Australian Forestry

ISSN: 0004-9158 (Print) 2325-6087 (Online) Journal homepage: https://www.tandfonline.com/loi/tfor20

Simple model of evapotranspiration by *Eucalyptus* plantations for data poor areas and tested using water balance data from a small catchment in Guangxi, China

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AUSTRALIAN FORESTRY
2019, VOL. 82, NO. S1, 66–79
https://doi.org/10.1080/00049158.2018.1555733

ARTICLE

Simple model of evapotranspiration by *Eucalyptus* plantations for data poor areas and tested using water balance data from a small catchment in Guangxi, China

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ABSTRACT

Measurements of catchment and stand water balance were made in a small, upland catchment in Guangxi province, China that was covered with a plantation of a *Eucalyptus urophylla* × *Eucalyptus grandis* hybrid. These data were used to investigate the relationship between streamflow and the net stand water balance and to test the efficacy of a relationship between the crop factor (ratio of evapotranspiration to potential evaporation) and relative plant available soil water for predicting evapotranspiration. The model was then used to quantify the effect of afforestation with *Eucalyptus* plantations on the water balance of (1) upland catchments with shallow soils and (2) catchments with deeper soil profiles such as those that can occur in lowland catchments in Guangxi.

During the experiment, the plantation experienced a dry year in 2014, when rainfall was 1095 mm, and a year with approximately average rainfall in 2015 (1493 mm). In 2014, plantation evapotranspiration was 779 mm or 71% of rainfall while during 2015 the annual plantation evapotranspiration was 931 mm or 61% of rainfall. Measured streamflow for a full year was only 18 mm (2%) less than the difference between rainfall and estimated evapotranspiration. The relationship between measured streamflow and the net stand water balance was also strong (r^2 = 0.8) and unbiased (slope of 1.006).

A model that predicted the crop factor as a function of relative plant available soil water explained more than 78% of the variation in observed evapotranspiration and had a model efficiency of 0.73. It also provided an unbiased prediction of monthly evapotranspiration. When used to model the effect of a change from grassland to a plantation of *E. urophylla*, it predicted an average annual decrease in drainage of 70 mm and a 5% increase in the number of months with zero flow.

ARTICLE HISTORY
Received 6 May 2018
Accepted 28 August 2018

KEYWORDS
upland catchment; soil depth; evapotranspiration; streamflow; crop factor; afforestation

Introduction

Water use by plantations of *Eucalyptus* is an important natural resource management issue throughout Southeast Asia and also in southern China (Watanabe et al. 2004; Liu et al. 2017). The Australian Centre for International Agricultural Research (ACIAR) commissioned a synthesis of unpublished and published results from the region. An analysis of some unpublished measurements of plantation and catchment water balance (from the Guangxi Forest Research Institute, Nanning, Guangxi Province, South-west China) that was included in ACIAR Technical Report 89 (White et al. 2016) is presented here in more detail. We aim to inform debate about the water use of the plantations of *Eucalyptus* (Zhu et al. 2015) that now occupy more than 50% of all land in the Nanning region. Just under half of the region are uplands that are completely covered by plantations of *Eucalyptus*. These plantations replaced perennial grasslands, plantations of Chinese Fir and *Pinus* species as well as some cropping and horticulture. In recent years, local television and print media in Guangxi have described *Eucalyptus* plantations as 'green deserts' and the trees as 'water pumping machines'. There is a need for tools and local data that quantify water use by these plantations.

There are important differences between plantations established in upland and lowland areas in the Guangxi region. Upland plantations occupy small, steep catchments, typically less than 100 ha and with local groundwater systems while lowland catchments are usually flatter, larger, have deeper soils and are associated with regional groundwater systems and larger rivers. In the lowland catchments, local people often collect woody debris and there is very little weed growth. The upland catchments are steep and inaccessible so that there is often a vigorous weed layer or understorey. For regional communities without well-developed water storage infrastructure, the effect of plantations on low- or dry-season flow in these small, upland catchments is an important water security issue (Khan et al. 2009). In these catchments, a small change in flow that increases the risk of reduced water availability in the dry season may be more important than a large change where there is good storage. A capacity to predict the effect of plantations on the dynamics of flow is crucial in this part of rural China and throughout Southeast Asia.

Concern about the effect of plantations on water resources has arisen wherever in the world large-scale establishment of *Eucalyptus* plantations has occurred (Dye 2000; Albaugh et al. 2013; Greenwood 2013; Zhou et al. 2015). Public interest in water use by exotic *Eucalyptus* dates to the first half of the 20th century (Gevers 1950). Since then a lot of research has been undertaken on the effects of

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plantations on water balance that has been summarised in a number of excellent reviews and meta-analyses (Zhang et al. 2001; Whitehead & Beadle 2004; Brown et al. 2005; Farley et al. 2005; Dye & Versfeld 2007; van Dijk & Keenan 2007). The majority of the data summarised in these reviews is from temperate climates with winter dominant rainfall. Of the published studies from summer rainfall climates in Brazil and China (Lane et al. 2004; Gerten et al. 2008; Li et al. 2014; Almeida et al. 2016), only a few provide a complete water balance (Lane et al. 2004).

Rapidly growing plantations use more water per year in a given location than annual crops or pastures (Zhang et al. 2001; Zhang et al. 2004). On average, plantations also use more water than native forest, although the difference is smaller and there are exceptions. For example, in a study is southern China, Zhou et al. (2002) found that more surface runoff was generated from a young *Eucalyptus* plantation than from a native forest of the same age. It is not totally clear that *Eucalyptus* plantations use more water than alternative tree crops. *Eucalyptus* plantations have been reported to transpire more than alternative plantation species (Myers et al. 1998; Maier et al. 2017). In a paired catchment study in South Africa, Scott and Lesch (1997) observed that plantations of *Eucalyptus grandis* Hill ex Maiden reduced streamflow more than plantations of *Pinus patula* Schiede ex Schltdl and Cham. In contrast, the only stand-scale study to compare the total water balance of a eucalypt (*Eucalyptus globulus* Labill.) with an alternative plantation species (*Pinus radiata* D.Don), concluded that evapotranspiration by these two species was similar on sites with and without shallow groundwater (Benyon & Doody 2015).

Studies of the water balance of *Eucalyptus* plantations in tropical environments have reached contrasting conclusions about the likely effect of *Eucalyptus* plantations on water resources. On the Leizhou Peninsula, Lane et al. (2004) concluded that plantations would not have an important effect on local water security. In Brazil, Almeida et al. (2007) found that a plantation of a similar species had an important effect on local streams. The apparently contradictory nature of these results can be explained by the differences between the climate in the two locations. On the Leizhou Peninsula, average monthly evaporation only exceeds potential evaporation in one or two months a year; plantation growth and water use is energy, rather than water limited (Lane et al. 2004). In the region of Brazil, where Almeida et al. (2007) did their work, the opposite is true; monthly potential evaporation nearly always exceeds rainfall. This highlights the limitations of water balance studies in one location for quantifying the effect of plantations in another region. Models of plantation water balance offer the opportunity to quantify the potential impact of plantations in new locations and for assessing the effect of species, site and climate on this water balance.

In areas without detailed soils, growth and climate data, such as in much of Southeast Asia and rural China, it is difficult to provide input data and parameter sets for process-based models of plantation growth and water balance. In these locations, simpler and more transparent models of plantation water balance are needed as the basis for a constructive and informed debate about water use by plantations. One simple approach for quantifying water balance is to estimate the ratio of evapotranspiration to potential evaporation (the crop factor) as a function of relative plant available soil water. The parameters of this type of model are very similar for commercial *Eucalyptus* plantations in temperate and tropical environments (White et al. 2001; White et al. 2016). The only inputs required are monthly rainfall and potential evaporation (average or real) and an estimate of maximum plant available soil water; these models are a realistic option for quantifying the water balance of plantations in data poor environments.

