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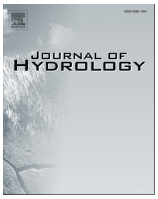

Research papers

Stand-level variation in evapotranspiration in non-water-limited eucalypt forests

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ABSTRACT

To better understand water and energy cycles in forests over years to decades, measurements of spatial and long-term temporal variability in evapotranspiration (E_a) are needed. In mountainous terrain, plot-level measurements are important to achieving this. Forest inventory data including tree density and size measurements, often collected repeatedly over decades, sample the variability occurring within the geographic and topographic range of specific forest types. Using simple allometric relationships, tree stocking and size data can be used to estimate variables including sapwood area index (SAI), which may be strongly correlated with annual E_a. This study analysed plot-level variability in SAI and its relationship with overstorey and understorey transpiration, interception and evaporation over a 670 m elevation gradient, in non-water-limited, even-aged stands of *Eucalyptus regnans* F. Muell. to determine how well spatial variation in annual E_a from forests can be mapped using SAI.

Over the 3 year study, mean sap velocity in five *E. regnans* stands was uncorrelated with overstorey sapwood area index (SAI) or elevation: annual transpiration was predicted well by SAI (R^2 0.98). Overstorey and total annual interception were positively correlated with SAI (R^2 0.90 and 0.75). E_a from the understorey was strongly correlated with vapour pressure deficit (VPD) and net radiation (R_n) measured just above the understorey, but relationships between understorey E_a and VPD and R_n differed between understorey types and understorey annual E_a was not correlated with SAI.

Annual total E_a was also strongly correlated with SAI: the relationship being similar to two previous studies in the same region, despite differences in stand age and species. Thus, spatial variation in annual E_a can be reliably mapped using measurements of SAI.

1. Introduction

Evapotranspiration is an important component of global water and energy budgets (Jung et al., 2010), accounting for two-thirds of global precipitation (Zhang et al., 2016). Covering 30% of the total land surface, forests are a large contributor to actual evapotranspiration (E_a) and therefore modelling of global water and energy budgets must accurately represent E_a of forests. Improved understanding of spatial and temporal variability of E_a in forests will aid prediction of effects of changes in forests on hydrology and climate (Alkama and Cescatti, 2016).

In mountainous terrain, E_a varies substantially over distances of a few hundred m (Ford et al., 2007; Loranty et al., 2008; Mitchell et al., 2012a,b), due to variability in topography, climate, soil and vegetation. For example, Mitchell et al. (2012b) observed 40% variation in annual E_a between upper, mid and lower slope positions in a 1.36 km^2 catchment.

Studies of E_a at tree to plot-scale, enable exploration of relationships between stand E_a and other attributes such as leaf area index or sapwood area index (ratio of sapwood cross-sectional area to

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Abbreviations: Baob, stand basal area measured over bark ($m^2\,ha^{-1}$); CHP, compensation heat pulse method used to measure sap velocity (V_s); dbh, stem diameter measured at 1.3 m height (cm); E_a, actual total evapotranspiration from overstorey, understorey and forest floor ($mm\,day^{-1}$ or $mm\,year^{-1}$); E_i, total interception by the overstorey and understorey (% of P or $mm\,year^{-1}$); Eo_i, interception by the overstorey (% of P or $mm\,year^{-1}$); Eu_i, interception by the understorey (% of P or $mm\,year^{-1}$); Eo_t, transpiration by the overstorey ($mm\,day^{-1}$ or $mm\,year^{-1}$); E_u, E_a from the understorey including interception, soil evaporation and transpiration ($mm\,day^{-1}$ or $mm\,year^{-1}$); Eu_t, transpiration and evaporation from dry understorey and forest floor (soil, litter, $mm\,day^{-1}$ or $mm\,year^{-1}$); HR, heat ratio method used to measure V_s; LAI, leaf area index: the ratio of leaf area to ground area; R_n, net radiation ($w\,m^{-2}\,s^{-1}$ or $Mj\,m^{-2}\,day^{-1}$); R_s, solar radiation ($w\,m^{-2}\,s^{-1}$ or $Mj\,m^{-2}\,day^{-1}$); SA, sapwood area: the cross-sectional area of sapwood measured at 1.3 m height (cm^2 or m^2); SAI, sapwood area index: the ratio of stand sapwood area to ground area ($m^2\,ha^{-1}$); TF_o, throughfall collected beneath the overstorey but above the understorey (% of P or $mm\,year^{-1}$); TF_u, throughfall collected beneath the understorey (% of P or $mm\,year^{-1}$); VPD, vapour pressure deficit (kPa); V_s, sap velocity (volume of sap passing through the sapwood area per unit of time, $cm^3\,cm^{-2}\,h^{-1}$ which simplifies to $cm\,h^{-1}$); V_{smax}, plot mean V_s based on the higher of V_s estimated by the HR or CHP methods ($cm\,h^{-1}$); V_{sHR}, plot mean V_s estimated using only HR sensors ($cm\,h^{-1}$).

