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**Quantifying the Heterogeneity of Transpiration Fluxes from Tree Crowns: Results from a Case Study on Eucalyptus Trees in the West-Australian Wheatbelt**

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**Introduction**

Trees and shrubs often grow in irregular patterns. Fluxes of heat and mass as well as momentum exchange are more difficult to quantify under such conditions and require consideration of intra-canopy processes. A generic model has been constructed to simulate the heterogeneity of transpiration fluxes from non-uniform plant canopies. It was parameterised and tested in a natural *Eucalyptus* forest located in the centre of the West-Australian wheatbelt, which is currently heavily affected by soil salinity due to inappropriate land management over the past decades. The general purpose of the study was to understand the water use patterns of the natural vegetation for redesigning agricultural systems.

**Model**

The model subdivides the canopy space into three-dimensional cubic cells called voxels. Each voxel is treated as a turbid medium and can be filled with different plant parts, such as leaves, twigs, or stems, whose orientation distribution functions and surface area densities are entered as input data. In this particular study we assumed that the canopy consists of leaves only, which is a reasonable approximation for *Eucalyptus* trees which have their leaves concentrated on top of their canopies. Heterogeneity of leaf area density is considered by changing the size or statistical attributes of individual voxels. Incident global radiation and standard physical air characteristics are the driving variables of the model. Radiation balances and fluxes of latent and sensible heat are simulated on an individual cell basis.

The probability  $P_k$  that a beam is intercepted in a particular voxel cell with address  $k_{x,y,z}$  is calculated with (Sinoquet et al. 2001):

$$P_k = (1 - \exp[-G_k(\Omega) a_k \delta_k]) \cdot \exp\left[-\sum_{k'=1}^k G_{k'}(\Omega) a_{k'} \delta_{k'}\right] \quad (1)$$

where  $k'_{x,y,z}$  are the addresses of those voxels which have been previously visited by each beam,  $G(\Omega)$  is the projection of leaf area along the beam direction  $\Omega$  (Ross 1981), “a” the leaf area density and  $\delta$  the beam path length within each individual cell.  $G(\Omega)$  is calculated by weighting the leaf projective area with a leaf inclination distribution function which is set to a step-width of 10 degrees. Equation (1) is numerically integrated over the sky hemisphere for determining the diffuse light interception probability. The step widths were set to 10° and 15° for the zenith and azimuth classes, respectively.

Thermal infrared radiation was computed by assuming that significant longwave radiation exchange takes only place from the canopy fraction directly exposed to the cloudless portion of the sky hemisphere.

The Newton-Raphson method (Press et al. 1992) was applied for computing the surface energy balances of the sunlit and shaded leaf fractions of each voxel:

$$T_{s,l} - T_{a,k} - r_b \frac{Q_{\text{net},l,k} - LE_{l,k}}{\rho c_p} = 0 \quad (2)$$

where  $T_{s,l}$  is the unknown surface temperature (K) of the leaf fraction  $l$ ,  $T_{a,k}$  the air temperature in cell  $k$  (Kelvin),  $r_b$  the boundary layer resistance ( $\text{s m}^{-1}$ ),  $Q_{\text{net},l,k}$  the net radiation balance of leaf fraction  $l$  (sunlit or shaded), and  $\rho c_p$  the volumetric heat capacity of the air ( $\text{J K}^{-1} \text{m}^{-3}$ ).

The momentum roughness length and zero displacement of the *Eucalyptus* forest were calculated following the procedures of Raupach (1994) for scaling temperature and humidity from the measuring height to the crown level by using the logarithm law without stability corrections (Campbell and Norman 1998). Although this method would have allowed a vertical scaling of scalars within the crown by assuming horizontal homogeneity within the woodland, we have omitted such a procedure because the variability of scalars and vectors are likely to be small in sparse tree canopies such as *Eucalyptus salmonophloia*. Wind speed, air temperature and humidity were thus regarded as constant within the crown volume.

The latent heat flux  $LE_{l,k}$  ( $\text{W m}^{-2}$ ) from each voxel  $k$  was calculated with:

$$LE_{l,k} = \frac{\rho c_{p,k} (e_{\text{sat},l,k} - e_{\text{air},k})}{\gamma (r_{b,l,k} + r_{s,l,k})} A_{l,k} \quad (3)$$

where  $\rho c_{p,k}$  is the volumetric heat capacity of the air,  $l$  are the leaf fractions (sunlit or shaded),  $A_{l,k}$  the corresponding leaf areas ( $\text{m}^2$ ),  $e_{\text{sat},l,k}$  and  $e_{\text{air},k}$  the saturation and actual vapour pressures (Pa) at leaf and voxel air temperatures,  $\gamma$  is the psychrometric constant ( $\text{C}^{-1}$ ), and  $r_{b,l,k}$  and  $r_{s,l,k}$  are the leaf boundary and stomatal resistances ( $\text{s m}^{-1}$ ) connected in series.

The boundary layer conductance  $r_{b,l,k}$  is determined with a relationship parameterized for *Eucalyptus* trees (Silberstein et al. 2003)

$$r_{b,l,k} = \frac{f \delta}{\text{LAI} [1 - \exp^{-\delta/2}]} \left( \frac{\omega}{u_h} \right)^{1/2} \quad (4)$$

where “ $f$ ” is a constant ( $50 \text{ s}^{1/2} \text{ m}^{-1}$ ),  $u_h$  the wind speed on top of the tree crown and  $\delta$  the damping coefficient for wind speed and eddy diffusivity within the canopy ( $1.5 + 0.6 u_h$ ). The average width of *E. salmonophloia* leaves was set to 1.5 cm.

