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## Measuring and modeling rainfall interception losses by a native Banksia woodland and an exotic pine plantation in subtropical coastal Australia

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## SUMMARY

Rainfall loss by canopy interception and subsequent evaporation to the atmosphere can be a significant portion of water loss from forested ecosystems. To quantify and compare interception losses from two forest types (exotic pine plantation vs. displaced native Banksia woodland) on Bribie Island in subtropical east coast Australia, we measured gross rainfall, throughfall and stemflow over a one-year period (May 2012–April 2013). Interception losses from both forests were also simulated by the revised Gash's analytical model (RGAM) and the WiMo model. The results show that the annual interception loss in the Banksia woodland was lower (16.4% of gross rainfall) than that in the pine plantation (22.9% of gross rainfall) over the study period, which can be explained by the lower canopy storage capacity and higher aerodynamic resistance of the Banksia woodland. Using fixed parameters obtained from wet season (November–April), the optimized RGAM and WiMo models predict the interception losses from both forest stands reasonably well, with an underestimation of 8.5–12.7% for the dry season (May–October), and a total underestimation of 5.2–8.2% for the entire year. The results indicate the development of commercial pine plantations in these areas would result in an increase in interception losses and thus reduce the net rainfall input in these forested ecosystems.

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## 1. Introduction

Quantifying the amount of rainfall interception loss by tree canopies can be of considerable importance for the hydrological budgets of forested catchments (Whelan and Anderson, 1996). Previous investigations have demonstrated that the canopy interception loss generally represents 9–36% of gross rainfall (Hörmann et al., 1996; Roth et al., 2007; Levia et al., 2011), while it has been estimated at up to 48% of gross rainfall for some coniferous forests (Rutter et al., 1975). Rainfall interception loss is largely dependent on the forest structure, rainfall characteristics and climatic variables governing the evaporation rates during and after rainfall events (Muzylo et al., 2009).

Interception loss  $(E_i)$  is usually quantified by the difference between measured gross rainfall  $(P_g)$  and net rainfall  $(P_n)$ , defined as throughfall  $(T_f)$  plus stemflow  $(S_f)$ . To predict interception losses using readily available meteorological variables, researchers have developed more than 15 physically-based rainfall interception

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the original and revised Gash's analytical models to be the most commonly employed. The revised Gash's analytical model (RGAM) was reformulated from the original model to predict  $E_i$  for sparse forests (Gash, 1979; Gash et al., 1995; Valente et al., 1997). Hörmann et al. (1996) developed a dynamic model of wind controlled canopy interception capacity (WiMo) in a coastal area of Germany which takes into account the effect of wind on canopy storage capacity, a factor that can be of importance in areas dominated by wind-driven rainfall. The RGAM model has been extensively applied over various climate types around the world, e.g., Mediterranean climate (Valente et al., 1007; Abcal et al., 1000; Čari et al., 2008), continental climate

models. Muzylo et al. (2009) compared these models and found

mate types around the world, e.g., Mediterranean climate (Valente et al., 1997; Aboal et al., 1999; Šraj et al., 2008), continental climate (Carlyle-Moses and Price, 1999; Price and Carlyle-Moses, 2003), tropical monsoon and montane climates (Asdak et al., 1998; Van Dijk and Bruijnzeel, 2001; Cuartas et al., 2007; Wallace and McJannet, 2008). Compared to the RGAM model, few studies have evaluated the WiMo model for interception predictions in windy areas (Hörmann et al., 1996; Klingaman et al., 2007). Ghimire et al. (2012) applied the RGAM model to two forests under the sub-tropical monsoonal montane conditions of Central Nepal and demonstrated the modeled results corresponded well with actual values when the optimized wet-canopy evaporation rate was used.





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Klingaman et al. (2007) compared three interception models for a leafless deciduous forest in the eastern United States and found the WiMo model performed better than the RGAM model. The RGAM and WiMo models, however, have not yet been applied under subtropical coastal forests and have seldom been compared against each other.

In subtropical Australia, as in many other regions and countries, exotic pine species have been largely planted for timber production (Kanowski et al., 2005), particularly in the natural distribution areas of native tree species like Banksia. The changes in vegetation in these areas can potentially affect the local hydrological processes. For example, Swank and Douglass (1974) reported annual streamflow was greatly reduced (20%) by converting a mature deciduous hardwood to white pine. Bosch and Hewlett (1982) reviewed 94 catchment experiments and found pine forests caused higher change in water yield (40 mm) than deciduous hardwood (25 mm) per 10% change in vegetation cover. Ford et al. (2011) revealed annual evapotranspiration (interception plus transpiration) by planted pine stands doubled the value of hardwood stands.

