



# Modeling the environmental controls on tree water use at different temporal scales



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## ABSTRACT

Tree water use ( $E_c$ ) can be simulated from environmental variables. Such  $E_c$  models can be categorized as firstly the Penman-Monteith (PM) equation where canopy conductance ( $g_c$ ) is simulated from the Jarvis-Stewart (JS) approach, secondly the models modified from the JS approach that link  $E_c$  directly with environmental variables (MJS), avoiding the calculation of  $g_c$ , and thirdly process-based models that incorporate plant physiological functions. Tree water use and canopy conductance are constrained by the root-zone soil water supply and atmospheric demand (e.g., radiation, temperature, humidity and wind speed). This study aims to determine which type of  $E_c$  models performs better at the daily and hourly scales, and which influencing factors are more critical for  $E_c$  modeling at each time scale. The transferability of parameter values across temporal scales is also examined as this is a common issue that modelers need to deal with. The results show that the MJS and a simplified process-based model (BTA) models produce generally better simulations than the PM models at the hourly scale, and the best PM model gives comparable results to the best MJS model at the daily scale. BTA fails at the daily scale on the tree under water stress likely due to its incorporation of soil water availability into an integrated parameter. Soil water content function is more important for daily  $E_c$  modeling than hourly in all models. For MJS models, soil water content function has a stronger influence than air temperature on hourly  $E_c$  modeling, while no significant difference is observed in the PM models. Parameter values are not transferrable across temporal scales; and calibrating parameters in each season rather than in the first a number of days of all seasons improves  $E_c$  simulations.

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## 1. Introduction

Vegetation covers 70% of the global land surface (Dolman et al., 2014), playing an important role in land surface hydrological and climatological processes, and coordinating land-atmosphere interactions in a wide range of spatial and temporal scales (Chen et al., 1996; Dickinson, 1987; LeMone et al., 2007). Vegetation affects water, carbon and energy transfer in the soil-plant-atmosphere system by altering surface albedo, roughness and soil macroporosity, intercepting rainfall and transpiring water from soil layers (Ivanov et al., 2008). Several studies confirmed that vegetation transpiration ( $E_c$ ) contributes a large proportion of total global terrestrial evapotranspiration (ET) (Jasechko et al., 2013; Miralles et al.,

2011; Schlaepfer et al., 2014; Schlesinger and Jasechko, 2014; Wang et al., 2010). Although the reported numbers vary over different ecosystems, they highlight the importance of quantifying rates of vegetation water use for understanding of land-atmosphere interactions.

Transpiration at the tree and plot scales can be estimated using sap flow techniques (Ford et al., 2007; Hatton et al., 1995). Alternatively, transpiration can be estimated from potential transpiration by applying stress functions related to different environmental variables, e.g., temperature, vapor pressure deficit, solar radiation, soil water content/potential and plant water potential (Damour et al., 2010; Jarvis, 1976; Tuzet et al., 2003; Wang et al., 2014), and CO<sub>2</sub> concentration (Ball et al., 1987). Such an approach can be applied over various spatial scales, and has long been incorporated into land surface and atmospheric models (Dai et al., 2004; Dickinson et al., 1991; Noilhan and Planton, 1989). The reduction of potential  $E_c$  is often realized by replacing the canopy conductance  $g_c$  under the optimal conditions in the Penman-Monteith (PM) equation with the one under the environmental stresses, well

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known as the Jarvis–Stewart (JS) approach (Jarvis, 1976; Stewart, 1988). In this study, PM equation with the embedded JS- $g_c$  model was labeled as the PMJS method.

Apart from studies using the Penman–Monteith equation, there have been several attempts to estimate  $E_c$  directly from environmental variables. For example, Whitley et al. (2009, 2013) applied such method for transpiration simulations at different Australian forest sites. Garcia et al. (2013) also applied a similar  $E_c$  model in a woody savannah in Mali and grassland in Spain using in-situ and satellite data. These models estimate transpiration from a maximum rate by applying a set of functions of the relevant environmental variables, based on a similar assumption with the JS- $g_c$  approach that the stress from environmental variables on plant water use is independent of each other. Essentially, these models are modified from and considered as variants of the JS approach. Compared to the PMJS method, they are much simpler to fit, require fewer measurements and specifically avoid the circularity of inverting the PM equation to calculate  $g_c$  from  $E_c$  and then using the PM again to estimate  $E_c$  from  $g_c$ . To differentiate this way of  $E_c$  modeling from the PMJS, we labeled this type of model as MJS in this study.

In addition, there have also been  $g_c/E_c$  models based on knowledge of the physical processes at cellular level, i.e. exploration on plant guard cell functions and the hydro-mechanical and biochemical influences in and around guard cells (Buckley and Mott, 2002; Dewar, 2002; Franks et al., 1998; Gao et al., 2002). On the basis of a series of assertions, Buckley et al. (2003) developed a process-based  $g_c$  model with clear physiological interpretations and later simplified it (Buckley et al., 2012) for transpiration as well as canopy conductance modeling. The simplified model (labeled as BTA model hereafter) has two to four parameters that are related to reduced processes and properties, allowing us to have a transparent understanding about how those parameters respond to environmental changes (Buckley et al., 2012).