This paper quantifies evapotranspiration and streamflow in a small catchment planted to *Eucalyptus urophylla* Blake × *E. grandis* in Guangxi province in South-west China (just across the border from Vietnam). The water balance was quantified using catchment scale estimates of streamflow and a stand-scale estimate of evapotranspiration. The data were used to (1) quantify the monthly evapotranspiration of an upland plantation of *E. urophylla* × *E. grandis* over a 30-month period, (2) test the hypothesis that changes in storage have a negligible effect of estimates of monthly and annual stream flow and (3) to test a simple model of plantation evapotranspiration based on prediction of the crop factor as a function of relative plant available soil water. This model was then used with a historical climate record to quantify the probability of change in monthly evapotranspiration and streamflow.

Methods

Site description

All measurements were made in a small catchment approximately 60 km from the city of Nanning in Guangxi province, China (22°41′10.89″N, 108°11′44.58″E). Located in the Nanning Forest Ecosystem Observation and Research Station, at an altitude of 616 m above sea level, the experimental catchment was planted with a hybrid of *E. urophylla* and *E. grandis* in August of 2004. In October 2010, the original crop was harvested and regenerated by re-sprouting from the cut stumps. The resultant stand was reduced to a single stem per stump in March 2011. The nominal stand spacing was 4 m between rows and 2 m within rows or 1248 trees ha^{-1}. The actual density of stems in the coppiced stand was approximately 1062 stems ha^{-1} after reduction to a single stem per stump in 2011. The catchment faces north-west and is very steep; the average slope exceeds 30%.

The soil in the catchment is a latosol with an average depth of between 80 cm and 100 cm. Using a steel ring, three soil samples of known volume were collected from each of four depths (0–20, 20–40, 40–60 and 60–80 cm) and from three locations giving a total of nine samples for each depth. The sampling locations were at the top of the catchment within the forest plot described below, mid-slope and in a lower location near to the weir. The samples were collected towards the end of the wet season in 2014 and were weighed after draining for two days in a cool room. They were then drained to permanent wilting point (1.5 MPa) in a suction plate before being reweighed. The volumetric water content was calculated as the product of density and gravimetric water content. The volumetric water fraction varied from 0.16 in the surface samples to 0.09 at 60–80 cm below the surface (Table 1). The average plant available volumetric soil water content was 0.12 mm or 120 mm rainfall equivalent per m of soil. Given that the soil was approximately 100 cm deep, we estimate that the maximum plant available soil water was approximately 120 mm.

Table 1. Bulk density and maximum plant available soil water content by soil depth. The numbers are the average ± standard error for three landscape positions, the top and bottom of the catchment and a mid-slope position

Soil depth range (cm)	Bulk density (g cm^{-3})	Maximum plant available volumetric soil water fraction
0–20	1.03 ± 0.11	0.16 ± 0.012
20–40	1.30 ± 0.06	0.13 ± 0.012
40–60	1.35 ± 0.04	0.11 ± 0.015
60–80	1.35 ± 0.06	0.09 ± 0.033
Profile average	1.26 ± 0.08	0.12 ± 0.015

In 2013, a v-notch weir was installed in the catchment (the details of these measurements are described below) and a measurement plot established on a north-facing slope in the upper third of the catchment. This plot was ten rows (40 m) by ten trees (20 m) covering an area of 800 m^2. The area of the catchment upstream of the weir was 15.6 ha.

The measurements described here were made between July 2013 and April 2016. A number of symbols are used throughout the paper. Table 2 provides a list of these symbols, the quantities they represent and their units.

Table 2. List and description of symbols used in this paper and their units

Symbol	Description	Units
h	Tree height	m
d	Diameter at breast height, over bark	cm
V_{tree}	The volume of a tree	m^3
BA_{tree}	The basal area, at 1.3 m above ground, of a tree	m^2
V_{plot}	The standing volume in a plot expressed per hectare	m^3 ha^{-1}
BA_{plot}	The total basal area of a stand expressed as cross-sectional area per hectare	m^2 ha^{-1}
SA_{plot}	The total sapwood area of the plot expressed as a cross sectional area per hectare	m^2 ha^{-1}
T	Air temperature	°C
RH	Relative humidity	%
R	Solar radiation	Wm^{-2}
R_n	Net radiation	Wm^{-2}
P_a	Atmospheric pressure	kPa
P	Rainfall	mm
T_{min}	Minimum daily temperature	°C
T_{max}	Maximum daily temperature	°C
θ	Volumetric soil water fraction	Dimensionless
S	Total soil water content of the soil profile	mm
W	Relative soil water content	Dimensionless
Q	Streamflow	mm
E_0	Reference evaporation calculated using the Priestley-Taylor equation	mm
s	Slope of the relation between saturated vapour pressure and temperature	kPa °C^{-1}
γ	Psychrometric constant	kPa °C^{-1}
λ	The latent heat of vapourisation of water	kJ kg^{-1}
c_p	Specific heat of dry air	kJ kg °C^{-1}
ε	Ratio of the molecular weight of water to dry air	
E	Evapotranspiration (total evaporation)	mm
v	Sap velocity	cm h^{-1}
ΔT_d	The difference in temperature between the heater and reference probes	°C
$\Delta T_{d,max}$	The maximum temperature difference between the heater and the reference probes recorded during the previous 24 hours	°C
v'	Mean sap velocity for all measurement trees	cm h^{-1}
E_t	Transpiration by the plantation	mm
E_i	Canopy interception of the plantation	mm
TF	Throughfall or rainfall measured underneath the plantation canopy	mm
E_u	Understorey evaporation (includes soil evaporation and interception and transpiration of the understorey)	mm
E_{eq}	Equilibrium evaporation rate	mm
W_0	A parameter in the equation for predicting the crop factor (k) as a function of plant available soil water. This parameter is the value of W for which k is 0.5	Dimensionless
a_w	The maximum slope of the relation (Equation 11) between the crop factor and relative plant available soil water	Dimensionless

Stand characteristics

The height (h, m) and over bark diameter at breast height (d, cm) of all trees in the measurement plot was measured on six occasions between July 2013 and March 2016. For each measurement, the volume of each tree (V_{tree}) was calculated using Equation 1 while stand volume (V_{plot}) and basal area (BA_{plot}) were calculated on a per hectare basis with Equation 2.

$$V_{tree} = \left(\frac{\pi}{12}\right)\left[\frac{d}{100}\left(\frac{h}{h-1.3}\right)\right]^2 h \quad (1)$$

$$V, BA_{plot} = \frac{10000}{800}\sum_{i=1}^{n} V, BA_{tree} \quad (2)$$

In June 2013, 30 trees were harvested from an area with comparable aspect and position to the measurement plot. A little pure water was applied to the cross sections at breast height to distinguish between heartwood and sapwood. The depth and area of the sapwood was estimated for all of these sample trees and the linear regression between sapwood area and basal area was calculated. This relationship was used to estimate stand sapwood area per hectare (SA_{plot}) using the tree data from within the measurement plot.

Weather variables

The weather conditions outside and inside the plantation were measured using a pair of automatic weather stations (Campbell Scientific, Logan, UT, USA) installed according to the 'Observation Methodology for long-term Forest Ecosystem Research', a National Standard of the People's Republic of China (GB/T 33027–2016). The first weather station was situated in a 25 m x 25 m clearing at the top of the catchment. In this clearing the grass was cut at least twice a year. This station recorded temperature (T), humidity (RH), total solar radiation (R), net radiation (R_n), barometric pressure (P_a), rainfall (P) and wind-speed and direction. The second, situated inside the plantation, had nearly all of the same sensors as the first station, except for the net radiometer. Measurements at both stations were made every ten minutes. Daily and average monthly values for minimum (T_{min}) and maximum temperature (T_{max}) and humidity (RH), total rainfall (P), net (R_n) and total incident radiation (R) were derived from these data.