The objectives of this research are to: (1) measure and compare  $E_i$  in a Banksia woodland and a pine plantation located in subtropical coastal Australia, (2) explore the underlying causes of differences in  $E_i$  between the native and exotic forests, (3) calibrate and validate the RGAM and WiMo models for both forest stands, compare the predicted and measured  $E_i$ , and (4) assess the canopy and climatic parameters required to apply the models.

## 2. Materials and methods

#### 2.1. Study area

The study plots are located in the commercial State Forest on Bribie Island (26°59′04″S, 153°08′18″E, 9 m a.m.s.l.) southeast Queensland, Australia (Fig. 1). This area experiences a subtropical climate characterized by hot humid summers (December–February) and mild dry winters (June–August). As shown in Fig. 2, mean annual rainfall (±SD), based on 1982–2012 data from Australian Bureau of Meteorology, is 1405 (±338) mm and 68.3% of the annual rainfall occurs during the wet season (November–April). Average monthly temperature is 21.4 °C, varying from 16.2 °C in July to 26.6 °C in January. The average annual pan evaporation is ~1700 mm (Jackson, 2007). Prevailing winds blow from east to west, particularly during rainfall events. The unconsolidated sandy soils comprise 88% fine sand and 12% medium sand (USDA soil classification system).

The exotic pine trees have replaced large areas of native vegetation in the two major beach ridge systems on the island. Two representative study plots were established in the adjacent Banksia woodland (BW) and pine plantation (PP), approximately 400 m from each other. The plot areas are 0.06 ha  $(25 \text{ m} \times 25 \text{ m})$  and 0.25 ha (50 m  $\times$  50 m) for BW and PP, respectively. The native BW was largely dominated by wallum Banksia (Banksia aemula R.Br.) with a sparse understory of grass species. The secondrotation exotic pine hybrid (Pinus elliottii Engelm. × Pinus caribaea Morelet var. hondurensis) was started in 2001 with roughly 5.0 m by 2.5 m spacing. The BW had a stem density of 371 tree ha<sup>--</sup> and a mean diameter at breast height (DBH, 1.3 m) of 0.30 m, while the corresponding values for PP were 840 tree  $ha^{-1}$  and 0.21 m, respectively. The leaf area index (LAI) measured using a LAI-2000 plant canopy analyzer (Li-COR, Lincoln, USA) was on average 2.33 m<sup>2</sup> m<sup>-2</sup> for BW and 2.05 m<sup>2</sup> m<sup>-2</sup> for PP. The LAI changed seasonally from 2.13 m<sup>2</sup> m<sup>-2</sup> in winter to 2.48 m<sup>2</sup> m<sup>-2</sup> in summer for BW and from 1.87 m<sup>2</sup> m<sup>-2</sup> to 2.16 m<sup>2</sup> m<sup>-2</sup> for PP, indicating small seasonal variations. The other forest structural features are illustrated in Table 1.

#### 2.2. Collection of gross rainfall, throughfall and stemflow

From 1 May 2012 to 30 April 2013, the measurements of  $P_{g}$ ,  $T_{f}$ and S<sub>f</sub> were conducted simultaneously for both forest stands. The  $P_g$  was measured using two HOBO RG3 tipping-bucket rain gauges (177 cm<sup>2</sup> orifice, Onset Computer Corp., Bourne, USA) and positioned at 0.5 m above the ground to avoid rain splash and prevent damage by animals. One rain gauge was situated in the middle of a 30 m wide track that borders the pine stands. The horizontal angle between the rain gauge and the top of the nearest trees was smaller than 45°, so little disturbance on gross rainfall measurement was caused by its surrounding environment (Asdak et al., 1998). The other rain gauge was located in a nearby well-exposed clearing next to the Banksia woodland. All the tipping-bucket rain gauges used in this study were calibrated to 0.2 mm per tip in the lab and recalibrated after deployments in the field every three months to ensure the accuracy of the rain gauges (Llorens et al., 1997). The bucket tipping time and numbers were automatically recorded by a self-constructed datalogger. The raw tip-time data were further converted into 15-min rain rates to coincide with the weather station data.