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ground area). In many forests, plot-scale measurements of tree numbers and sizes have routinely been collected over decades. If these inventory data can be related to mean annual E_a through plot-scale studies of E_a and its components, there is the opportunity to map variation in mean annual E_a in space and time using allometric relationships applied to the inventory data. For example, in even-aged eucalypt forests in south-eastern Australia, catchment mean overstorey sapwood area index (SAI), estimated from a relationship between stand mean sapwood thickness and tree density (trees ha^{-1}), applied to repeated measurements of tree density and mean tree diameter over several decades, was strongly correlated with catchment mean annual E_a, estimated as annual precipitation minus annual streamflow (Benyon et al., 2015). Jaskierniak et al. (2015b, 2016) developed methods for accurate spatial mapping of SAI using airborne LiDAR and temporal mapping of SAI using long-term forest inventory data and growth models and applied this across three catchments with a combined area of 100 km^2, to accurately predict annual streamflows over an 80 year period. These recent studies were largely empirical, deriving catchment annual E_a as precipitation minus streamflow and relating this "catchment loss" to estimates of SAI.

Applying such methods more broadly requires an understanding of how forest stand properties derivable from forest inventory data are related to the various components of annual E_a. This approach not only utilises routinely collected forest inventory data, but also puts the "forest" squarely into forest hydrology, as opposed to relying on over simplified assumptions about forest "cover" and E_a. Further, exploring the relationship between a stand attribute that is an integrated metric of stand productivity and longer term site conditions, and the stand's hydrologic signal, assists in improved understanding of ecosystem functioning.

For this article we measured components of annual E_a at the plot-scale in the Maroondah catchment near Melbourne, Australia, to understand the relationship between annual E_a and SAI. We use SAI rather than LAI because SAI can easily be estimated using commonly collected forest inventory data, if the relationship between sapwood mean thickness and stand density is known (Benyon et al., 2015) and because SAI is probably less variable seasonally than LAI. Deriving allometric relationships between simple measures, such as tree diameter, and sapwood area is easier than obtaining whole tree measurements of leaf area: a few wood cores are collected near the stem base (typically at 1.3 m height) compared with destructive, whole tree sampling required to accurately measure tree leaf area. In several previous plot-scale studies of E_a components in eucalypt forests in southern Australia, decadal variation in transpiration (often the largest component of E_a), was more strongly correlated with changes in SAI than with changes in LAI (Dunn and Connor, 1993; Vertessy et al., 1995, 1997, 2001; Roberts et al., 2001; Macfarlane et al., 2010; Buckley et al., 2012). A shortcoming of most of these studies was their use of only one sap-flow-measurement plot in each age class and use of study periods of only a few months. The spatial variability in mean sap velocity within forest age classes was not determined. The range in SAI (4.0–11.9 m^2 ha^{-1}, Benyon et al., 2015) observed recently within a single age class of *Eucalyptus regnans* F. Muell., is greater than reported between stands aged from 15 to 230 years in the same species (see Table 5), suggesting that, if mean sap velocity does not differ substantially between stands with low and high SAI, annual transpiration and E_a must be highly spatially variable, even within a single forest age class.