Soil water content

The volumetric soil water fraction (θ) was measured outside the plantation at 5, 10, 20 and 40 cm below ground and inside the plantation at 5, 10 and 20 cm below ground. These measurements were made using capacitance sensors (CS161, Campbell Scientific). The total soil water content at each location (S, mm) was calculated in mm as a sum of the water content calculated for each depth as the product of the volumetric soil water fraction measured at each depth

(θ_i) and the depth of soil associated with that sensor (z_i) (Equation 3).

$$S = \sum_{i=1}^{n} \theta_i z_i \qquad (3)$$

The relative soil water content (*W*) was calculated as the ratio of the ith measurement and the maximum value recorded during the experimental period (Equation 4).

$$W = \frac{S_i}{S_{max}} \qquad (4)$$

The absolute and relative water contents were both calculated for assumed soil depths of 0.5 m and 1 m. The soil depth in the catchment varied between 50 cm and 100 cm. This means that the total available soil water varies between 120 mm and 75 mm based on the measured water storage values provided in Table 1.

Streamflow (Q, mm)

The flow at the main catchment outlet was measured in a v-notch weir with a filter tank and a stilling pond. A small building was erected at the weir in which a logging well was established with hydraulic connectivity to the stilling pond. An automatic depth gauge (ONSET, U20, USA) was installed in the well. This gauge recorded water level at ten-minute intervals. Flow (*Q*) was calculated after Eli Robert (1986) as a function of the height of the v-notch above the bottom of the stilling pond and the height of the water in the v-notch.

Net and solar radiation

Solar (*R*) and net radiation (R_n) were measured outside the plantation while only solar radiation was measured inside the plantation. Total daily solar radiation measured underneath the plantation and in the nearby clearing were strongly correlated (r^2 of 0.92). Daily total solar radiation (*R*) measured underneath the plantation was 38% of the value in the clearing. This relationship was used to fill gaps in the daily record of solar radiation both outside and inside the plantation.

Similarly, a strong relationship was observed between net and solar radiation in the clearing; net radiation was 69% of total solar radiation. Given that the vegetation in the clearing was similar to that in the understorey, the same relationship between net and total solar radiation was assumed to apply under the plantation.

Using these correlations, a complete record of daily total and net solar radiation outside the plantation and underneath the *Eucalyptus* canopy but above the understorey was constructed.

Potential evaporation (E_0, mm)

Potential or reference evaporation (E_0) was calculated using the Priestley-Taylor equation (Priestley & Taylor 1972). This method calculates reference evaporation as a product of equilibrium evaporation and a coefficient which reflects the vegetation roughness (1.26 in this case, Equation 5),

$$\lambda E_0 = 1.26\left(\frac{s}{s+\gamma}\right)R_n \qquad (5)$$

where R_n is net radiation in kJ m^{-2}, λ is the latent heat of vapourisation of water (2245 kJ kg^{-1}), s is the slope of the relationship between saturated vapour pressure and temperature (kPa °C^{-1}) and γ is the psychrometric constant or slope of the relationship between actual vapour pressure and temperature (kPa °C^{-1}). The 'constants' are temperature dependent; *s* was calculated using the empirical model in Equation 6 (Hahn & Landeck 1998) and γ was calculated using Equation 7 in which T_a and P_a are air temperature and atmospheric pressure measured at the site, c_p is the specific heat of dry air (1.013 kJ kg °C^{-1}) and ε is the ratio of the molecular weight of water to dry air (0.622).

$$s = 0.04145e^{0.06088T_a} \qquad (6)$$

$$\gamma = \frac{c_p P_a}{\varepsilon\lambda} \qquad (7)$$

T_a is air temperature measured at the weather station, P_a is atmospheric pressure (kPa), c_p is the specific heat of dry air (1.013 kJ kg °C^{-1}) and ε is the ratio of the molecular weight of water to dry air (0.622).

Evapotranspiration

The components of evapotranspiration were measured or estimated within the measurement plot.

Stand transpiration (T, mm)

Six sample trees were selected from within the measurement plot to represent the range of tree sizes in the plot. Heat dissipation probes (Dynamax Inc., Houston, Texas, USA) were installed in each of these trees in March 2013. These probes were installed at breast height on a northerly aspect using the protocol described in Baker and van Bavel (1987). A heater probe provided a constant input of energy and every 30 min the temperature at the heater probe and a reference probe 10 mm downstream of the heater was recorded. Sap velocity was calculated after Granier and Loustou (1994) as:

$$v = 0.000119\left(\frac{\Delta T_d - \Delta T_{d,max}}{\Delta T_{d,max}}\right)10^6 \qquad (8)$$

where ΔT_d was the difference in temperature between the heater and reference probes and $\Delta T_{d,max}$ was the maximum temperature difference recorded during the previous 24 hours.

Sap velocity measurements of this kind are subject to errors due to the sensitivity of the temperature sensors to electrical interference. These erroneous measurements were removed from the data by plotting the data from each sensor against sensor one and removing data that deviated from the relationship between the sensors by more than one standard deviation. This resulted in the removal of sap velocities in excess of about 65 cm h^{-1} and less than 4 cm h^{-1}. Mean sap velocity for the six trees (v') was calculated for each measurement time and was the mean of between two and six measurements.

Transpiration or water use for the stand (E_t, mm) was calculated as the product of the mean sap velocity (v', numerical equivalent of sap flux density) and the area of sapwood of the stand per hectare. As for the other variables, stand transpiration (E_t, mm) was calculated on a daily and monthly basis.

Canopy interception (E_i)

Throughfall (*TF*) and rainfall (*P*) were measured using a pair of tipping bucket rain gauges situated, respectively, inside and outside the plantation. Interception (E_i), on a daily time step, was calculated as the difference between rainfall measured outside the plantation (*P*) and throughfall measured inside the plantation. A simple linear model was developed from the data that calculated throughfall as a function of rainfall measured outside the plantation. Interception was then calculated as the difference between rainfall and throughfall.

Stemflow was not measured in this study. The error introduced by this omission is between 2% and 5% of annual rainfall based on published results for *E. globulus* in Portugal (2.7%) (de Almeida & Riekerk 1990) and *Eucalyptus* in general for which Crockford and Richardson (1990) found that stemflow was about half of that observed for *Pinus* species.

Understorey water use (E_u)

For this water balance, understorey water use E_u was assumed to include interception by the understorey plants, transpiration by the same plants and evaporation from the soil surface. The understorey was very dense in this plantation and was approximately 2 m tall. In most places it was too dense to walk through without first clearing a path with a machete. This was not the case in the cleared plot where the grass was cut regularly.

Understorey evaporation was calculated (Equation 9) as a product of a crop factor (k_u), and equilibrium evaporation (E_{eq}, Equation 10).

$$E_u = k_u E_{eq} \tag{9}$$

$$\lambda E_{eq} = \left(\frac{s}{s+\gamma}\right) R_n \tag{10}$$

To account for variations in resistance within the soil and vegetation, the model of Battaglia and Sands (1997), with parameter values from White et al. (2016), was used to calculate k_u as a function of relative plant available soil water (Equation 11). For the calculation of W, it was assumed that the dense weed layer could access 1 m of soil.

$$k = \frac{W^2 e^{a_w W}}{w_0{}^2 e^{a_w w_0} + W^2 e^{a_w W}} \tag{11}$$

The parameters in this model are the value of W for which k is 0.5 (w_0) and the maximum slope (a_w) and were, respectively, given values of 0.5 and 6 after Benyon and Doody (2015). In this case net radiation (R_n) is that estimated for underneath the plantation which was 38% of the value measured outside the plantation.

Evapotranspiration (E)

Evapotranspiration was calculated as the sum of transpiration (E_t), interception (E_i) and understorey evaporation (E_u).

$$E = E_t + E_i + E_u \tag{12}$$

Modelling evapotranspiration

A simple, three parameter model was parameterised using data from between July 2013 to June 2014 and then used to estimate monthly evapotranspiration from July 2014 to March 2016. This model calculates evapotranspiration using Equation 13, as the product of a crop factor (*k*) and potential evaporation (E_0, see Equation 5).

$$E = kE_0 \tag{13}$$

Potential evaporation was estimated using the Priestley-Taylor method (Priestley & Taylor 1972), and the crop factor was estimated using the same model used by Battaglia and Sands (1997) with parameters as modified by White et al. (2016). The model calculated the crop factor as a function of relative plant available soil water (*W*, from Equation 4). As noted above, the parameters of this model are the value of plant available soil water (*W*) for which *k* is 0.5 (w_0) and the maximum slope of the relationship (a_w). The values of 0.5 for w_0 and 6 for a_w used were derived by White et al. (2016) using measurements in this study made between July 2013 and June 2014 and the data reported by Lane et al. (2004). In this case net radiation used in the Priestley-Taylor equation is that estimated for outside the plantation.

