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A modified Jarvis-Stewart model for predicting stand-scale transpiration of an Australian native forest

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Abstract

Rates of water uptake by individual trees in a native Australian forest were measured on the Liverpool Plains, New South Wales, Australia, using sapflow sensors. These rates were up-scaled to stand transpiration rate (expressed per unit ground area) using sapwood area as the scalar, and these estimates were compared with modelled stand transpiration. A modified Jarvis-Stewart modelling approach (Jarvis 1976), previously used to calculate canopy conductance, was used to calculate stand transpiration rate. Three environmental variables, namely solar radiation, vapour pressure deficit and soil moisture content, plus leaf area index, were used to calculate stand transpiration, using measured rates of tree water use to parameterise the model. Functional forms for the model were derived by use of a weighted non-linear least squares fitting procedure. The model was able to give comparable estimates of stand transpiration to those derived from a second set of sapflow measurements. It is suggested that short-term, intensive field campaigns where sapflow, weather and soil water content variables are measured could be used to estimate annual patterns of stand transpiration using daily variation in these three environmental variables. Such a methodology will find application in the forestry, mining and water resource management industries where long-term intensive data sets are frequently unavailable.

Keywords: Jarvis model of transpiration; canopy conductance, woodland

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Introduction

Measuring tree water use is an important step in determining the water balance of woody landscapes (Komatsu et al. 2006a, Wullschleger et al. 2006, Rollenbeck et al. 2007, Simonin et al. 2007) and determining landscape water balances is important to forestry and mining industries and to water and landscape management agencies. Whilst estimating tree water use can be undertaken using sapflow technologies (O'Grady et al. 1999, 2006), such measurements are made at the scale of individual trees, usually over relatively short time frames (days and weeks) and typically only during the growing season (Wullschleger et al. 1998, Lundblad and Lindroth 2002). However, to obtain the required annual estimates of stand transpiration rate, up-scaling spatially and temporally are required, even when there is continual monitoring of a few trees at a site. Whilst eddy covariance measurements of stand water use give integrated measures of vegetation water use (Eamus et al. 2001, Ewers et al. 2007), these are expensive, technically challenging and require large, flat homogenous landscapes. Key end-users of such annual estimates of vegetation water use, including mine-site managers, catchment management authorities and water resource managers require a methodology that is sufficiently robust to be useful, but not too resource (time, equipment, data) intensive and one that is applicable to uneven terrain or small plots. An application of a simplified model of vegetation water use, as applied to management of groundwater dependent ecosystems, can be found in Howe et al. (2005).

Theoretically, in a well-coupled forest canopy, stand water use (E_c) can be calculated from canopy conductance (G_c) and vapour pressure deficit (D) since $E_C = G_C\, D$ and $G_C = LAI\ G_S$ where LAI is leaf area index and G_s is stomatal conductance (Whitehead 1998). G_s is a function of its driving environmental variables and can be estimated using the non-linear, multiplicative, independent functions originally described by Jarvis (1976) and subsequently widely applied (for example Wright et al. (1995), Harris et al. (2004) and Komatsu et al. 2006a, b) and discussed by Whitehead (1998). Thus, canopy water use can be calculated from:

$$E_C = LAI\ G_S(R_S, D, \theta)D \qquad (1)$$

for well coupled forests (Jarvis 1976, Whitehead 1998). This formulation is functionally equivalent to the Penman-Monteith (PM) equation, yet is much simpler to fit, requires fewer measurements and specifically avoids 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, as has been applied in the past (Ewers and Oren 2000, Lu et al. 2003, Pataki and Oren 2003). Furthermore, the PM is known to predict E_c poorly under soil moisture limiting conditions (Zeppel 2006) and appears to correlate with observation best when E_c is large (David et al. 1997, Rana et al. 2005).

The aim of the work contained herein is to describe a relatively simple model whereby scaled estimates of stand water use can be made from measurements of a few environmental variables. Due to its relative simplicity and practicality (Whitehead 1998, Wright et al. 1995, Harris et al. 2004), we based our approach on the Jarvis-Stewart model (Stewart 1988) that requires only three parameters and short-term measurements of sapflow. Jarvis-type models have been used extensively because of their simplicity and they allow calculation of G_s as a function of meteorological variables and soil moisture content (Jarvis 1976, Harris et al. 2004, Komatsu et al. 2006a,b, Ewers et al. 2007). Stewart (1988) refined the Jarvis model to predict G_c which has since been applied to poplar trees (Zhang 1997), maritime pine forest (Gash, 1989), oak forest (Ognick-Hendricks 1995), spruce and pine forests (Lagergren and Lindroth 2002), an Amazonian pasture (Wright et al.1995) and rainforest (Dolman et al. 1991, Sommer et al. 2002, Harris et al. 2004). The problem with the application of J-S models to-date is that they require good estimates (high spatial and temporal replication) of stomatal or canopy conductance and the subsequent use of the PM equation to calculate transpiration rate.

We present the results from a field campaign that measured soil moisture content, net radiation, tree water use, vapour pressure deficit and leaf area index, with the primary goal of scaling vegetation water use without the need to measure either G_s or G_c and without, therefore, use of the PM equation. We compare the model's output (E_C^{mod}) using our modified Jarvis-Stewart model (see below), with the observed sapflow data (E_C^{obs}). Two modifications of the J-S model are described. First, we model canopy water use directly without the intermediate calculation of G_c. Second, we add leaf area index (LAI) to the model as LAI is an important determinant of water use and shows seasonal and inter-annual variability (Eamus et al. 2006).