The  $T_f$  was sampled under and between trees in the pine plantation using 15 rain gauges identical to those used for gross rainfall measurements. In the Banksia woodland, the  $T_f$  was collected using 16 U-shaped troughs connecting to 8 Hobo tipping-bucket rain gauges. The troughs were made of split UPVC pipes, 1.0 m long by 0.1 m wide and randomly located within the plot. The collection troughs with larger collecting areas were used to integrate the spatial variability of  $T_f$  and reduce the sampling error (Limousin et al., 2008), since the BW plot was more heterogeneous than the PP plot. The S<sub>f</sub> was measured on eight representative pine trees (0.15 m < DBH < 0.30 m) and on six Banksia trees (0.20 m < DBH)< 0.40 m). The S<sub>f</sub> was collected using spiral-type stemflow collars constructed from wired rubber. Each stemflow collar was fixed around the tree trunk and sealed with silicon sealant. The collected stemflow was diverted to a HOBO tipping-bucket rain gauge using a rubber hose with 2.5 cm in diameter. Following Hanchi and Rapp (1997), the tree-level  $S_f$  was upscaled to the stand-level  $S_f$  for both forest stands using Eq. (1):

$$S_f = \sum_{i=1}^n \frac{S_n \cdot m}{A \cdot 10^4}$$
(1)

where  $S_f$  is the upscaled stemflow depth (mm) for a specified stand area of A (m<sup>2</sup>), n the number of DBH classes, and  $S_n$  the average stemflow volume (ml) collected from m trees in the DBH class.

#### 2.3. Meteorological instruments

Meteorological variables were observed from an automatic weather station mounted on a 15-meter-high mast (~1.5 m above the pine canopy) in the center of the PP plot. Air temperature (T, °C) and relative humidity (RH, %) were measured with an HMP155 sensor (Vaisala, Vantaa, Finland). Wind speed (WS, m s<sup>-1</sup>) and direction (WD, deg) were measured by a wind sentry set (model 03002, RM Young, Michigan, USA). A CNR4 net radiometer was deployed to measure net radiation ( $R_n$ , W m<sup>-2</sup>) (Kipp & Zonen, Delft, The Netherlands). Two HFP01 soil heat flux plates (Hukse-flux, Delft, The Netherlands) were buried at 5 cm depth to measure soil heat flux (G, W m<sup>-2</sup>). Meteorological data were automatically sampled at 5-min intervals and recorded at 15-min intervals by a CR3000 datalogger (Campbell Scientific, Logan, USA).

## 2.4. Model descriptions

#### 2.4.1. The RGAM model

The RGAM model was used to model interception losses base on a series of individual rainfall events, with enough time to



Fig. 1. Locations of study sites on Bribie Island in southeast Queensland of Australia.



Fig. 2. Seasonal trend in rainfall for 30-year average and the 2012/2013 season, and mean monthly temperature on Bribie Island.

completely dry the tree canopy between two successive events (Gash, 1979). The model requires canopy and climatic parameters for interception calculations, which include the canopy storage capacity (*S*), canopy cover (*c*, assumed to be one minus free throughfall coefficient *p*), rainfall fraction converted to stemflow ( $p_t$ ), trunk storage capacity ( $S_t$ ), mean rainfall intensity ( $\overline{R}$ ) and

mean evaporation rate ( $\overline{E}$ ) during rainfall. The amounts of rainwater needed to entirely saturate the canopy ( $P_g'$ ) and the trunk ( $P_t'$ ) were calculated using Eqs. (2) and (3), respectively:

$$P'_{g} = -\overline{R}/\overline{E}_{c}S_{c}\ln\left(1 - \overline{E}_{c}/\overline{R}\right) \tag{2}$$

$$P'_t = S_t / p_t \tag{3}$$

where  $S_c$  is the canopy storage capacity per unit area of canopy cover, calculated as  $S_c = S/c$ , and  $\overline{E}_c$  is the mean evaporation rate during rainfall upscaled to canopy cover, defined as  $\overline{E}_c = \overline{E}/c$ .

The RGAM model distinguishes three sequential phases, i.e., a wetting-up phase, a saturating phase during rainfall, and a drying-out phase after rainfall. Evaporative losses from the canopy take place during each phase and the total interception for a given event is obtained as the sum of different components listed in Table 2 (Gash et al., 1995).