Quantifying the effect of land-use change from grass to plantations

Monthly evapotranspiration was then modelled using monthly climate data for Nanning from 1901 to 2014, downloaded from the East Anglia Climate Research Unit. This data does not include either solar or net radiation. The average of total solar radiation (MJ day^{-1}) was therefore calculated from average monthly maximum and minimum temperatures using Equation 14 after Hargreaves and Samani (1985) and as described in Allen et al. (1998).

$$R = \left(0.16\sqrt{T_{max} - T_{min}}\right) R_a \tag{14}$$

where R_a is extraterrestrial radiation (the radiation received by the outer atmosphere) which is in turn a function of time of year (declination angle of the sun) and latitude (see Allen et al. 1998). Net radiation (R_n) was calculated after Green et al. (1995) and Alados et al. (2003) as 0.7 times total solar radiation and potential evaporation was calculated after Priestley and Taylor (1972).

Although the plantation in this study replaced sparse plantings of Chinese Fir and local species, the water use of plantations was compared to water use by catchments or plots covered with grass. This was done to maximise the difference between the plantation and the modelled alternative or to provide a worst-case scenario for land-use change. It would also have been difficult to parameterise the model for the previous mixed land use. The evapotranspiration of grass was also estimated using Equation 13. It was assumed that the maximum value of the crop factor (*k*) was 0.8 for grass and 0.92 for the plantation. This is because of the greater turbulence and aerodynamic conductance of plantations compared to grass. It was assumed that the maximum plant available soil water fraction was 0.1 and that the grass could access only 1 m of soil. The model was run from January 2001 to December 2015. The residual or net water balance, again from Equation 14, was calculated for every month and a flow duration curve, the relationship between a calculated flow and the probability of exceedance, was plotted under different soil depth scenarios. The values of the model parameters represent a 'worst-case scenario' and will tend to maximise the predicted difference between the evapotranspiration from plantations of *Eucalyptus* and grass.

Data analysis

To test hypothesis 1, that storage is negligible in small upland catchments, streamflow was calculated from a simple catchment water balance in which flow (Q) is the net water balance or rainfall (*P*) less, evapotranspiration (*E*) and the change in soil water content (DS) (Equation 15).

$$Q = P - E - \Delta S \tag{15}$$

Streamflow estimated in this way, and assuming zero change in storage, was compared with measured streamflow and linear regression was used to quantify bias. This was done for monthly and weekly time steps.

The model was tested by calculating the Nash-Sutcliffe model efficiency (Nash & Sutcliffe 1970) for the period from November 2014 to December 2015 (Equation 16).

$$Efficiency = 1 - \frac{\sum_{i=1}^{n}\left[E_{M,i} - E_{O,i}\right]^2}{\sum_{i=1}^{n}\left[E_{O,i} - \bar{E}\right]^2} \tag{16}$$

Where $E_{M,i}$ is modelled evapotranspiration in month *i* of *n* months, $E_{O,i}$ is observed evapotranspiration for the same month and $\bar{E}$ is average evapotranspiration. Values of the Nash-Sutcliffe model efficiency (ENS) between 0 and 1 indicate that the model is a better predict than the sample mean. Values closer to 1 indicate superior model efficiency.

Results

Climate and weather

The average annual rainfall in nearby Nanning (60 km from the field site) is 1466 mm, average annual potential evaporation is 1030 mm, and the rainfall is summer dominant. January is the coolest month with an average minimum air temperature of 9.8°C and maximum of 24.7°C. During July, which is the warmest month, the average minimum and maximum air temperature are, respectively 17.4°C and 31.7°C (Fig. 1).

At the research site the rain gauge did not function correctly during June and July 2014. A relationship between the rainfall at the nearby Nanning climate station and the experimental site was used to estimate the rainfall for these months. After these corrections, rainfall measured in the catchment was much lower than the long-term average during 2014 (1095 mm) and a little more than average in 2015 (1493 mm) (Fig. 1).

Soil water content

The relative water content was similar in the grassed area outside the plantation and under the plantation for much of the study period. The water content was lower under the plantation than outside the plantation for a period of three months between March and June 2015. During this period the relative plant available water content decreased to approximately 0.4 under the plantation (Fig. 2).

Evapotranspiration and components, a bottom up water balance

The maximum monthly evapotranspiration, calculated as the sum of interception, soil evaporation and transpiration, was observed between July and September in each of 2013, 2014 and 2015 and was between 130 mm and 147 mm (Fig. 3). During the subsequent months of each year, evapotranspiration decreased and was between 30 mm and 60 mm per month during the cooler and drier months between January and April (Fig. 3). Total annual evapotranspiration was estimated to be 779 mm in 2015 or 78% of potential evaporation

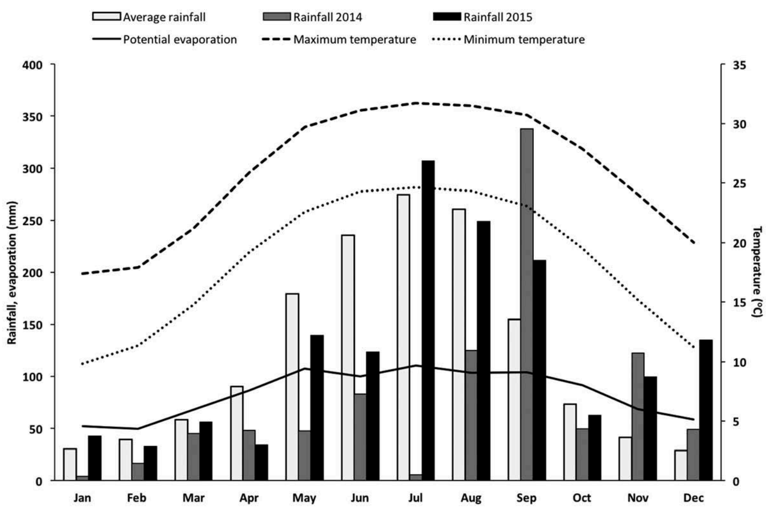

Figure 1. Average monthly rainfall, potential evaporation, maximum and minimum temperature for the location of Nanning. Data are average values for the period from 1901 to 2014 from the East Anglia climate research unit. Also shown are observed monthly rainfall during 2014 and 2015

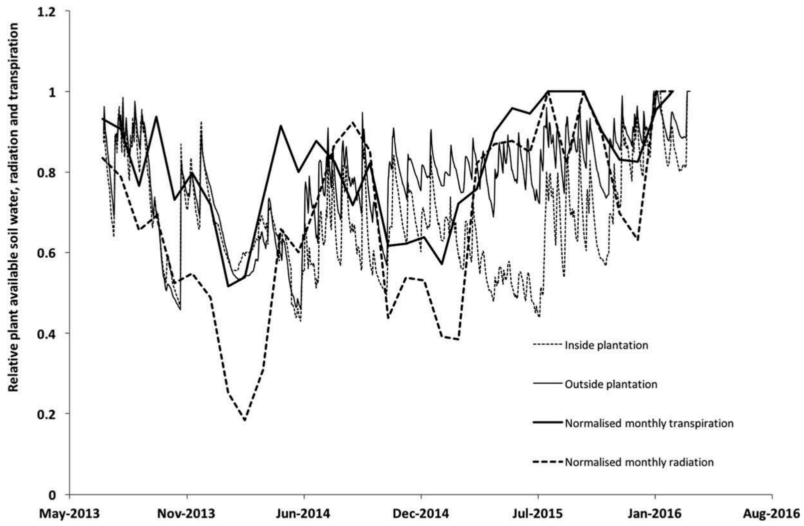

Figure 2. Normalised monthly transpiration and radiation shown with relative available plant available soil water (*W*) measured inside and outside the plantation for the period from July 2013 to March 2016. The soil water content is estimated from 0 cm to 100 cm from soil water measurements between 0 cm and 40 cm in the grass plot and 0 cm and 20 cm in the plantation plot. In each case the deepest sensor is extrapolated to 100 cm. For all variables the normalised value is calculated as the ratio of the measure value and the maximum observed during the experiment. There is a much closer correspondence between transpiration and radiation (correlation coefficient 0.62) than between transpiration and soil water content

