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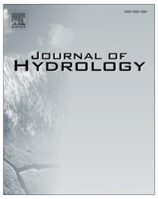

Validation of canopy transpiration in a mixed-species foothill eucalypt forest using a soil–plant–atmosphere model

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SUMMARY

Studies of the hydrology of native eucalypt forests in south-east Australia have focused on ash-type eucalypt species that are largely confined to Victoria and Tasmania. Mixed species foothill forests comprise the largest proportion of the forest estate in south-east Australia, yet are poorly known hydrologically. The ability to predict forest transpiration, both with reasonable accuracy and in response to changes in the environment, is essential for catchment management.

A soil–plant–atmosphere model (SPA) was validated for 222 days in a mature, mixed species forest of north-east Victoria using measurements of overstorey transpiration (*Eucalyptus radiata* and *Eucalyptus goniocalyx*) and site-specific climate and vegetation parameters. There was a stronger relationship between average daily transpiration (0.71 mm day^{-1}) and daily minimum relative humidity ($R^2 = 0.71$), than between average daily transpiration and daily maximum temperature ($R^2 = 0.65$). Stand water use could be predicted best from vapour pressure deficit ($R^2 = 0.89$).

SPA successfully predicted stand transpiration ($R^2 = 0.85$) over a range of soil water and climatic conditions. A sensitivity analysis suggests that among the various required inputs, leaf area index (LAI) was the most important, and accurate estimates of LAI could significantly improve estimation of stand transpiration.

1. Introduction

Forested catchments in south-east Australia supply water to cities, agriculture and industry, and to millions of people. Water yield is largely governed by the loss to the atmosphere via plants (e.g. trees and other vegetation), of soil water and intercepted rainfall. At the scale of the Australian continent, almost 3,100,000 GL of the 3,200,000–3,900,000 GL water received annually as rainfall is lost by evapotranspiration (Eamus et al., 2006) and for some parts of the native forest estate evapotranspiration accounts for all (100%) of the annual rainfall (e.g. Bren and Hopmans, 2007).

In the State of Victoria in south-east Australia, almost 79% of the total forested area is dominated by mixed species eucalypt forest (Attiwill, 1994). Even so, most studies investigating impacts on forest hydrology of stand age (Dunn and Connor, 1993; Haydon et al., 1997; Vertessy et al., 2001), forest disturbance (Kuczera, 1987; Langford, 1976), climate (Pfautsch et al., 2010), and stand structure (Vertessy et al., 1995), have been confined to ash-type eucalypt forests due to their dominance of catchments for the City of Melbourne. By contrast we have little knowledge of the patterns and drivers of tree water use for the millions of hectares of mixed species eucalypt forest or base-level quantification of tree water use.

Topographic, geological and climatic variations across forested catchments in south-east Australia are accompanied by variation in dominance by tree species. Mixed species eucalypt forests are common in the foothills of the Great Dividing Range and the overstorey often comprises combinations of peppermints (e.g. *Eucalyptus radiata*, *Eucalyptus dives*), stringybarks (e.g. *Eucalyptus obliqua*, *Eucalyptus macrorhyncha*, *Eucalyptus baxteri*) and boxes (e.g. *Eucalyptus gonniocalyx*, *Eucalyptus polyanthemos*). These forests typically grow on soils that are duplex in structure with high proportions of sand or rock throughout soil profiles, and clearly differ hydrologically to adjacent wet ash-type forests of *Eucalyptus regnans* and *Eucalyptus delegatensis* that grow on deep, well-structures soils (Lacey and Grayson, 1998).

Recently Mitchell et al. (2012) showed that at the catchment scale, overstorey transpiration (E_c) in mixed species eucalypt forests strongly influences water balance. They noted that such influence varies with forest structure that was in turn influenced by aspect and topography. Canopy transpiration is regulated by a number of biological and environmental variables which are

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expected to vary among sites and species. Among environmental variables that underline variations in E_c, canopy transpiration is expected to depend mainly on temporal (Gazal et al., 2006; Oren and Pataki, 2001) and spatial (Granier et al., 2000; Tromp-van Meerveld and McDonnell, 2006) variations in soil moisture and sensitivity to the combination of temperature and relative humidity in the air (Ewers et al., 2013) as reported by previous studies.

More generally, soil and atmospheric conditions regulate water use in eucalypt forests. For example, water extraction from deep in soil profiles must be invoked to explain observed transpiration rates by some eucalypt species during drought periods (e.g. Leuning et al., 2005). In other cases, eucalypt water use is insensitive to large changes in soil moisture content in the upper soil profile (e.g. Zeppel et al., 2008; Buckley et al., 2012). Eucalypts though are not different to other genera with respect to mechanisms and controls of water uptake from soils, which vary widely among species and sites. In contrast, there are clear and reasonably well-understood mechanisms that underpin relationships of atmospheric variables to forest water use (Dierick and Hoelscher, 2009; Oren and Pataki, 2001).

Climate variables such as radiation and vapour pressure deficit (VPD) explain a considerable proportion of variation in tree water use in a number of eucalypt forests, with accompanying diurnal and seasonal variations (O'Grady et al., 1999; Pfautsch et al., 2010; Zeppel et al., 2004). Zeppel et al. (2004) for example, reported that radiation was the dominant driver of tree water use in a coastal eucalypt forest while Pfautsch et al. (2010) found maximum daily temperature to be an appropriate proxy for atmospheric control of water use in mountain ash forests with sufficient soil moisture.