#### 2.4.2. The WiMo model

The WiMo model incorporates a dynamic *S* based on the maximum wind speed ( $u_{max}$ ) during each rainfall event. The  $E_i$  is calculated using a bucket model at hourly time steps as shown in Table 3 (Hörmann et al., 1996). The rainfall ( $P_g^i$ ) falling on leaves

Table 1			
Forest structural	characteristics of Banksia	woodland (BW) a	nd pine plantation (PP)

Forest type	Stem density (tree $ha^{-1}$ )	DBH <sup>a</sup> (m)	Basal area (m² ha <sup>-1</sup> )	$LAI^{a} (m^{2} m^{-2})$	Canopy height <sup>a</sup> (m)	Crown diameter <sup>a</sup> (m)
BW	371	0.30 ± 0.05	21.32	$2.33 \pm 0.14$	6.82 ± 0.28	$7.44 \pm 0.54$
PP	840	0.21 ± 0.02	23.65	$2.05 \pm 0.08$	$13.34 \pm 0.41$	3.56 ± 0.36

<sup>a</sup> Data are given as mean  $\pm$  standard deviation (n = 25). LAI denotes leaf area index and DBH diameter at breast height.

Table 2

Components of interception in the revised Gash's analytical model.

Components of interception	Equation
1. For m rainfall events $P_g < P'_g$ (1) Evaporation from unsaturated canopy 2. For n rainfall events $P_g > P'_g$	$c\sum_{j=1}^m P_{g,j}$
<ul> <li>(2) Wetting up the canopy</li> <li>(3) Wet canopy evaporation during rainfall</li> <li>(4) Evaporation after rainfall ceases</li> <li>(5) Evaporation from trunks for <i>q</i> events, which saturate the trunks (<i>P<sub>g</sub></i> &gt; <i>P<sub>t</sub></i>')</li> </ul>	$nc(P'_g - S_c)$ $c\overline{E_c}/\overline{R}\sum_{j=1}^{n}(P_{g,j} - P'_g)$ $ncS_c$ $qS_t + P_t\sum_{j=1}^{n-q}P_{g,j}$
sucurate the trains (ig if)	
(5) Evaporation from trunks for $q$ events, which saturate the trunks ( $P_g > P_t'$ )	$qS_t + P_t \sum_{j=1}^{n-q} P_{g,j}$

is added to the canopy storage content of last hour  $(C_{i-1})$  and actual evaporation  $(E_a^i)$  is subtracted from the canopy until *S* is empty. The throughfall  $(T_f^i)$  is calculated as the difference of hourly water balance (WB<sub>i</sub>) and canopy storage content  $(C_i)$  when WB<sub>i</sub> exceeds  $C_i$ .

## 2.5. Estimation of model parameters

## 2.5.1. Canopy parameters

Following Wallace and McJannet (2006), the *S* values for BW and PP were obtained as the negative intercept of linear regression between  $P_g$  and  $P_n$ . The *p* values were derived as the slope of the linear regression of  $T_f$  against  $P_g$  for small rainfall events that were insufficient to exceed *S* (Jackson, 1975). The trunk parameters  $p_t$  and  $S_t$  were estimated by the method of Gash and Morton (1978), as the slope and negative intercept of the linear regression of  $S_f$  and  $P_g$ , respectively.

#### 2.5.2. Mean rainfall intensity

The individual rainfall events in this study were separated by at least 6 h without rainfall to allow the tree canopy to be completely dried before the next rainfall (Murakami, 2006). The mean rainfall intensity ( $\overline{R}$ ) during rainfall was calculated as the arithmetic mean of the individual event rainfall intensities or as the median value when rainfall intensity was not normally distributed. Small rainfall events less than 2 mm were, however, removed from the analysis of mean rainfall intensity because it was difficult to accurately determine their durations (Wallace and McJannet, 2006).