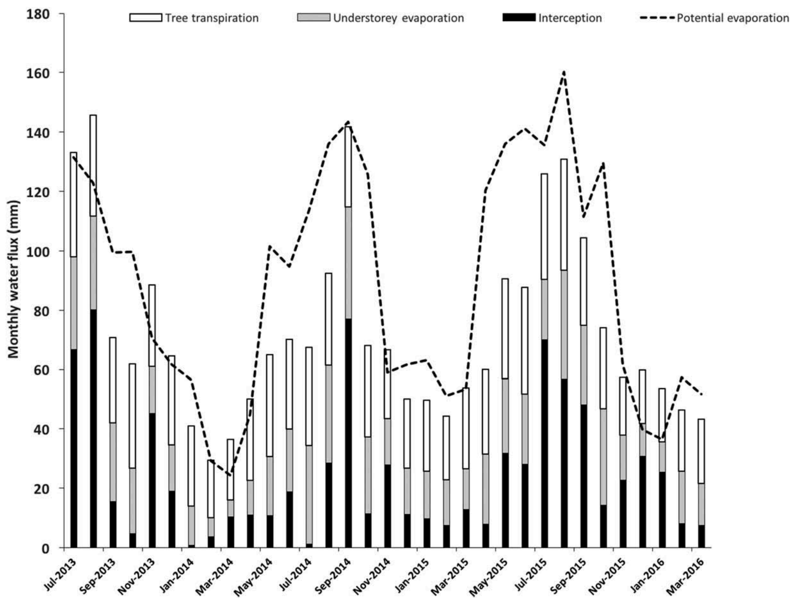

Figure 3. Monthly potential evaporation, transpiration, interception and understorey evaporation from July 2013 to March 2016

and 71% of annual rainfall (Fig. 3). In 2015, during which rainfall was close to the long-term average, the estimated total evapotranspiration was 939 mm. This was also 78% of potential evaporation and 61% of rainfall (Fig. 3).

During the wet months of July and August, interception was as much as 60% of evapotranspiration. In the dry months between December and April, interception was between 3% and 10% of evapotranspiration. The absolute value of understorey evaporation was also largest during the warm, wet months and lowest when there was less radiation and the soil was dry. Monthly transpiration was less variable than either soil evaporation or interception and varied between 17 mm and 40 mm (Fig. 3). Total annual transpiration, interception and understorey evaporation were, respectively, 327, 213 and 239 mm in 2014 and 338, 340 and 260 mm in 2015. Over this two-year period, transpiration, interception and understory evaporation were, respectively, 39%, 32% and 29% of evapotranspiration.

The seasonal patterns suggest that radiation was a stronger determinant of evapotranspiration and transpiration than available soil water. This observation was confirmed by analysis of the data. While neither monthly transpiration nor evapotranspiration were strongly correlated with plant available soil water content (coefficient of correlation less than 0.2), there was a significant positive relationship (r^2 of 0.62) between transpiration and radiation. This can be seen in Figure 2 where the seasonal pattern of transpiration corresponds much more closely to that of radiation than soil water content. Although radiation was the primary determinant of transpiration there were probably short periods during which transpiration was limited by water, particularly during 2014 (Fig. 2).

Streamflow, measured and determined from the water balance

During the course of this experiment there were a number of periods when the streamflow gauge did not record reliably. The most reliable continuous year of streamflow data was recorded between the beginning of November 2014 and the end of October 2015. During this period, 536 mm of flow were recorded at the gauge while the net water balance, the difference between rainfall and evapotranspiration, was estimated to be 554 mm. The cumulative difference between these measures is very small and indicates a net increase in storage of 18 mm over this period of 12 months. The inclusion of stemflow in the throughfall would have increased this disparity between measured streamflow and the net water balance by between 30 mm and 45 mm.

During the same period, monthly streamflow measured at the gauge was strongly correlated with the net water balance of the measurement plot. Even when the change in soil water storage was assumed to be zero, the net water balance explained 88% of the variation in measured streamflow and the relationship has a slope of 1.005 (Fig. 4), indicating that the net water balance was an unbiased predictor of monthly streamflow. Notwithstanding the strength of the relationship there were a number of months when the net water balance was zero or negative and a positive streamflow was recorded, and several months when streamflow was zero and the net water balance indicated some net drainage (Fig. 4). Allowing for the observed change in soil water content did not improve the relationships. When the time period was reduced to weekly the correlation between streamflow and net water balance was reduced to 0.6 and net water balance underestimated streamflow by 10% (relationship not shown). This analysis indicates that annual change in storage was approximately zero but that over shorter time periods it can be an important component of the water balance.

When monthly streamflow (measured) was plotted as a function of the rainfall the relationship was very strong and indicated that flow occurred in months where rainfall exceeded potential evaporation by more than 75 mm (Fig. 5). This is of the same order as the estimated total storage in the unsaturated zone (120 mm). An even stronger relationship was evident when monthly runoff was plotted as a function of the difference between rainfall and potential evaporation (Fig. 6).

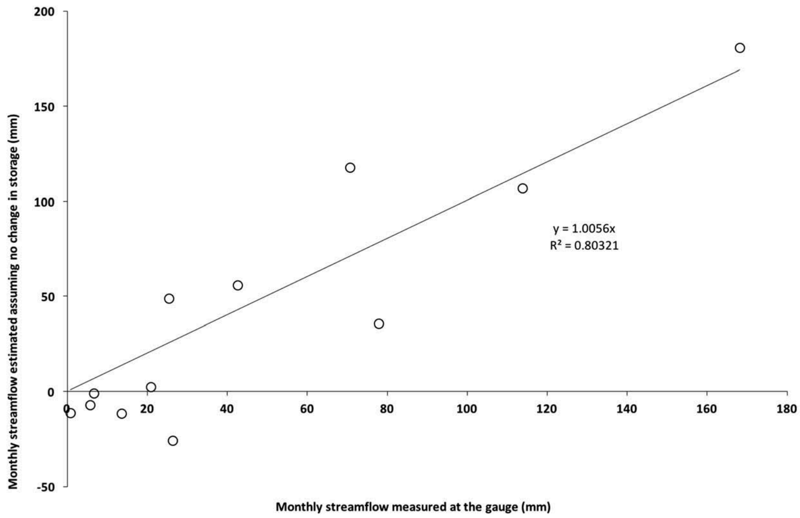

Figure 4. Monthly streamflow, between November 2014 and October 2015, estimated as the difference between rainfall and evapotranspiration as a function of streamflow measured at the gauge

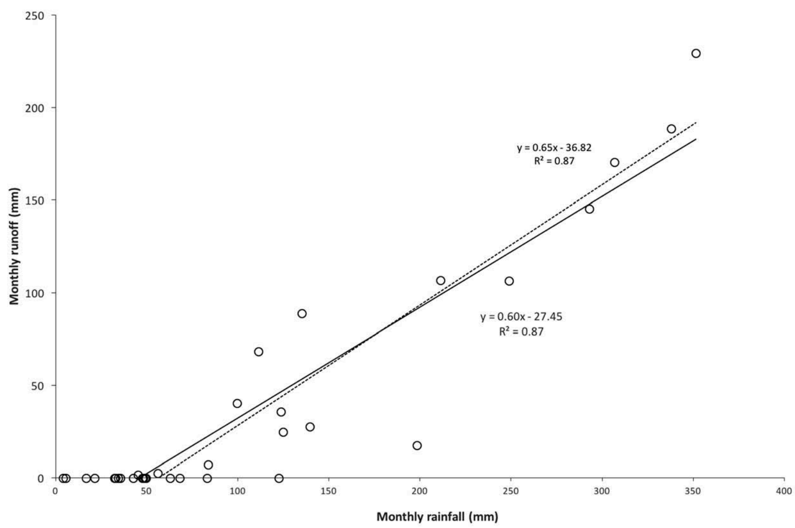

Figure 5. Monthly runoff as a function of monthly rainfall. Two linear relationships are shown. One is fitted to all the data (solid line) while the other (dashed line) is fitted only to data from months with non-zero streamflow