Methods

Site description

The study was conducted in remnant woodland within the Liverpool Plains, approximately 70 km south of Tamworth, in north-western NSW (31.5 ° S, 150.7 ° E, elevation 390 m), as described by Zeppel et al. (2004) and Zeppel and Eamus (2005). The open woodland has an average height of 15 m and is dominated by *Eucalyptus crebra* and *Callitris glaucophylla*. These two species contributed approximately 75% of the tree basal area at the site. The total tree basal area at the site was 23.8 ± 3.4 m^2 ha^{-1}. The eucalypt population had a lower density than that of the *Callitris* (42 stems ha^{-1}

compared to 212 stem ha^{-1}) but contributed about 75 % of the basal area of the site because its average diameter was much larger than that of the *Callitris*. Grasses including *Stipa* and *Aristada* species dominated the understorey. Soils at the site were shallow (15 to 30 cm) with well-drained acid lithic bleached earthy sands (Banks 1998) with occasional exposed sandstone.

The Liverpool Plains are characterised by summer dominant rainfall, as was evident during the study period, when there were 19 rain events during January and late February. Maximum hourly radiation reached 1342 W m^{-2} in summer and vapour pressure deficit (VPD) averaged 1.4 kPa at 0900 h in February.

Radiation and temperature data were obtained from a weather station located in a cleared pasture (> 4 ha) approximately 100 m from the remnant woodland. Radiation, wet and dry bulb air temperatures were recorded at hourly intervals. Wind speed was measured with a cup anemometer located approximately 3 m above the canopy and soil moisture measured with Theta Probes (Measurement Engineering Australia, Adelaide) at 10 cm, 40 cm and 50 cm depths at two locations, and at 10 cm and 40 cm at one other location (8 Theta Probes in total). For the analyses presented here, soil moisture measurements at 50 cm were used.

Leaf area index was measured at seven representative points in the woodland, as previously described (Zeppel 2006) using a Li-Cor 200 Plant Canopy Analyser, on 10 occasions between March 2003 and September 2004.

Water use by individual trees

The volume of water transpired by individual trees (Q; L d^{-1}) was measured using commercial sap flow sensors (model SF100, Greenspan Technology, Pty Ltd, Warwick, Australia) following the procedures described previously (Zeppel et al. 2004). For each species 10-12 trees were chosen to cover the range size distribution at the site and these were instrumented with 4 sensors per tree (2 probe sets per tree). The sensors were stratified with depth to account for previously measured variation in sap flow across the radial profile of each tree (Medhurst et al. 2002; Zeppel et al. 2004) and sensors were placed at 1/3 and 2/3 of the depth of the sapwood. Sapflows were corrected for the effects of wound, radial variability in flow, sapwood area and volumetric fractions of water and wood (Zeppel et al. 2004). Wound width was measured for both sensor sets in each of seven trees of each species, as described by O'Grady et al. (1999), at the end of the sampling period. A wound width of 2.5 mm for *C. glaucophylla* and 3.7 mm for *Eucalyptus crebra* was used to correct velocity estimates. Basal area and diameter at breast height (DBH) of all trees were measured in 7 replicate 50 m x 50 m plots, as previously described (Zeppel et al. 2004).

Scaling to stand transpiration

Scaling from individual trees to stand transpiration required a number of steps. First, the relationship between sapwood area and DBH was determined for each of the two species. Second, using the *census* data of DBH for all trees within each of the 7 plots, the sapwood area of a hectare of the stand was calculated by summing the sapwood area of the 2 species (ΣSA_{plot}). Third, an ANOVA was conducted to determine whether there was a relationship between tree size (DBH) and sap velocity. We found no relationship between tree size and sap velocity, as was observed in an adjacent eucalypt plantation (Barton, pers. comm.). Consequently, the average hourly sap velocity

(SV_{plot}) for all trees measured with sap flow sensors was used to calculate total tree water use of the plot, by multiplying total sapwood area of each plot by the average hourly sap velocity (Equation 2). Each 24 hour period was summed to give the daily sap flux (cm^3 day^{-1} plot^{-1}).

$$J_S = \sum \left(SA_{plot}\right) \times \left(SV_{plot}\right) \qquad (2)$$

The water use (cm^3 water d^{-1} plot^{-1}) of each plot (with an area of 2500 m^2) was converted to stand transpiration (mm^3 of water d^{-1} mm^{-2} ground area).

The DBH of all trees in 7 replicate plots was measured and therefore there were 7 estimates of stand water use (cm^3 sap flux day^{-1} cm^{-2} ground area) for each day on which intensive field campaigns was undertaken. The mean (and standard error) of all 7 plots, for each day, was then estimated, and converted from cm^3 water d^{-1} cm^{-2} ground area to yield stand water use (E_C, mm d^{-1}).

Modelling

Stand water use (E_C, mm d^{-1}), was determined from functions of soil moisture content (θ, %), solar radiation levels (R_S, W m^{-2}) and vapour pressure deficit (D, kPa). The functions (Fig. 2) were modelled by their dependence between stand water use (estimated using Equation 1) and each of the three driving environmental variables. Two modifications to the J-S model (Stewart 1998) have been made in the present work. First, we model E_C directly (E_c^{mod}) rather than calculating G_c and then using the PM equation to calculate E_c. Second, we include leaf area index in the model. Thus E_c^{mod} can be expressed as a function of (R_S, D and θ).

$$E_C^{mod} = LAI\ E_{max} f_1(R_S) f_2(D) f_3(\theta) \quad (3)$$

E_{max} is defined as the observed maximum rate of stand transpiration for each driving variable and LAI represents a site-specific leaf-area index term.

To determine the response functions for E_C in terms of its driving environmental variables, it is assumed that the response of E_C to each variable is independent of the other variables when values for the other variables are not limiting. This gives a set of functions expressing the separate dependence of E_C on each of the driving variables. The functional forms of $f_1(R_S)$ and $f_3(\theta)$ for this study were based on those of Stewart (1988), Wright et al. (1995) and Harris et al. (2004); $f_2(D)$ is a new function based on measurements and observations made in a controlled environment and tested in the field (Thomas and Eamus 1999, Eamus and Shanahan 2002, Zeppel 2006). The functional forms for each of the independent variables are described below. The reader is referred to San Jose et al. (1998), Magnani et al. (1998), Wullschleger et al. (2000) and Kosugi et al. 2007 for examples of the application of these response functions.