#### 2.5.3. Mean wet-canopy evaporation rate

The mean evaporation rate  $(\overline{E})$  from the wet canopy during rainfall was derived using three approaches. First, the evaporation rate  $(\overline{E}_{PM})$  was estimated using Penman–Monteith (PM) equation (Monteith, 1965), assuming canopy resistance  $r_c = 0$ :

$$\overline{E}_{PM} = \frac{\left[\Delta R_n - G + \rho_a c_p D / r_a\right]}{\lambda \Delta + \gamma} \tag{4}$$

where  $\triangle$  is the slope of the saturation vapor pressure against temperature curve (kPa K<sup>-1</sup>),  $R_n$  the net radiation at the canopy surface (W m<sup>-2</sup>),  $\rho_a$  the air density (kg m<sup>-3</sup>), *G* the soil heat flux (W m<sup>-2</sup>),  $c_p$  the specific heat of the air (J kg<sup>-1</sup> K<sup>-1</sup>), *D* the vapor pressure deficit (kPa),  $\lambda$  the latent heat of vaporization of water (kPa K<sup>-1</sup>),  $\gamma$  the

#### Table 3

Algorithm used in the WiMo model to calculate through fall for time step i.

Parameter	Equation
Maximum wind speed $(u_{max})$	Input
Rainfall $(P_g)$	Input
Actual evaporation $(E_a)$	Input
Canopy storage capacity (S)	$S = f(u_{max})$
Water balance (WB)	$Max(P_g^i + C_{i-1} - E_a^i, 0)$
Throughfall (T <sub>f</sub> )	If WB <sub>i</sub> > $C_i$ then WB <sub>i</sub> – $C_i$ , else 0
Canopy storage content (C)	If $WB_i > C_i$ then $C_i$ , else $WB_i$

psychometric constant (J kg<sup>-1</sup>), and  $r_a$  the aerodynamic resistance (s m<sup>-1</sup>), which is calculated by the logarithmic boundary layer equation for neutral stability conditions (Allen et al., 1998):

$$r_{a} = \frac{\ln [z_{u} - d)/z_{om}] \ln [(z_{e} - d)/z_{ov}]}{k^{2} u}$$
(5)

where *u* is the wind speed  $(m s^{-1})$ ,  $z_u$  the height at which the wind speed was measured (m),  $z_e$  the height of the relative humidity instrument (m), *d* the zero plane displacement height (m),  $z_{om}$  the roughness height controlling momentum (m),  $z_{ov}$  the roughness height controlling transfer of vapor and heat (m), and *k* von Karman's constant (0.41).

Usually, *d* and  $z_{om}$  are estimated from the average canopy height  $h_c$ . For forest stands in this study, it is assumed that  $d = 0.7h_c$ ,  $z_{om} = 0.1h_c$  and  $z_{ov} = 0.5z_{om}$  (Brutsaert, 1979; Verseghy et al., 1993). The  $\overline{E}_{PM}$  was then determined as the arithmetic mean of evaporation rates calculated for individual rainfall events using PM equation. The mean wet-canopy evaporation rate ( $\overline{E}_{TF}$ ) was also determined from the value of  $\overline{E}/\overline{R}$  as obtained from the linear regression of  $P_g$  against observed  $E_i$ . The mean evaporation rate ( $\overline{E}_O$ ) was finally optimized by minimizing the root mean square error (RMSE) between paired simulated and observed  $E_i$  for all rainfall events.

# 2.5.4. Relationship between canopy storage capacity and maximum wind speed

The *S* for each rainfall event as a function of  $u_{max}$  was derived by the regression of the optimum canopy storage capacity ( $S_o$ ) and  $u_{max}$ . To obtain the  $S_o$  for each rainfall event, a bucket model that calculates  $T_i^f$  at each hourly time step was used:

$$T_f^i = \begin{cases} cP_g^i & \text{if } C_i \le S\\ cP_g^i + C_i - S & \text{if } C_i > S \end{cases}$$
(6)

where  $C_i$  is

$$C_i = C_{i-1} + P_g^i - E_a^i \tag{7}$$

The  $C_i$  was reset to S at the end of the time step when it exceeded S.

A MATLAB program was used to find  $S_o$  for each rainfall event by running the bucket model from 0 mm to 3.0 mm. The *S* was optimized to yield the minimum RMSE between the modeled and measured  $T_f^i$ . Paired  $S_o$  and  $u_{max}$  from 15-min meteorological observations for each rainfall event were fitted to generate a regression equation.