Widely used environmental variables in  $E_c/g_c$  modeling can be divided into two groups as to how they affect tree water uptake, i.e. atmospheric demand and water supply. The demand group includes solar radiation, air temperature and humidity, and wind speed. Air temperature function is often neglected in  $g_c$  models that use humidity as one variable (Lhomme et al., 1998; Mascart et al., 1991). Vapor pressure deficit is also favorably used for  $E_c/g_c$  modeling, and is highly correlated with air temperature (Alves and Pereira, 2000). Some studies included both functions of air temperature and vapor pressure deficit while others used only one (Damour et al., 2010). The supply group mainly refers to the root-zone soil moisture, determined by water content, soil hydraulic properties and root distribution. It is worth mentioning that plants respond to soil water potential rather than soil water content (Gregory and Nortcliff, 2013; Marshall et al., 1996; Mullins, 2001; Verhoef and Egea, 2014). Soil water content in most studies was measured in shallow soil layers, up to 2 m deep and usually 0.5 m (Whitley et al., 2009). It is uncertain whether such measurements can capture the entire picture of root-zone water availability (Schulze et al., 1996), especially for deep rooted trees. It is the gradient of water potentials in soil, stem and leaves that drives water transport in the soil–plant system (Vandegheuchte et al., 2014). Plant water potential is a sensitive indicator for vegetation water status (Choné et al., 2001; Nortes et al., 2005) and can be in equilibrium in the whole soil–plant system at predawn unless significant nocturnal transpiration occurs (Palmer et al., 2010; Richter, 1997). Therefore, predawn plant water potential is a better approximate of root-zone soil water availability than the shallow layer soil water content. Previous studies have proved the feasibility of using predawn stem water potential to indicate plant water stress and simulate canopy conductance (Wang et al., 2014; Yang et al., 2013).

Despite the wealth of literature in considering the supply factor for  $E_c$  and  $g_c$  modeling, some studies showed success without including this factor (Bunce, 2000; Leuning, 1995; Whitley et al., 2013). Typical examples are transpiration from trees with ground-water access by deep roots (Eamus and Friend, 2006) and from trees growing in riparian sites (O'Grady et al., 2006). However, at other sites, it is difficult to determine the significance of soil water availability for  $E_c$  or  $g_c$  modeling without long-term monitoring of the relevant variables. Furthermore, soil water availability has seasonal variations in correspondence with precipitation (Findell and Eltahir, 1997), which means that the necessity to include a soil water stress function may vary seasonally. Note that seasonality of soil water content is also strongly influenced by plant water uptake.

Usually parameters need to be re-calibrated when models are applied at a different site or temporal scale, however, in many land surface models parameters are prescribed for lumped vegetation functional types, for example, evergreen needle-leaf trees, deciduous broad-leaf trees, etc. (Chen and Dudhia, 2001). These parameter values remain the same for simulations at various temporal/spatial scales in practice. This can be problematic given the nonlinear relationship between transpiration and the environmental variables, and the fact that environmental variables' values differ from one spatial-temporal scale to another.

This study examined the performance of selected PMJS, MJS and BTA  $E_c$  models at daily and hourly scales. By comparing the simulation results, we focus on the following four specific questions: (1) Which type of  $E_c$  modeling approach performs better? (2) Are soil water content and air temperature functions critical for  $E_c$  simulation? (3) At which time scale and in which season do soil water and air temperature functions pose a stronger influence on  $E_c$  modeling? (4) Are parameter values transferable across different temporal scales (daily and hourly) for the same  $E_c$  model?

## 2. Methodology

### 2.1. Site and measurements

The study site is on the campus of Flinders University (138°34'28"E, 35°01'49"S), located in a Mediterranean climate zone. Annual mean temperature is about 17 °C, and annual rainfall is around 546 mm, most of which occurs in May to September (Guan et al., 2013). Ground surface is covered by sparse trees with short shrubs and grass at substrate. Soil type is characterized as sandy mixed with gravel. The soil condition makes it difficult to bury soil moisture probes in deep root-zone soil layers near the tree. Therefore, as discussed in previous work (Wang et al., 2014; Yang et al., 2013) stem water potential was used as an indicator of root-zone soil water availability. We conducted measurements on four Drooping Sheoak (*Allocasuarina verticillata*) trees over different time periods in 2011, 2012 and 2014. The discussion in this study is based on one tree with continuous measurements in January to April and October to December in 2012. Data from the other three trees covered shorter periods, and were mainly for consistency check on results of canopy conductance modeling among trees in a previous work (Wang et al., 2014), and not included in this study.

Sap flow was monitored at 30-min intervals in the tree trunks at 1.3 m above ground using the compensation heat-pulse technique (Green and Clothier, 1988). Three thermocouples were embedded inside each temperature probe at the depths of 5, 15 and 25 mm underneath the cambium. One temperature probe was installed 10 mm above the heater and the other 5 mm below the heater. Two sets of such probes were installed in the south and north sides of the tree. Transpiration was calculated from heat transport velocity and corrected for wounding, sapwood area, volume fraction of wood and water following Green et al. (2003).

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