The radiation response is described by Equation (4), and gives the form of an asymptotic increase that plateaus at approximately 1000 W m^{-2}, with k_1 (W m^{-2}) describing the rate of change between E_c and R_S.

$$f_1(R_S) = \left(\frac{R_S}{1000}\right)\left(\frac{1000 + k_1}{R_S + k_1}\right) \quad (4)$$

The functional form of $f_2(D)$ is:

$$f_2(D) = k_2 D^n \exp(-D/k_3), \quad n \in 1,2,3...N \qquad (5)$$

This vapour pressure deficit function (Equation 5), is a new term, modelled on the basis that the response observed shows a shape similar to that of the Boltzmann distribution. Most importantly this response function can replicate the three-phase response of transpiration plotted against stomatal conductance as D is increased from low to high values. Monteith (1995) has reviewed this topic and Eamus and Shanahan (2002) and Thomas and Eamus (1999) provide experimental and modelling verification. The parameter k_2 describes the rate of change at lower atmospheric demand up until a peak value, k_3 describes the rate of change at higher atmospheric demand and n is power term that may take on values 1, 2, 3...N and this can be restrained or free in the optimisation. For this study we have set n=1

The functional form of $f_3(\theta)$ is given by:

$$f_3(\theta) = \begin{cases} 0 & ,\theta < \theta_W \\ \dfrac{\theta - \theta_W}{\theta_C - \theta_W} & ,\theta_W < \theta < \theta_C \\ 1 & ,\theta > \theta_C \end{cases} \qquad (6)$$

Equation (6) shows the soil moisture response to be a three-phase relationship, where θ_W and θ_C denote the wilting point and critical points respectively, of the relationship between water use and soil moisture content.

Maximum likelihood estimation

A full multivariate optimisation was applied to the experimental (measured) data using ordinary least squares (OLS). For an OLS regime to be valid, the variance must be homoscedastic (constant variance with increasing measurement). In cases where the data is seen to be heteroscedastic (increasing variance with increasing measurement) weighted least squares must be used in order to account for the increasing uncertainty in the measurement. A weighted least squares criterion uses a weighting term in the fitting regime in order to account for the heteroscedasticity of the data. By including a weighting term, the changing uncertainty in the measurements can be accounted for and the optimised free parameters will be maximum likelihood.

The parameters k_1, k_2, k_3, θ_W and θ_C are the optimised free parameters that represent response constants in the Jarvis-Stewart model. These response functions give values between 0 and 1, and hence the product of these functions act as scaling terms, which are used to reduce a maximum transpiration term (E_{max}) to an 'actualised' value E_C^{mod} (mm d^{-1}). Optimisation of Equations 4 - 6 was done by taking the weighted sum of the square of residuals (*WSSR*), given k_1, k_2, k_3, θ_W and θ_C set at starting values based on visual observations of the relationships and field measurements. Where we express the *WSSR* as:

$$WSSR = \sum \left(\frac{y_i - \hat{y}_i}{\sigma_i} \right)^2 \tag{9}$$

where

$$\sigma_i = \beta y_i \tag{10}$$

where y_i is the ith experimental value E_C^{obs} $\hat{y}_i$ is the ith predicted value based on the equation fitted to the data and σ_i where 'i' is the ith standard deviation.

We presuppose the heteroscedasticity to be explained by Equation (10), expressing the standard deviation to be proportional to the experimental data y_i, multiplied by some constant of proportionality β. In order to specify whether σ_i is normally distributed, we have assumed that the residuals to be some surrogate for σ_i such that $(y_i - \hat{y}_i) \equiv \sigma_i$. For this study we assume random measurement error (σ_i) to be normally distributed and heteroscedastic based on observations of the weighted residuals (Fig. 3).

Filtering the Data Set

Daily measurements of sapflow were filtered to exclude hours when solar radiation was zero (night). Days with rainfall events were also excluded to avoid wet-canopy conditions. This filtered data-set were used to define the boundary conditions for equations (4), (5) and (6).

To avoid circularity (using the same data to both parameterise the model and to compare with model outputs), the 59 day period of measurements during Jan-Feb were partitioned into two separate data sets of alternate days. The first data set (days 1, 3, 5 ….) was used to optimise the seasonal response parameters, and the second data set (days 2, 4, 6 ….) was used to validate the model. It was found that no systematic patterns with a day variation were evident in the data and there was no change in model outputs when allocation of each half of the data set to either optimisation or validation was reversed.

Results

Weather variables, soil moisture content, LAI and scaled rates of stand water use

Mean daily values for R_S, D, θ and E_C show daily fluctuation over the 59 day period (Fig. 1a-c). Variation in daily mean stand transpiration varied up to 8 fold between consecutive days. Mean daily scaled stand transpiration (scaled by sapwood area) varied between 0.1 mm d^{-1} during a rainy day (24th Feb) and approximately 2.8 mm d^{-1} (Feb 28th) on a rain free day. Declining stand water use between the 4th Feb and 22nd Feb was associated with declining soil moisture content, whilst large increases in stand water use occurred after the 13th Jan and after 24th Feb following rain events and soil moisture increased.

The three largest rainfall events increased soil moisture at 50 cm depth (Fig. 1c) but smaller rain events did not influence soil moisture at this depth. Daily mean vapour pressure deficit ranged from about 0.1 kPa on a rainy day to almost 6 kPa (20th Feb) after a period (17 days) with very little ($<$ 6 mm) rain in summer (Fig. 1a). Leaf area index varied between 0.9 in March 2004 and 1.5 in March 2003 but was typically in the range 0.8 to 1.2 (data not shown).