Stomatal light responses were calculated with an inverse Michaelis-Menten-type hyperbolic function. Responses to changes in air vapour pressure deficits were quantified with a power function (Jarvis 1976; Silberstein et al. 2003). Temperature corrections were omitted, as their influence on predictive qualities of the energy balance model were found to be generally small under the specific conditions of this experiment (Langensiepen et al. 2006).

## Material and Methods

The study was conducted in a species-rich nature reserve of the Corrigin Water Authority, which is located in the Western Australian wheatbelt. The reserve is approximately 1100 ha, has a catena of soil types and plant communities typical of the wheatbelt landscapes before they were

largely cleared for agricultural production at the beginning of the 20<sup>th</sup> century. A meteorological field station was operated at 800 m distance outside the woodland, which is dominated by mature *E. capillosa*, *E. salmonophloia* and *E. wandoo* trees.

For illustrative purposes we focus here on the results from a study which was performed on an individual *E. salmonophloia* tree. Its crown volume and distribution of total leaf area was estimated from silhouette images which were taken with a conventional digital camera. Projective cover and canopy porosity of the *E. salmonophloia* stand were derived from vertical camera images taken with a 70-mm lens (MacFarlane et al. 2005). The size of the voxels was set to 1 m x 1 m x 1 m according to the observed mean branch length of 1 m. Foliage orientation functions were taken from the literature (King 1987).

Stomatal responses to light and vapour pressure deficit were measured with a portable gas exchange system to define the minimum stomatal resistance and the shapes of the response curves of the Jarvis function. The model was tested against independent measurements of tree sap flow made using the heat ratio method (Burgess et al. 2001). Sap velocities were measured with three sensors positioned at the tree base and averaged. The resulting value was multiplied by the total cross-sectional area of the xylem to give total xylem water flow for the whole tree. The model was written with the Java programming language.

## Results and Discussion

Weather conditions underwent considerable seasonal changes during the period of study from March 6th 2004 until March 21st 2005 and set high requirements on the predictive quality of the model. Daily solar radiation ranged between 1 and 28 MJ m<sup>-2</sup> day<sup>-1</sup>, and average daytime vapour pressure deficit ranged from 0.1 kPa to extreme values of up to 5.0 kPa, which are seldom reported in the literature. Average daily windspeed showed comparatively little fluctuations over the season and typically ranged between 1.7 and 3.5 ms<sup>-1</sup>. The amplitude of mean daily temperature between summer and winter was 25°C.

Measurements of leaf area indices at Corrigin yielded a median value of 1.1 with an error range of 20% (MacFarlane 2005). The effect of this range of observations on simulation precision was tested in a sensitivity analysis. Increasing or decreasing LAI from 1.1 strongly affected the quality of predictions in all simulation experiments. In contrast, changing the tree foliage dispersion from a uniform to clumped distribution did not significantly affect simulation precision. One of the striking properties of most *Eucalyptus* trees is their nearly vertically oriented foliage, an adaptation to high midday solar radiation loads. We expected therefore that daily transpiration will increase when changing the leaf angle distribution to more horizontal orientations, but were surprised to find no differences between the mean squared and bias errors of the corresponding validation experiments. A closer analysis of the spatial changes in radiation absorption patterns during daily cycles revealed, however, that the crowns were indeed behaving in the expected manner: light absorption was concentrated on the sun-facing peripheral crown regions at low sun heights and shifted into deeper crown levels with increasing sun elevations, depending on the chosen leaf angle distribution. This indicates that the parabolic shape of the crown together with a sparse and slightly clumped leaf area distribution seems to be laid out for optimizing radiation absorption during the entire day. This optimization would have been prevented if the leaf area were concentrated on the crown periphery. It is reported in the literature that *Eucalyptus* trees might have developed this strategy in response to two different ecological factors: (1) High radiation loads paired with limiting water availability and (2) Shade intolerance that may be related to a dependence on fire for regeneration and dominance (King 1997). Further analyses must be performed on the intracanopy and less than hourly time scales to verify this hypothesis.

The qualities of model computations were largely influenced by stomatal parameterization. Bias errors became as high as 0.47 mm/day when the stomatal response function was driven by light alone. Transpiration was particularly overestimated when crown air vapour pressure deficits exceeded 2.0 kPa. This observation is in agreement with studies on other *Eucalyptus* species that reported a stomatal closing response beyond this threshold level (see Silberstein et al. 2003 for example). The following two-parametric function was selected for correcting the light response function with respect to VPD effects:

$$f(\text{VPD}) = \left(1 + \frac{\text{VPD}_k}{P_1}\right)^{P_2} \quad (5)$$

It reduced the RMSE of model computations from 1.49 mm/day to 0.68 mm/day and the bias error from 0.47 mm/day to -0.06 mm/day.

By applying simple parameterization, the model was able to simulate the daily water uptake of the *E. salmonophloia* tree with reasonable predictive quality over an entire seasonal cycle (RMSE=0.68 mm/day; Bias error=-0.06 mm/day; Systematic and random error=0.62 mm/day; r=0.84; Slope=1.03; Intercept=-0.12 mm/day). Computed and measured transpiration ranged between 4.5 mm during winter and 0.8 mm during summer (Langensiepen et al. 2006). The predictive qualities of the model were primarily influenced by the accuracy of information about leaf area density, stomatal light and VPD responses and to a lesser extent by foliage dispersion.

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