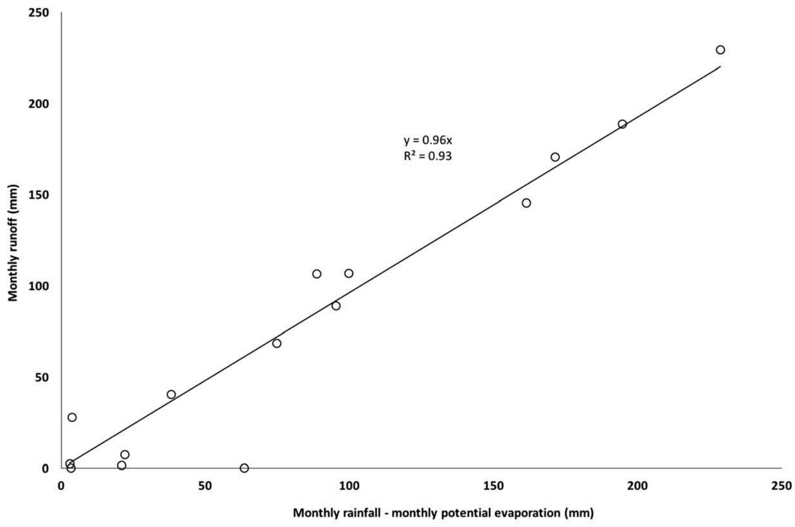

Figure 6. Monthly runoff as a function of the difference between rainfall and potential evaporation. The line shown is a linear regression

The slope of this relationship was 0.96 indicating that flow is very nearly 100% of the surplus of rainfall over potential evaporation. This is consistent with the earlier observation that estimated evapotranspiration was approximately equal to potential evaporation in most months (Fig. 3).

Modelled evapotranspiration

During 2014, based on the published data of Lane et al. (2004) and measurements in this study from July 2013 to June 2014, White et al. (2016) modified the parameters of the relationship between the crop factor (*k*, ratio of evapotranspiration to potential evaporation) and available soil water that was developed for *E. globulus* by Battaglia and Sands (1997). The modifications indicated stronger leaf shedding and stomatal closure in response to drought by *E. urophylla* × *E. grandis* than was the case for *E. globulus*. The relationships for *E. globulus* and *E. urophylla* × *E. grandis* are plotted in Figure 7 alongside data for *E. globulus* (Honeysett et al. 1996) and *E. urophylla* × *E. grandis* (this study). These data indicate that the *E. urophylla* × *E. grandis* did not experience severe water stress between July 2013 and March 2016 (Fig. 7).

During the period from July 2014 to March 2015, modelled evapotranspiration was strongly correlated with evapotranspiration estimated as the sum of transpiration, interception and understorey evaporation and the Nash-Sutcliffe model efficiency was 0.73; the model was a good, unbiased predictor of plantation water use and therefore of streamflow (Fig. 8).

The effect of land use change in small upland catchments

The model was then applied, assuming continuous plantation cover and using the climate data downloaded from the East Anglia Climate Research Unit for the period between 1900 and 2014. This modelling assumed a maximum crop factor for grass and plantation of 0.8 and 0.92, respectively. When the soil depth was only 1 m, similar to the situation in the experimental catchment at Qipo, predicted annual streamflow was always greater than 250 mm for both the plantation of *E. urophylla* × *E. grandis* and the grassland (Fig. 9). Predicted annual drainage

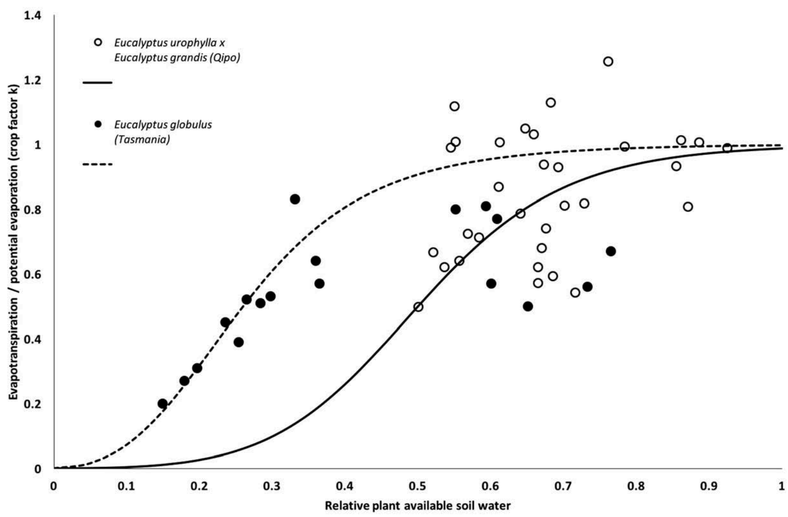

Figure 7. The crop factor (rainfall/potential evaporation) as a function of relative plant available soil water at the end of the month, calculated assuming both a 50 cm and 100 cm deep soil profile. The curve is from White et al. (2016) and was fitted derived as a fit to the upper boundary of the 2013/2014 data using the function described in Battaglia and Sands (1997)

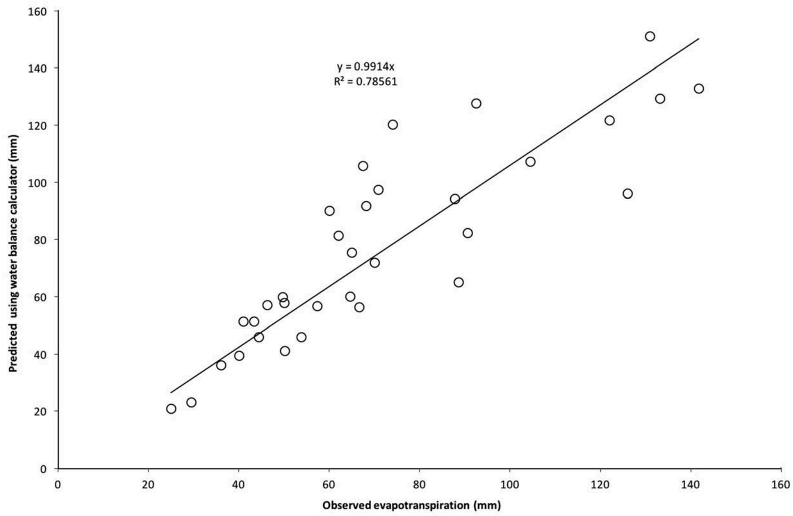

Figure 8. Predicted monthly evapotranspiration as a function of the observed evapotranspiration during the experiment. The Nash-Sutcliffe model efficiency is 0.73

was more than 500 mm for both grass and plantations in more than half of the years. The establishment of the plantation increased the number of months with zero flow by 5% (Fig. 10). The effect was much larger when the soil profile was increased to a depth of 5 m (Fig. 11) and the probability of zero monthly flow was increased by 10%. Importantly, increasing soil depth beyond 5 m, to 6, 10 and 20 m had no further effect on the relationship between drainage or runoff and the probability in exceedance over what is shown in Figure 11. This is because 5 m of storage is sufficient to buffer the difference between rainfall and potential evaporation in all years so that plantations are never water limited.