Pfautsch et al. (2010) observed a strong correlation between daily transpiration and air temperature in *E. regnans*. Since air temperature would vary substantially across the ~800 m elevation range of this species, annual transpiration and E_a might differ between low and high elevation stands, or there may be a difference in the relationship between SAI and E_a at low and high elevation, or perhaps stand SAI varies with elevation. Variation in E_a with elevation might also indicate changes in E_a at specific elevations that will occur in a warming climate.

This paper examines spatial variation in the components of annual E_a and its relationship with SAI in non-water-limited *E. regnans* forests of a uniform age. Our objectives were to: (1) determine whether there are statistically significant differences in annual mean sap velocity between stands of the same age having low and high SAI across an elevation gradient; (2) determine whether throughfall, and therefore interception, is correlated with SAI; (3) determine whether E_a from the forest floor and understorey is correlated with overstorey SAI; and (4) estimate total annual E_a, examine the correlation between E_a and SAI and compare the E_a/SAI relationship with two previous studies to determine the broader utility of SAI measurements for mapping spatial and temporal variation in E_a across forests in the region. These four objectives primarily provide the sub-headings used in the Methods, Results and Discussion sections.

2. Methods

2.1. Sites

Six circular plots with overstorey SAI of 4.0–11.6 m^2 ha^{-1}, were established in Maroondah catchment, 80 km northeast of Melbourne, Australia, within 2 km of latitude 37°35′45″ S, longitude 145°35′54″ E (Table 1, Fig. 1). Plots were either flat (Plot 4), or on south-east (Plots 3, 5 and 6) or south-west (Plots 1 and 2) aspects along an elevation gradient from 217 m to 889 m. Based on precipitation mapping by Watson et al. (1998) using 73 rain gauge sites located within 15 km of the centre of Maroondah catchment, mean precipitation increases from ~1300 mm $year^{-1}$ at the lowest elevation site to ~1800 mm $year^{-1}$ at the highest elevation site. The climate is warm, temperate and rainy, while soils are 10–15 m deep, well-structured krasnozems, having high infiltration and water holding capacity (Langford and O'Shaughnessy, 1977).

The dominant *E. regnans* overstorey in Plots 1 to 5 regenerated as even-aged stands after high intensity wildfire in 1939. Unlike many fire-tolerant *Eucalyptus* species which resprout after wildfire, *E. regnans* is usually killed by moderate to high intensity wildfire with the forest regenerating in dense, even-aged stands from seedlings (Ashton, 1976). Understorey of each plot regenerated following low intensity wildfire in 2009 that was hot enough to remove the previous understorey but not so hot as to kill the 73 year old *E. regnans* overstorey.

The sixth plot, located within about 30 m of Plot 3, was dominated by *Pomaderis aspera* Sieber ex DC. Plots 1 to 5 contained seven to nine overstorey *E. regnans* trees, while Plot 6 contained 45 *P. aspera* trees (Table 1).

Two automatic weather stations, located in clearings at ~200 m and ~800 m elevation, within 1 km of the lower and higher sites (Fig. 1), collected measurements of precipitation, air temperature, relative humidity, solar radiation and wind speed every 6 min from October 2012 to October 2015.

2.2. Sap velocity, sapwood area and overstorey transpiration (Objective 1)

Daily (24 h from 6 am to 6 am) and annual mean sap velocity (V_s) was calculated from measurements every 30 min using the heat pulse technique for the periods indicated in Table 1. Overstorey transpiration (Eo_t) was estimated as the product of plot mean V_s and plot SAI.

Sapwood area (SA) in all *E. regnans* trees was estimated from measurements of stem diameter at 1.3 m height (dbh), bark thick-