## 3. Results

## 3.1. Rainfall characteristics

The average relative error between two gross rainfall measurements was only 2.6%, so it is assumed that the spatial variability of gross rainfall over the study area was negligible and the average value was used as gross rainfall. Over the study period, 102 discrete rainfall events produced 1492.1 mm of annual gross rainfall, with 71.3% and 28.7% of gross rainfall occurring during the wet season and dry season, respectively. However, the frequency distributions of rainfall amount and intensity were similar between the wet and dry seasons (Fig. 3). Small rainfall events (<5 mm) occurred much more frequently than heavier rainfall, especially during the dry season (Fig. 3a). Average event rainfall intensities varied from 0.4 to 10.8 mm h<sup>-1</sup>, with the maximum 15-min intensity reaching 58 mm h<sup>-1</sup>. Rainfall events with intensity lower than 2 mm h<sup>-1</sup> accounted for 30% of total rainfall, while 50% of rainfall intensities lay between 2 and 4 mm h<sup>-1</sup> (Fig. 3b). Since the



Fig. 3. Frequency distributions of (a) rainfall amount and (b) rainfall intensity over the wet season (n = 59), dry season (n = 43) and entire year (n = 102).

distribution of rainfall intensity data deviated from normal distribution, the median rainfall intensity was thus used to estimate  $E_i$ .

#### 3.2. Throughfall, stemflow and interception loss

The measured annual  $T_f$  amounted to 1241.3 mm for BW and 1135.0 mm for PP, which accounted for 83.2% and 76.1% of  $P_g$ , respectively (Table 4). The average standard errors of mean  $T_f$  for individual events were 8.6% and 13.1% for BW and PP, respectively. The stand-level estimate of annual  $S_f$  for BW was only 0.4% of  $P_g$ , while  $S_f$  for PP was slightly higher, estimated at 1.0% of  $P_g$ . The standard errors of the  $S_f$  estimates were much higher, 28.7% for BW and 20.4% for PP. By subtracting  $T_f$  and  $S_f$  from  $P_g$ , the annual  $E_i$  were estimated to be 245.0 mm for BW and 342.8 mm for PP, which accounted for 16.4% and 22.9% of  $P_g$ , respectively. The average standard errors of the  $E_i$  for individual events, which were calculated as the root sum of the variances of  $T_f$  and  $S_f$ , were 14.5% for BW and 17.8% for PP. The percentage of canopy interception was higher during the dry season than that during the wet season for both forest stands.

## 3.3. Derived model parameters

## 3.3.1. Canopy parameters

The derivation of the average canopy parameters during wet season for both forest stands is presented in Fig. 4. The following canopy parameters were determined for BW and PP, respectively: canopy storage capacity (*S*), 0.45 and 1.31 mm; free throughfall fraction (*p*), 0.52 and 0.47, and thus canopy coverage (*c*), 0.48 and 0.53. The fraction of rainfall contributing to stemflow ( $p_r$ )

and the trunk storage capacity  $(S_t)$  were obtained at 0.005 and 0.021 mm for BW, and at 0.014 and 0.066 mm for PP.

#### 3.3.2. Mean wet-canopy evaporation rate

The  $\overline{E}_{PM}$  obtained using the PM equation were 0.19 mm h<sup>-1</sup> for BW and 0.22 mm h<sup>-1</sup> for PP. The estimated  $\overline{E}/\overline{R}$  values from the regression method were 0.141 and 0.165 for BW and PP, respectively. Based on the median rainfall intensity of 2.76 mm h<sup>-1</sup>, the resulted  $\overline{E}_{TF}$  were 0.39 mm h<sup>-1</sup> and 0.46 mm h<sup>-1</sup> for BW and PP, respectively.

## 3.3.3. Relationship between canopy storage capacity and maximum wind speed

The effect of wind speed on the canopy storage capacity is shown in Fig. 4(d). The calculated  $S_o$  has a general tendency to decrease with increasing  $u_{max}$  despite scatter distribution. We derived a power regression equation ( $r^2 = 0.314$ , p < 0.05) for BW and a logarithmic regression equation ( $r^2 = 0.488$ , p < 0.05) for PP to calculate *S* in the WiMo model.

## 3.4. Model calibration and validation

The rainfall events observed during the wet season (n = 59) were used to calibrate the RGAM and WiMo models, whereas the calibrated models were validated for the dry season (n = 43). Canopy and climatic parameters used in the RGAM model for both forest stands are summarized in Table 5.

The observed and simulated total  $E_i$  during the wet season for three RGAM model runs and for the WiMo model are compared in Table 6. The predicted  $E_i$  by PM model was underestimated by

Table	4
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Measured seasonal and annual gross rainfall, throughfall, stemflow, and interception losses for Banksia woodland (BW) and pine plantation (PP).