Discussion

This paper presents measurements of evapotranspiration and streamflow for a 15-ha catchment planted with a hybrid of *E. urophylla* × *E. grandis*. The measurement period included a dry year (2014, 1095 mm annual rainfall) and a year with approximately average rainfall (2015, 1493 mm annual rainfall). Streamflow in these two years was, respectively, 289 mm (estimated from water balance) and 523 mm (measured directly) while evapotranspiration was 779 mm and 939 mm. In 2014, the runoff to rainfall coefficient was 0.26 and increased to 0.35 in 2015. In 2014, the difference between measured streamflow and the residual of rainfall after evapotranspiration was only 3%. Moreover, the simple model (ramp function) developed in White et al. (2016) based on the relationship between the crop factor and relative plant available soil water was an unbiased predictor of net water balance (streamflow) at a monthly timestep.

Evapotranspiration was 779 mm in a dry year (2014) and 939 mm in an average year (2015). Although direct measurements of evapotranspiration by *Eucalyptus* plantations are rare, there are sufficient published results to suggest that these observations are broadly similar to previous observations in tropical *E. urophylla* × *E. grandis* plantations. In neighbouring Guangdong province, evapotranspiration by plantations of *E. urophylla* × *E. grandis* was measured over two years and at two sites. The range for annual evapotranspiration was 969–1150 mm (Lane et al. 2004). Further east in sub-tropical Fujian province, Liu et al. (2017) measured

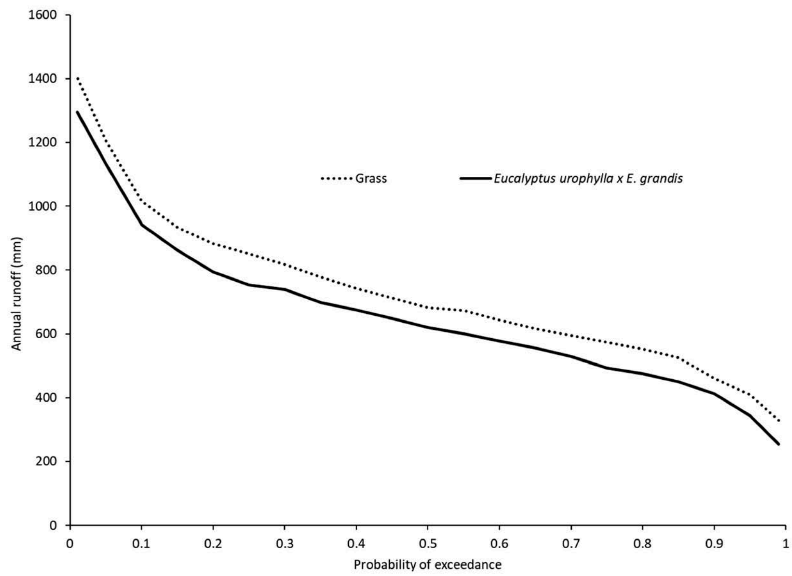

Figure 9. Annual drainage (or streamflow) for a plantation of *Eucalyptus urophylla* × *E. grandis* and a grass as a function of the probability of exceedance (for a 1 m deep soil with a maximum plant available water fraction of 0.1)

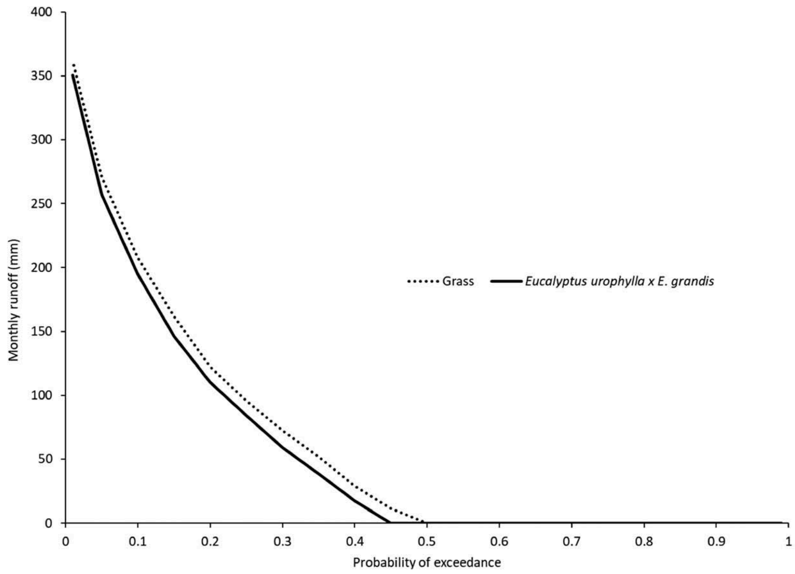

Figure 10. Monthly drainage (or streamflow) for a plantation of *Eucalyptus urophylla* × *E. grandis* and a grass as a function of the probability of exceedance (for a 1 m deep soil with a maximum plant available water fraction of 0.1)

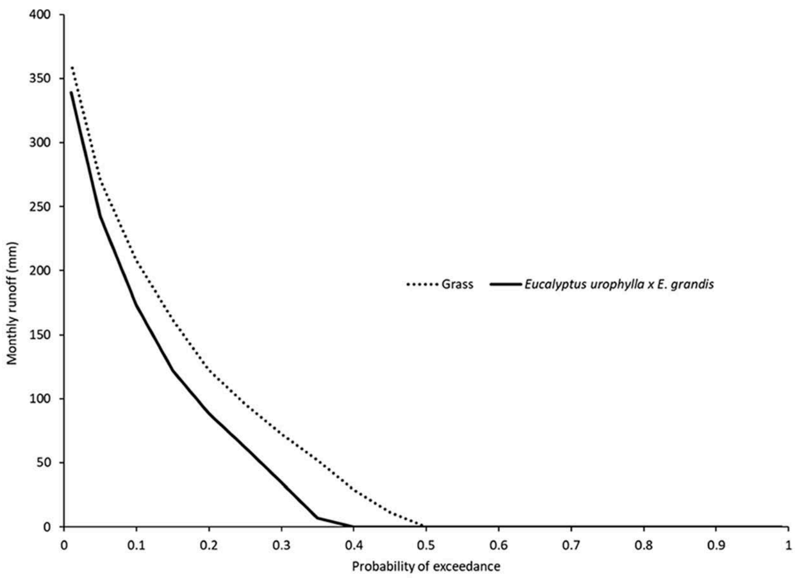

Figure 11. Monthly drainage (or streamflow) for a plantation of *Eucalyptus urophylla* × *E. grandis* and a grass as a function of the probability of exceedance (for a 5 m deep soil with a maximum plant available water fraction of 0.1)

annual evapotranspiration rates of between 877 mm and 1001 mm. Across the three provinces the runoff to rainfall ratio was between 0.26 and 0.55. Considered together with the work of Liu et al. (2017) and Lane et al. (2004), this study provides further evidence that even in dry years evapotranspiration by a *Eucalyptus* plantation is less than 70% of annual rainfall throughout southern China.

In this study, transpiration was only 39% of annual evapotranspiration. Although this is lower than previously observed in temperate *E. globulus* and *P. radiata* plantations (52%) (Benyon & Doody 2015), it is comparable to the values observed by Lane et al. (2004) and Liu et al. (2017) in tropical and sub-tropical China. Plantations of *Eucalyptus* and *Pinus* have been observed to partition energy and rainfall so that in a given climate the sum of soil evaporation and interception are quite conservative (Benyon & Doody 2015). The leaf area index of tropical plantations is generally lower than for temperate plantations and they therefore develop strong weed growth (White et al. 2016). This results in more evaporation from the understorey. Management of weeds under the relatively open canopies of tropical *Eucalyptus* plantations represents an opportunity to improve the water use efficiency of these plantations by increasing the ratio of crop tree transpiration to evapotranspiration (White et al. 2014).

Monthly streamflow was strongly correlated with net water balance (drainage) estimated from a plot water balance. At the annual timestep the change in catchment water storage was negligible compared to the other components of the water balance. Together, these results indicate that this small upland catchment in Guangxi was very responsive to rainfall. For the period from July 2015 to March 2016, a simple model based on a relationship between the crop factor and relative plantation soil water was an unbiased predictor of evapotranspiration and therefore streamflow. The Nash-Sutcliffe model efficiency (Nash & Sutcliffe 1970) of 0.73.