Figure 2 shows the functional forms of the curves described by equations 3 - 5 respectively, fitted to the experimental data. Note that the independent variable is a scaled stand water use, with a range from zero to one. Similar forms to these responses can be observed in Kelliher et al. (1993) and Komatsu et al. (2006b). These boundary curves show that as solar radiation increased, stand water use increased from zero to a maximum, asymptotically, whilst increasing vapour pressure deficit (D)

caused stand water use to increase for low values of *D* as evaporative demand increases, shows minimal change in water use for a narrow intermediate range of *D* and then declines with increasing *D* beyond this narrow range (*D* > 3 kPa). Stand water use showed a three phase response to soil moisture content. At high values of soil moisture (above the field capacity), stand water use was independent of soil moisture content. As soil moisture content declined below field capacity, stand water use declined linearly, as has been described previously (Harris et al. 2004). At very low soil water content, stand water use was zero.

Modelled stand water use

A total of six free parameters were estimated using a multivariate weighted least squares regime. Minimisation of the *WSSR* was done using *Mathematica*©, producing a set of optimised parameter values best describing the seasonal responses. The optimised parameters, as well as their standard errors are shown in Table 1. The residuals between E_C^{obs} and E_C^{mod} (Fig. 3) revealed a minor heteroscedasticity of the data, as is made evident by the slight pattern of the residuals. In order to properly account for this, we used a weighted least squares approach and Equation 9 was thus optimised. A weighted least squares approach was considered to be viable as the random errors in the measurements were seen to be normally distributed assuming a Gaussian distribution. Thus the six free parameters were considered to be maximum likelihood. The seasonal response parameters were used in the full form of Equation (3) to give E_C^{mod}; a set of predicted stand transpiration values.

The estimated maximal value for E_{max} of 0.260 mm hr^{-1} is very close to, yet under the observed maximal value of 0.280 mm hr^{-1}. This suggests that the model may slightly under-predict stand transpiration (Fig. 4) over the January-February period. This can be considered acceptable, as the model does not predict night-time transpiration due to the radiation component of the model. There are also two short periods where the model has failed; these are 15^{th}-16^{th} Jan and 25^{th}-29^{th} Feb where large rainfall events occurred. The weighted sum of modelled stand water use for the split 59-day period was 40.13 mm whilst the measured water use was 42.0 mm (data not shown). As only half the days were parameterised, these total values can be assumed to be 50% of the January-February total stand water use. The weighted mean for modelled stand water use was 1.38 mm d^{-1} and for measured stand water use it was 1.62 mm d^{-1}. Fig. 4 shows the outputs of our modified Jarvis-Stewart model. The regression of the observed and modelled rates of stand water use has a slope of 0.96 and an R^2 of 0.9 (Fig. 5). Values for θ_W = 6.72 % and θ_C = 11.79 % are also close to the graphically observable points shown by the scattering plot in Fig. 2c. This indicates further that the modelling is producing a reasonable description of the observed data (Table 1).

Discussion

As solar radiation increases, stand water use increased from zero to a maximum, asymptotically. Hyperbolic saturating functions to canopy conductance or water use have been applied extensively at leaf, tree and canopy-scales (Kelliher et al. 1993, Granier et al. 2000). At low levels of incident radiation, energy supply limits evaporation, but at high levels of radiation, other factors (especially soil moisture content and hydraulic conductance of soil and plant), limit evaporation (Williams et al. 1998). In agreement with Sommer et al. (2002) and Harris et al. (2004) we found that incorporating the soil moisture response function was critical to the ability of the model to satisfactorily fit the observed data.

The response of stand water use to increasing vapour pressure deficit (D) was more complex than that observed for radiation. For low values of D, increasing D resulted in stand water use increasing as evaporative demand increased. For a narrow range of D (3 kPa > D > *2* kPa), a minimal change in stand water use occurred as D increased. For large values of D (D > 3 kPa) stand water use declined with increasing D. This three-phase behaviour of stand water use is comparable to that of stomatal behaviour observed at the leaf-scale (Monteith 1995, Thomas and Eamus 1999, Eamus and Shanahan 2002) and of canopy conductance (Pataki et al. 2000, Komatsu et al. 2006b, Zeppel 2006). The initial response of E_C to increasing D for low values of D is unlikely to be a response to the covariance of R_S in the morning because even under a constant, saturating level of light, the same three-phase behaviour was observed (Thomas and Eamus 1999). The threshold of 2 – 3 kPa observed in the present study is larger than that observed in Pataki and Oren (2003) and Komatsu et al. (2006b) and the decline in water use was more severe than the decline in G_C they observed. This is probably because the site used in the present study is much drier, experiences a much larger range of D and was recovering from a long period of drought, compared to those used by Pataki and Oren (2003) or Komatsu et al. (2006b). The response of stomata (and hence water use) to D is strongly influenced by soil moisture content and drought (Thomas et al. 1999, 2000).

With some exceptions, the response of stand water use to increasing D did not fully describe the relationship shown in Figure 2 b) in terms of its boundaries. Whereas Equations (3) and (5) describe a normalised function of values between 0 and 1, Equation (4) does not due to the model being based on a distribution function, i.e. values are not restricted to boundary conditions $0 < f_2(D) < 1$, and may fall outside this region depending on the choice of starting values and the optimisation itself. This undoubtedly causes problems in the optimisation with the free parameters k_2 and k_3, perhaps not accurately describing the relationship between E_C and D. However the function does appear to describe the observed data with reasonable precision and has practical applications in the full model. Future work is required to develop a clear functional form of the response of water use to *D*.

The pattern of variation in measured hourly stand water use (Fig. 4) reflected changes in solar radiation and *D* and the model was able to capture this variation even at hourly time-scales. For example, the interval 9th – 18th Jan encompassed a period where observed hourly stand water use varied 12 fold because of the rainfall that occurred during this period. The model was able to replicate this range and the time course of the response of stand water use to fluctuations in solar radiation, *D* and soil moisture content that occurred before, during and after the rainfall. Similarly, more gradual declines in the maximum rate of stand water use that were observed during drying periods (late Jan to late Feb) were captured in the model. The ability of the model to capture this variability is further supported by the regression of E_C^{obs} and E_C^{mod} which produced a slope of 0.96 (Fig. 3), whilst the optimised observed daily maximum E_C^{obs} (0.280 mm h^{-1}) and modelled E_C^{mod} (0.260 mm h^{-1}) were very close. Unlike the use of the PM equation, this model appeared to be equally applicable to conditions of low and high E_c, and at hourly or daily time-steps, making it generally more applicable than the PM equation, which appears to be less successful under conditions of low E_c or hourly time-steps (David et al. 1997, Rana et al. 2005, Whitehead 1998).