Forest type	Season	Gross rainfall (mm)	Mean rainfall intensity (mm h <sup>-1</sup> )	Median rainfall intensity (mm h <sup>-1</sup> )	Throughfall (mm)	Stemflow (mm)	Interception (mm)
BW	Wet season	1063.4	3.25	2.76	898.2 (84.5%)	3.8 (0.4%)	161.4 (15.2%)
	Dry season	428.7	2.72	2.52	343.1 (80.0%)	2.0 (0.5%)	83.6 (19.5%)
	Annual	1492.1	3.02	2.62	1241.3 (83.2%)	5.8 (0.4%)	245.0 (16.4%)
PP	Wet season	1063.4	3.25	2.76	833.1 (78.3%)	10.6 (1.0%)	219.7 (20.7%)
	Dry season	428.7	2.72	2.52	301.9 (70.4%)	3.7 (0.9%)	123.1 (28.7%)
	Annual	1492.1	3.02	2.62	1134.9 (76.1%)	14.3 (1.0%)	342.8 (22.9%)

Values in parentheses are the percentage to corresponding gross rainfall.



**Fig. 4.** Estimation of (a) canopy storage capacity (*S*), (b) coefficient of free throughfall p, (c) the stemflow fraction ( $p_t$ ) and trunk storage capacity (*S*<sub>t</sub>), and (d) canopy storage capacity (*S*) as a function of maximum wind speed ( $u_{max}$ ) for Banksia woodland (BW) and pine plantation (PP).

28.1% for BW and by 21.2% for PP. The predicted  $E_i$  using  $\overline{E}_{TF}$  were closer to observed  $E_i$  with an overestimation of 11.6% for BW and 14.3% for PP. The optimized  $\overline{E}_0$  for RGAM model using wet season rainfall data were  $0.34 \text{ mm h}^{-1}$  and  $0.35 \text{ mm h}^{-1}$  for BW and PP, respectively. Simulated  $E_i$  using  $\overline{E}_0$  agreed well with observed values for both forest stands, underestimating by only 1.8% and 3.5%, respectively. The use of optimized wet-canopy evaporation rate improves RGAM interception predictions for both forests, where the error reduces from  ${\sim}25\%$  to  ${\sim}2.5\%$ , and the Nash–Sutcliffe efficiency (Nash and Sutcliffe, 1970) increases from ~0.70 to ~0.95. The simulated total  $E_i$  by WiMo model was underestimated by 7.7% for BW and by 4.3% for PP. Different components of the wet season *E<sub>i</sub>* simulated by the optimized RGAM is presented in Table 7. The result suggested that 77.3% and 16.6% of  $E_i$  evaporated during and after rainfall for BW, while the corresponding values for PP were 51.6% and 34.8%, respectively. Evaporation losses from other phases played a small role in total  $E_i$  for both forest stands.

The optimized RGAM model and WiMo model were then used to estimate the dry season  $E_i$  from two forest stands (Table 6). As for the RGAM model, the predicted total dry season  $E_i$  was underestimated by 12.1% and 8.5% for BW and PP, respectively. The

Table 5

WiMo model also underestimated  $E_i$  during the dry season, with an agreement of 9.4% for BW and 12.7% for PP. Generally, the dry season  $E_i$  predicted by optimized RGAM model exhibits slightly lower error and higher Nash–Sutcliffe efficiency than those estimated by WiMo model. Totally, the cumulative simulated  $E_i$  by RGAM model using  $\overline{E}_0$  over the entire year were 232 mm for BW and 325 mm for PP, with an underestimation of 5.3% and 5.2%, respectively (Fig. 5). The corresponding values by WiMo model were 225 mm for BW and 318 mm for PP, with an underestimation of 8.2% and 7.3%, respectively. The comparison between the observed and simulated  $E_i$  for individual rainfall events over the study period using the optimized RGAM and WiMo models is shown in Fig. 6. The results indicated that the RGAM model generally underestimates  $E_i$  for small rainfall events but it overestimated  $E_i$  for some heavy events, which is not evident for the WiMo model.