The correlation between monthly streamflow measured at the gauge and calculated as the residual in a water balance suggests that in the Qipo catchment, the lag in the response of the stream to rainfall is generally less than one month. The relationship between runoff and rainfall also indicates that between 50 mm and 100 mm of rain are required in any given month to generate runoff. This is very similar to the estimate of maximum storage in the unsaturated zone made from the soil samples collected in the catchment (120 mm). Moreover, monthly runoff also showed close to one to one correspondence with the monthly surplus of runoff over potential evaporation. The responsiveness of this catchment makes it possible to represent streamflow in the catchment at a monthly time step using a simple model of evapotranspiration. This greatly simplifies the task of representing the dynamics of flow in small upland catchments with shallow soils. This is important for predicting the effect of plantations throughout South-east Asia. In many of the important plantation regions of Northern Thailand, Northern and Central Vietnam and Lao and South-west China, small upland catchments with shallow soils are commonly planted with *Eucalyptus* (Hardiyanto 2003; Wongprom et al. 2012; Nambiar & Harwood 2014).

A relationship between the crop factor and plant available soil water from White et al. (2016) was used here to estimate monthly evapotranspiration for an *E. urophylla* × *E. grandis* plantation. This model of evapotranspiration was used in the process-based model, ProMod (Battaglia & Sands 1997) and was derived from the data of Honeysett et al. (1996). The features of this relationship are a plateau where the crop factor is approximately 1.0 and a rapid decline once a threshold water content is reached. The relationship used in Figure 7 predicted a maximum crop factor of one and a greater sensitivity of the crop factor to soil drying than was been observed for temperate species (White et al. 2001). This is consistent with our current understanding of the coordination of leaf and stem hydraulic traits and the relationship between these traits and the growing climate (Bartlett et al. 2014; Zhu et al. 2015). In this study, the *E. urophylla* × *E. grandis* were not exposed to severe water stress. The minimum crop factor observed here was 0.5. In other studies of the water relations of *Eucalyptus* plantations in tropical China a number of authors have observed that trees rarely, if ever, experience severe water stress (Morris et al. 1998; Lane et al. 2004; Zhu et al. 2015). Plantation species and trees exposed to more severe water stress will regulate water use through leaf shedding and stomatal closure among a range of other drought responses. This will result in reduced stem hydraulic conductivity in a coordinated response to water stress (Thomas & Eamus 1999; Zhang & Cao 2009). Trees that grow in a moist environment would be expected to have a high maximum conductance and xylem that is vulnerable to cavitation. *Eucalyptus saligna* Sm., *E. grandis* and other subtropical *Eucalyptus* species have been shown to behave in this way (Dye 2000). Similar behavior has also been observed in temperate species from the symphyomyrtus sub-genus of *Eucalyptus* such as *E. globulus* and *Eucalyptus nitens* (H. Deane & Maiden) Maiden (White et al. 1999; White et al. 2003; White et al. 2009).

The climate in southern China is characterised by a summer dominant rainfall. The period without rain coincides with reduced radiation and evaporative demand (Fig. 1). These features of the climate near Nanning and on the Leizhou Peninsula result in plantations experiencing very little water stress during the dry season. In an unusually dry year, the minimum crop factor observed here was 0.5. These environments have lower annual rates of potential evaporation than might be experienced by plantations in temperate and Mediterranean climates (e.g. between 1400 mm and 1600 mm in south-western Australia; White et al. 2014). In this study transpiration and evapotranspiration were better correlated with radiation than with available soil water. The growth and water use of plantations in these environments is energy limited in summer because rainfall exceeds potential evaporation and in winter because while there is less rain than in summer, potential evaporation is also quite low. In these environments, radiation imposes an absolute limit on potential water use by plantations.

This ramp function developed for *E. urophylla* × *E. grandis* was used to model monthly evapotranspiration and drainage from plantations and grass between 1900 and 2014 at Nanning. Two scenarios were simulated, a shallow soil profile typical of small upland catchment and a deeper profile more typical of a lowland catchment. The model predicted a 5% increase in the likelihood of months with zero drainage in the upland scenario and a 10% increase in the lowland scenario. Increasing the soil depth beyond 5 m did not increase the impact of plantations as a 5 m soil was sufficient to buffer the difference between rainfall and potential evaporation in all rainfall years between 1900 and 2014.

This modelling suggests that plantations of *Eucalyptus* catchments are unlikely to have a large effect on annual streamflow or catchment water balance in the upland plantations near Nanning, especially on shallow soils. The soil in the experimental catchment at Qipo forest farm is estimated to be between 0.5 m and 1 m deep. Under these circumstances both grass, annual or perennial, and the plantation would occupy the entire soil profile. The main difference between the plantation and shorter statured crops and pastures is that the plantation presents a rougher profile to wind resulting in greater turbulence and exchange of moist air from inside to outside the canopy. White et al. (2001) observed that the maximum rate of evapotranspiration from agricultural crops was approximated by the equilibrium rate of evaporation or was approximately 0.8 times the Priestley-Taylor potential evaporation while commercial *Eucalyptus* plantations have a maximum crop factor of about 0.95 of Priestley-Taylor potential evaporation. These were the values used for modelling the difference between land uses here. The result was a prediction of about a 70 mm reduction in annual average runoff and a 5% increase in the likelihood of a month without drainage. Even in dry years, such as one that occurred during this study, more than 250 mm of runoff would be expected.

When soil depth was progressively increased to simulate the maximum potential impact of plantations in the Nanning climate, the annual reduction in runoff increased to approximately 200 mm and the likelihood of dry month was increased by 10% due to the establishment of plantations on grassland. Increasing soil depth to 6, 10 and then 20 m did not result in any further change in the flow duration curves compared to the simulation for a 5 m deep soil profile. This is because a 5 m soil profile is sufficient to buffer the difference between potential evaporation and rainfall in all years so that the plantation becomes totally energy limited. This represents the maximum possible water use by the plantation and under these circumstances neither access to groundwater nor irrigation would increase the rate of water use by the plantation.

Thus, depending on soil depth, the annual impact of a plantation on stand and catchment water balance was estimated to be between 50 mm (on shallow soils) and 200 mm. This range is consistent with previous observations at catchment scale in southern China (Zhu et al. 2015; Liu et al. 2017).

Conclusions

(1) Streamflow in the study catchment was very responsive to rain and to periods without rain. Annual change in catchment storage was negligible, even in a dry year.
(2) The empirical and modelled results of this study suggest that plantations of *E. urophylla* × *E. grandis* are unlikely to have a large impact on the annual water balance in the small upland catchments in southern Guangxi catchments.
(3) On deeper soils, large-scale planting may reduce drainage, but in general these catchments will be larger, and the proportional impact of plantations will be diluted by the presence of other land uses.
(4) The modelling impact of plantation establishment increased as a function of soil depth up to a soil depth of 5 m. Access to more soil and water did not cause further changes in modelled drainage.
(5) A simple model, with three parameters, did a good job of representing the water balance of stands and catchments of *Eucalyptus.*

Acknowledgement

The study was funded by Guangxi Major Science and Technology Project [AA17204087-9], Guangxi Natural Science Foundation (2013GXNSFBA019082), Guangxi Key Laboratory of Superior Timber Trees Resource Cultivation [15-B-04-01] and supported by CFERN & TECHNO Award Funds on excellent academic achievements. The authors would like to thank CX Lu, DQ Guo and YF Liang for assistance with data collection and trail management.

The contribution of Dr DA White to the analysis of the data and drafting of the manuscript was supported financially by both the Australian Centre for International Agricultural Research (Project SRA FST/2014/016) and the Guangxi Forestry Research Institute.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by Guangxi Major Science and Technology Project [AA17204087-9], Guangxi Natural Science Foundation [2013GXNSFBA019082]; Guangxi Key Laboratory of Superior Timber Trees Resource Cultivation [15-B-04-01].

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