Optimisation problems have been noted in using an OLS criterion, with the obvious problem of a large 6-dimensional parameter space. By increasing the number of functions and hence the number of free parameters, the complexity of the problem increases. As a consequence, the optimisation must cover a large, complex parameter space in order to find the global minimum that equates to the maximum likelihood for all free parameters. Problems of local minima hamper the search by causing early convergences over the large parameter space. This is a hindrance in determining values for the free parameters best describing the seasonal response, and will overall have an effect on the outcome of the model. Due to the sensitivity of the optimisation, there are also problems in choosing starting values for the free parameters. In order for the optimisation to converge close to the perceived global minimum, the starting values must be close to an observable value. A possible solution to these problems is by using heuristic search algorithms such as simulated annealing or genetic algorithms, which cover the entire parameter space with all possible solutions. These solutions evolve and undergo a simulated process of natural selection until the best solution is found. Although heuristic search algorithms can be applied to these high dimensionality problems, they are only acquiring part of an underlying distribution that describes these seasonal response parameters. A more desirable method of parameterising this model would be the application of Monte Carlo Markov Chain (MCMC) techniques such as those used by Richardson and Hollinger (2005). By acquiring a distribution for each parameter and hence a mean and standard deviation, a better understanding of the seasonal responses can be obtained. This is seen as the next step in this analysis.

This model has been applied to a single season (summer) at a single site. In the future we will compare summer and winter data at this site to determine the extent to which parameter values vary between seasons and investigate the requirement for a temperature response function in this model. Komatsu et al. (2006b) demonstrate the need for a temperature response function to extend the models to annual time-frames. Clearly, within the single summer season used in this paper, the temperature response function was not required because of the relatively narrow range of temperatures experienced during the day.

Conclusions

For this study a Jarvis-Stewart model has been modified to investigate whether stand-scale water use can be estimated from incident solar radiation, vapour pressure deficit and soil moisture content in conjunction with a limited number of sapflow measurements (30 days) made over a 2 month period. Functional forms of the Jarvis-Stewart functions were found to adequately describe the response of stand water use to variation in solar radiation, vapour pressure deficit and soil moisture content. Despite having only 30 days of sapflow data (half of the 59 day study period) with which to parameterise the model, the regression of modelled *versus* observed stand water use had a slope of 0.96 and an R^2 of 0.90. Thus the model has been shown to work well, with an acceptable level of error between experimental and modelled measurements. Some of the uncertainty present in the measurements has been accounted for by considering a weighting term in the optimisation of the model and gave a slight improvement over an unweighted optimisation.

In the case of the *D* relationship a new functional form was developed to incorporate the three-phase response of stomatal or canopy conductance to changes in transpiration rate. Where estimates of stand transpiration are required by forestry, mining and land and water resource managers, with limited access to sapflow data, but access to simple meteorological and soil moisture data, this approach offers a reasonable estimation of water use, thereby assisting in the determination of water balances for salinity control, water resource planning, vegetation management in relation to groundwater management and impact assessments of mining and rehabilitation.

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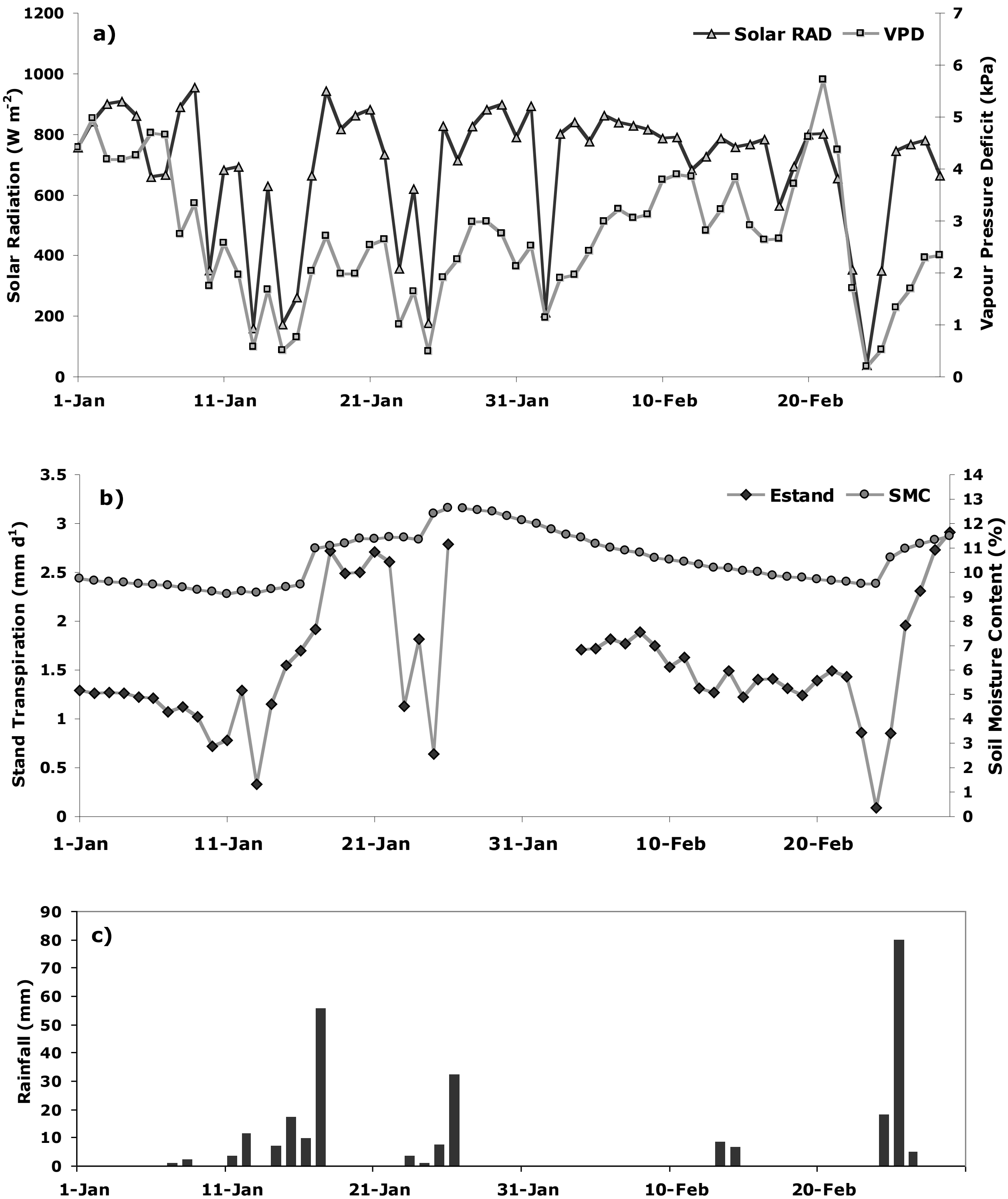