Similar knowledge about the patterns and dynamics of water use is missing for the foothill forests of south-east Australia, and is the focus of this study. Improved knowledge of the dynamics of water use by mixed species eucalypt forests is critical to improving the hydrological models that are relied upon by those who manage the large water basins and catchments in SE Australia (Murray Darling Basin Authority, 2011). These models need also to be better informed in choosing appropriate parameters and assumptions for simulating transpiration. For example, night time transpiration has now been reported as comprising up to 10% of diel (24 h) water use for a range of eucalypt forests (Buckley et al., 2011; Pfautsch et al., 2011; Phillips et al., 2010; Zeppel et al., 2010), and up to 20% around the world (Dawson et al., 2007). These observations bring into question the common assumption made by many hydrological models that night-time transpiration is negligible due to the controlling influence of solar radiation on overall transpiration. In this study we explored the contribution of water loss during the night to total water use in mixed species eucalypt forests. In addition, some important biological variables that explain the observed variations in canopy transpiration include changes in transpiration with age which is associated with hydraulic limitations of stomatal conductance (Delzon and Loustau, 2005), or tree size (Dawson, 1996), and regulation of transpiration by stomatal conductance as it is simulated by a range of physiological processes (Collatz et al., 1991). In this study biological controls of transpiration were tested within a scheme as represented by a soil–plant–atmosphere model. In this scheme stomatal conductance optimizes daily carbon (C) gain per unit leaf nitrogen (N) within the limitations of the hydraulic system, minimizing the risk of cavitation and damage to the tree. Leaf-level photosynthesis is simulated by the Farquhar model (Farquhar and Von Caemmerer, 1982) and the Penman–Monteith equation is used to determine transpiration.

Bio-hydrological models that can successfully reproduce and predict water fluxes can replace costly and labour-intensive alternatives; however applicability of such models is not assured for every forest type. One such model is the soil–plant–atmosphere (SPA) model of Williams et al. (1996). SPA is a process-based model that simulates eco-hydrological processes between soil, plant and atmosphere, including evapotranspiration, soil energy flux, and gross primary production. The model employs variable stomatal conductance, and carbon uptake is maximized within limitations of canopy water availability (Jones and Sutherland, 1991). The scale of parameterization (leaf level) and prediction (canopy level) allow for scaling up leaf-level processes to canopy and landscape scales (Williams et al., 2001b).

SPA has been tested in a number of forest types. These include: mixed deciduous (oak-maple) forest (Williams et al., 1996), boreal forest (Williams et al., 2000) and tropical rainforest (Williams et al., 2002). In Australia, Zeppel et al. (2008) validated the model for a eucalypt-dominated coastal woodland. Owing to the great variability in species dominance and structure of eucalypt forests in Australia (Specht and Specht, 1999), it remains unclear how much confidence can be attributed to predictions made using SPA or any other similar model in the majority of forests of south-east Australia. If SPA successfully predicts forest water use without intensive parameterization and input collection, it provides a valuable tool for a range of purposes.

The objective of this study was to directly measure overstorey (*E. radiata* and *E. goniocalyx*) transpiration in a mature mixed species eucalypt forest in north-eastern Victoria, Australia, and ascertain which variables (e.g. soil moisture, atmospheric conditions, forest structure) could best explain patterns of transpiration by first parameterizing SPA and then testing its sensitivity to input variables.

2. Materials and methods

2.1. Experimental site

Our research site lies within a mixed-species forest in south-eastern Australia (36.745°S, 147.188°E), within 5 km of the township of Mount Beauty. The site is around 250 km north east of the City of Melbourne in the State of Victoria. Mean annual rainfall (1971–1994) in the general area of Mt Beauty is 1263 mm with 113 days of rainfall >1 mm, and 25% of rainfall events in July and August (Bureau of Meteorology, as recorded 3.5 km north east of the site).

The forest is dominated by *E. radiata* Sieber ex DC (narrow-leaved peppermint) and *E. goniocalyx* Miq. (long-leaved box), however, as is typical of such forests, one species (*E. radiata* in this case) provides the bulk of leaf area and basal area (93% of the basal area and 88% of the stocking). Measured tree density was 264 stems ha^{-1} and the stand had a total basal area of 30.3 m^2 ha^{-1}. Our experimental period ran from July to November 2009 and February to May 2012.

2.2. Soil measurements

Soils were classified visually using Isbell (2002) and the Australian Soil Resource Information System (ASRIS), as a Chromosol with a strong contrast between A and B horizons. Soil depth was estimated at 1 m, beyond which lay decomposing bedrocks. The soil profile was duplex in structure, with a strong texture contrast between upper and lower soil horizons (Northcote, 1979).

Five replicate soil samples from 10 cm, 50 cm, and 100 cm were collected using a 75 mm auger and transported to the lab in zip-locked plastic bags for particle analysis. Proportions of sand and clay were measured following methods of Allen (1989). Mineral and organic soil fractions were directly measured by loss on ignition at 550 °C for 5 h in a muffle furnace (Allen, 1989).