible resistance in the xylem. Lag times (2.5 h) have also been observed for *S. superba* in the dry season (Mei et al., 2010).

Despite its application limitations, Eq. (1) has been used in some research on canopy water regulation of broadleaf species (e.g., Ewers et al., 2007; Whitley et al., 2009), where a dimensionless decoupling coefficient (Ω) was calculated to analyze the dependence of canopy transpiration on physical or physiological factors. However, because Ω is not constant due to the temporal and spatial variance of the environmental conditions throughout a day, it may not be appropriate to apply Eq. (1) using an averaged value of Ω. Thus, there is a need to test whether a simple plant hydraulic model can capture the inherent features of G_S with the daily and seasonal variability in Ω.

The Penman–Monteith equation (Monteith and Unsworth, 2007) is the most commonly used method to describe the process of canopy transpiration by integrating both plant physiology and micrometerological factors (Lu et al., 2003), and has frequently been applied to calculate a reference evapotranspiration (ET_o) index as a function of weather parameters. Its inverse form (Eq. (7)) is also widely applied to quantify canopy parameters (Zeppel and Eamus, 2008). This equation describes the relative importance of radiative and advective energy for the tree transpiration rate (E_T), the dominant evaporation component (Kelliher et al., 1992). This depends on the ratio of the aerodynamic to canopy conductances (Köstner et al., 1992). The model can be written as (Jarvis, 1976):

$$E_T = \Omega E_{eq} + (1 - \Omega) E_{imp} \quad (2)$$

where E_{eq} is the transpiration rate obtained in equilibrium with an extensive, homogeneous wet surface via the energy balance, which is dominated by the airflow on the canopy. E_{imp} is the transpiration rate imposed by the effects of the air saturation deficit (D, kPa). When Ω is small enough and E_{eq} can be ignored, the G_S estimation of Eq. (1) will be recovered from E_{imp} (Köstner et al., 1992). Alternatively, the overestimated E_{imp} would result in an overestimation of G_S. Therefore, we assume that the estimation of G_S with Eq. (1) would be overestimated compared to the Penman-Monteith equation when applied to broadleaf species.

The objectives of this research were to: (1) evaluate the dynamic of the decoupling conditions of two planted forests, *E. urophylla* and *S. superba*, with similar environmental conditions throughout the year and (2) estimate the seasonal variation of stomatal control for the planted forests via two different methods and to compare their accuracy for the calculation of the canopy stomatal conductance in an attempt to acquire more accurate knowledge of stomatal conductance responses to environmental changes. We assumed that the simplified equation would underestimate G_S for broad-leaf species because of its limitations. Based on this, we focused on the extent of the underestimation of the two broad-leaf species with different canopy structures, and aimed to determine the underlying mechanism of the underestimation among species based on the calculation of Ω.

2. Materials and methods

2.1. Site description

This study was conducted in separate *S. superba* and *E. urophylla* plantations. The *S. superba* plantation is situated in the South China Botanical Garden, Chinese Academy of Sciences, Guangdong Province, China (23°100′N, 113°210′E, altitude 41 m). It is characterized by a low subtropical monsoon climate, with an annual precipitation of 1612–1909 mm and a mean annual temperature of 21.4–21.9 °C. The wet season lasts from April to September, followed by the dry season, which lasts until the next March (Zhu et al., 2012). The *S. superba* stand was planted in the mid-1980s on a northeast-facing slope, with an inclination of 11.7°. The area contains a loam soil with a pH of 4.0, organic content of 2.3% and total nitrogen content of 0.07%. The *E. urophylla* plantation grows on a south-facing slope (inclination 28°) located at the Huangmian Forest Farm, Guangxi Province, China (24°78′N, 109°87′E). The *E. urophylla* experimental site is in the transitional zone between the low- and mid-subtropics, receiving abundant radiation and