Figure 1 a) Comparisons between incident solar radiation (R_S), vapour pressure deficit (D), b) soil moisture content (θ), stand transpiration (E_C) and c) rainfall over the periods of January and February 2004. Diurnal changes in the three driving environmental variables R_S, D and θ shows a resulting change in E_C.

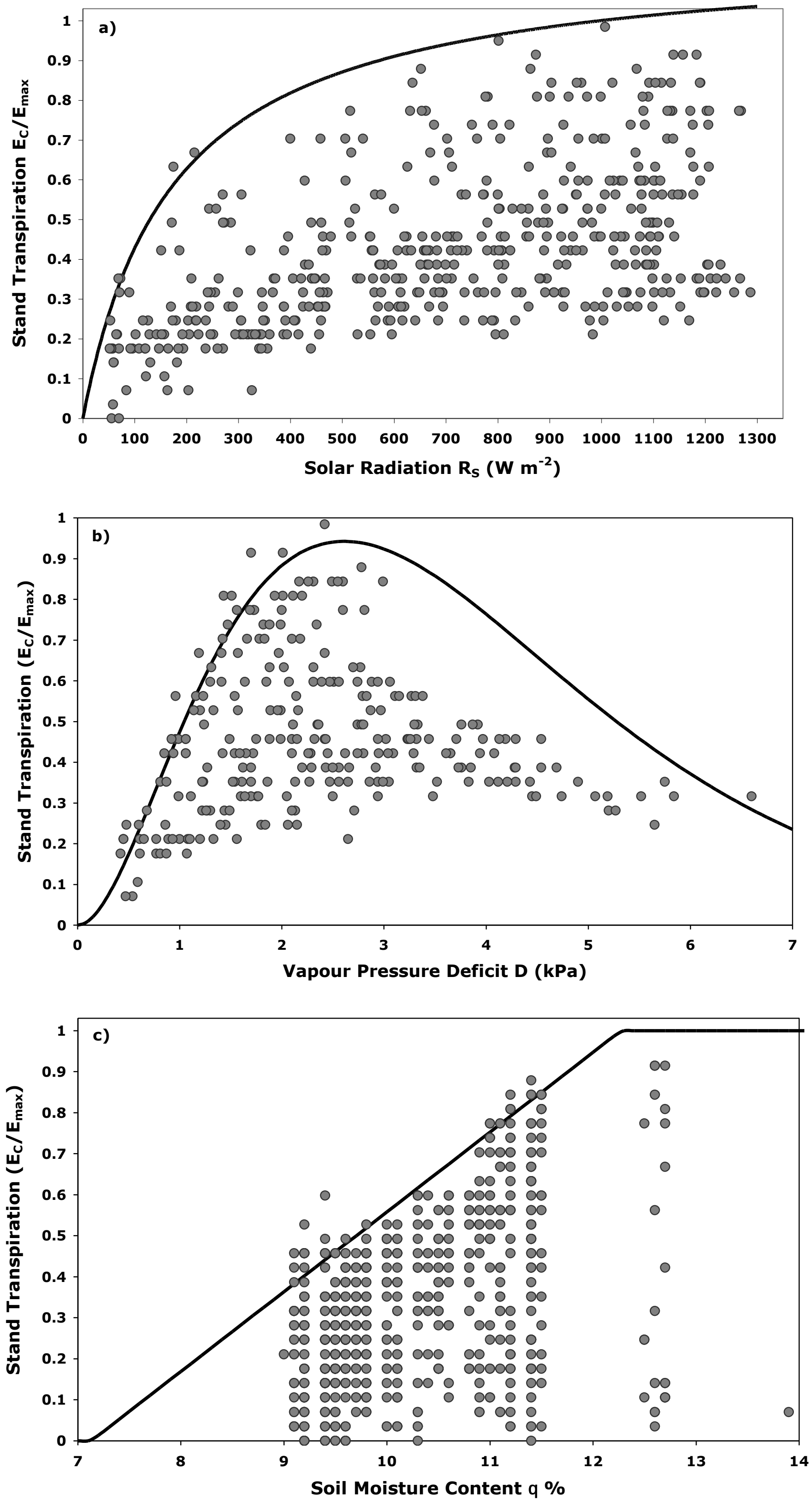

Figure 2: The form of the environmental response functions for a) incident solar radiation (R_S), b) vapour pressure deficit (D) and c) soil moisture content (θ), with relation to the boundaries of the scattered data points.

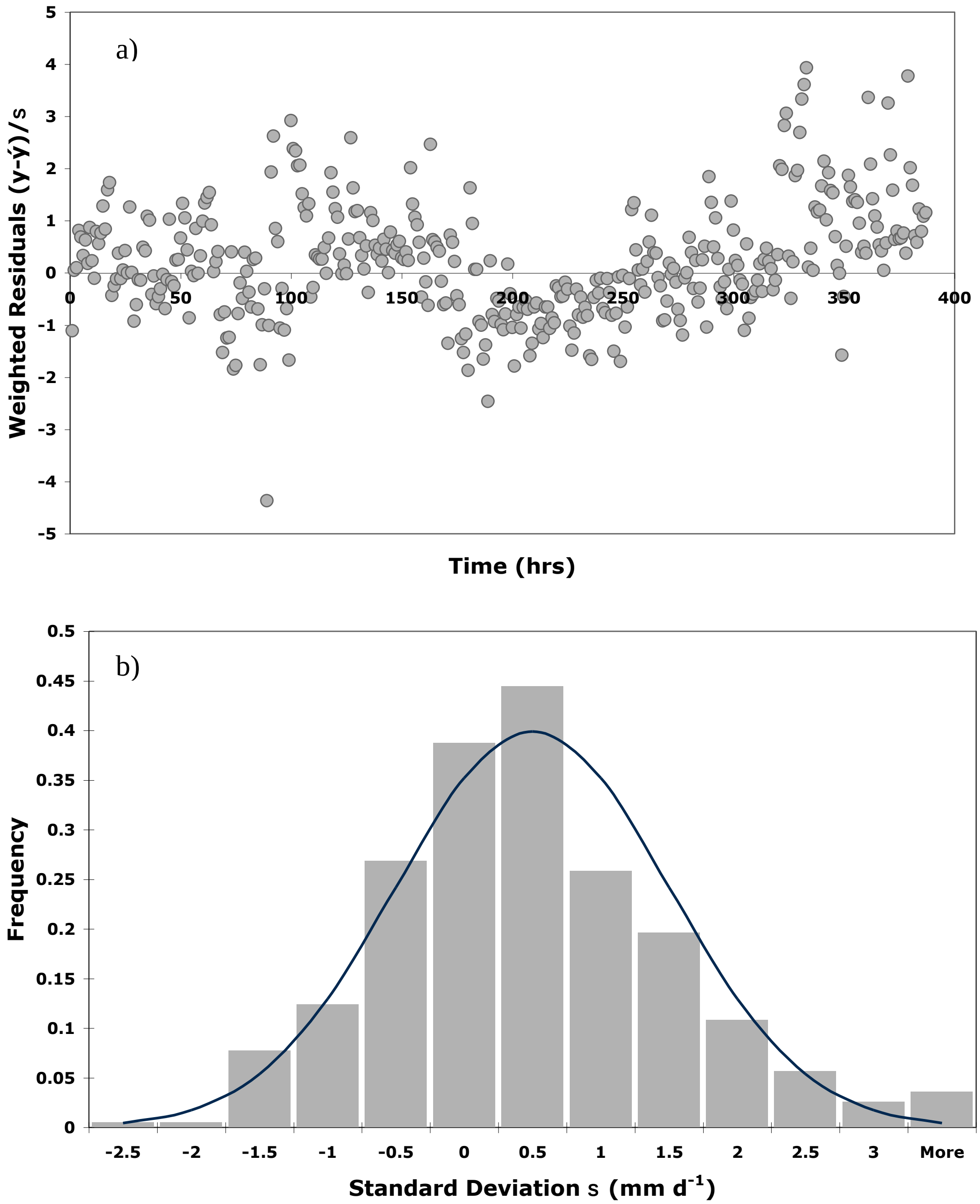

Figure 3: Weighted residuals expressed in terms of standard deviations for the modified Jarvis model showing a slightly sinusoidal pattern in the residuals (a). The dashed lines show the regions for which the residuals fall between ±1 standard deviations, representative of a 68% confidence region. The distribution of weighted residuals assuming a normal assuming a Gaussian distribution (b), where the residuals are evenly distributed within the 68% confidence region or ±1 standard deviations.

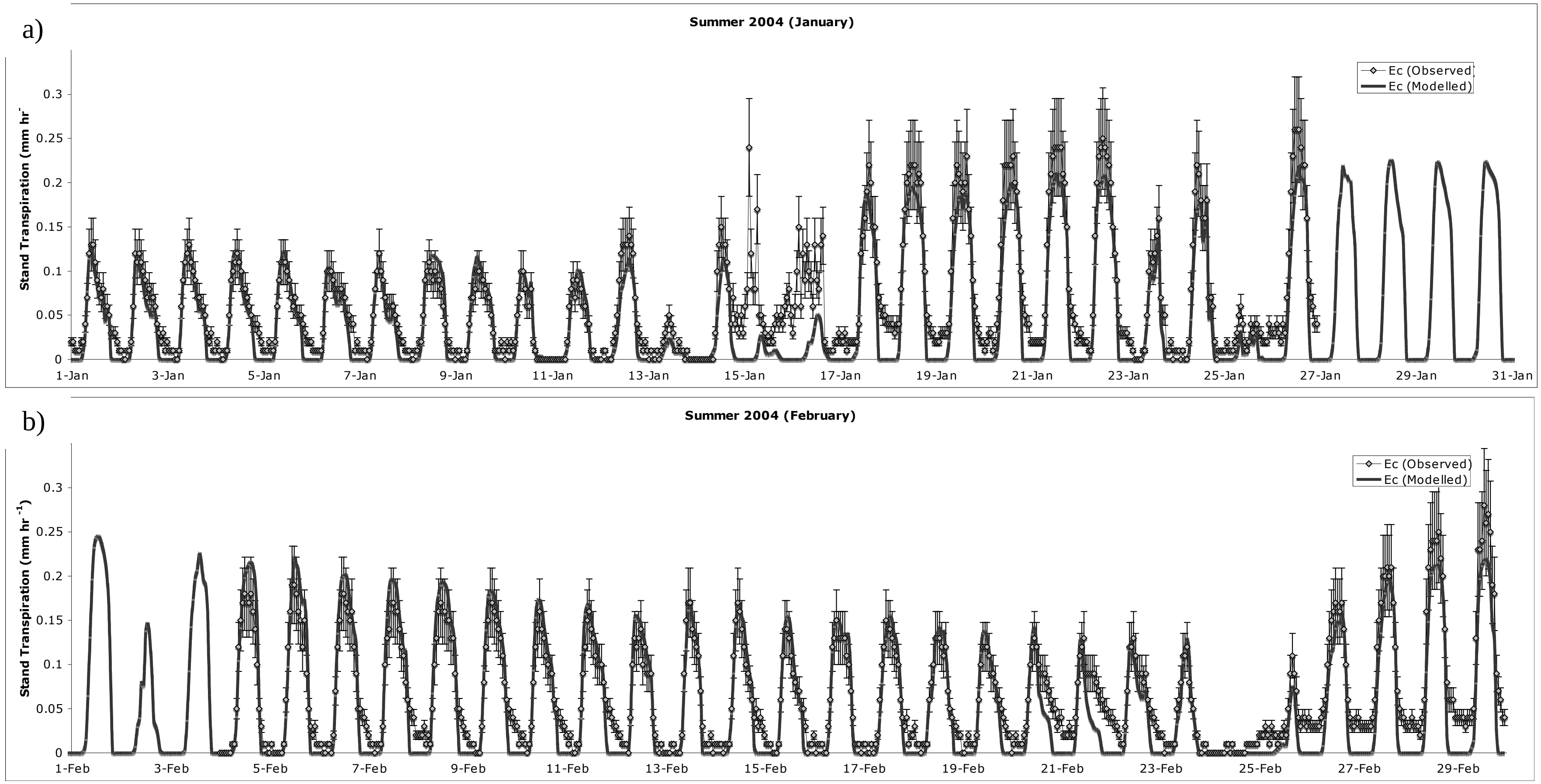

Figure 4: Estimated stand transpiration compared with field data over the 2 month period of a) January and b) February 2004. The model output is in good agreement with the observed measurements; uncertainty in the measurements is indicated by the error bars.

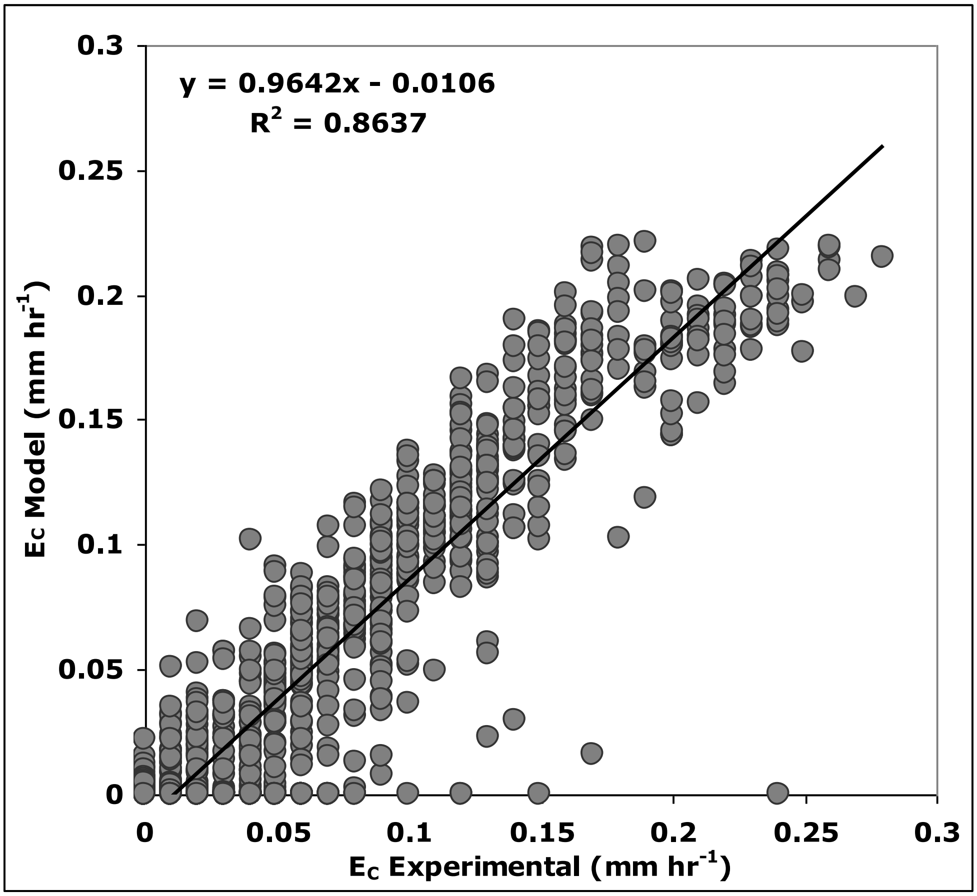

Figure 5: Comparison between estimated and observed stand transpiration, including the increasing uncertainty in the measurements (dotted lines). The slope corresponds to a value of 0.96 and an $R^2 = 0.90$.

Table 1: Parameters from the optimisation of the modified Jarvis model estimating stand transpiration for an Australia native forest for a weighted nonlinear least squares regime. Parameters defined a maximum stand transpiration (E_{max}), environmental functional dependencies on solar radiation (k_1), vapour pressure deficit (k_2, k_3), soil moisture content at wilting (θ_W), and critical points (θ_C).

	Value	S.E
E_{max}	0.260	0.004
k_1	143.40	19.43
k_2	0.917	0.016
k_3	1.372	0.010
θ_W	6.72	0.16
θ_C	11.79	0.09
β	0.23	
WSSR	128.55	
AIC	920.13	
R^2	0.90	