#### 3.5. Parameter sensitivity

To identify the relative importance of the parameters in RGAM model, we conducted a sensitivity analysis with respect to canopy and climatic parameters (Fig. 7), whereas no sensitivity analysis

Summary of canopy and climatic parameters used in the revised Gash's analytical model for Banksia woodland (BW) and pine plantatic	on (PP
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Forest type	Canopy para	meters			Climatic parameters (mm h <sup>-1</sup> )				
	<i>S</i> (mm)	р	с	$p_t$	$S_t$ (mm)	$\overline{R}$	$\overline{E}_{PM}$	$\overline{E}_{TF}$	$\overline{E}_{O}$
BW PP	0.45 1.31	0.52 0.47	0.48 0.53	0.005 0.014	0.021 0.066	2.76 2.76	0.19 0.22	0.39 0.46	0.34 0.35

#### Table 6

Comparison of observed total interception ( $I_o$ ) and modeled total interception ( $I_m$ ) by the RGAM model using different wet-canopy evaporation rates and by the WiMo model for the calibration and validation datasets from Banksia woodland (BW) and pine plantation (PP).

Interception	Calibrati	on (wet sea	r season)				Validation (dry season)					
	Using E <sub>P</sub>	M	Using <i>E</i> <sub>TF</sub> Using <i>E</i> <sub>O</sub>		WiMo		Using Eo		WiMo			
	BW	PP	BW	PP	BW	PP	BW	PP	BW	PP	BW	PP
$P_{g}$ (mm)	1063	1063	1063	1063	1063	1063	1063	1063	429	429	429	429
$I_o(mm)$	161	220	161	220	161	220	161	220	84	123	84	123
$I_m$ (mm)	116	173	180	252	158	212	149	211	74	113	76	107
Modeled-observed (%)	-28.1	-21.2	11.6	14.3	-1.8	-3.5	-7.7	-4.3	-12.1	-8.5	-9.4	-12.7
Nash-Sutcliffe model efficiency	0.73	0.69	0.83	0.74	0.97	0.94	0.78	0.83	0.84	0.75	0.72	0.79

#### Table 7

Components of interception loss simulated by the RGAM model for Banksia woodland (BW) and pine plantation (PP) during the wet season.

Components of interception	Simulated interception (mm)	
	BW	PP
1. For m rainfall events $P_g < P_g$		
(1) Evaporation from unsaturated canopy	0 (0%)	2.9 (1.4%)
2. For n rainfall events $P_g > P'_g$		
(2) Wetting up the canopy	4.0 (2.5%)	10.3 (1.9%)
(3) Wet canopy evaporation during rainfall	122.5 (77.3%)	109.1 (51.6%)
(4) Evaporation after rainfall ceases	26.4 (16.6%)	73.6 (34.8%)
(5) Evaporation from trunks for q events, which saturate the trunks $(P_g > P_t')$	5.7 (3.6%)	15.7 (7.4%)
Simulated total interception	158.6	211.6

Values in parentheses are the percentage to corresponding total interception.



**Fig. 5.** Cumulative measured and modeled interception over the one-year period using the RGAM and WiMo models for Banksia woodland (BW) and pine plantation (PP).

was performed for the parameter *S* in the WiMo model as it was calculated by the model itself. A decrease of 25% in *R* and *E* resulted in an increase 21% and a decrease of 16% in simulated  $E_i$ , but reducing *S* and *c* by 25% decreased  $E_i$  by only 6% and 3%. A change of 25% in  $p_t$  and  $S_t$  produced less than 0.5% changes in simulated  $E_i$ . The results showed that the RGAM model is highly sensitive to changes in climatic parameters *R* and *E*, less sensitive to canopy parameters *S* and *c*, but fairly insensitive to trunk parameters  $p_t$  and  $S_t$ .

## 4. Discussion

## 4.1. Throughfall

The observed  $T_f$  for BW (83.2% of  $P_g$ ) was comparable with the reported value in a Mediterranean Banksia woodland of south Western Australia (Farrington and Bartle, 1991), ranging from



**Fig. 6.** Measured and modeled interception for each rainfall event over the oneyear period using the RGAM and WiMo models for Banksia woodland (BW) and pine plantation (PP).

80% to 85% of  $P_g$ , but the  $T_f$  for PP (76.1% of  $P_g$ ) was lower than those recorded in other pine forests of similar basal area, e.g., 82–87% by Farrington and Bartle (1991) and 85% by Shi et al. (2010). Since the LAI was similar between two forests, the lower  $T_f$  fraction in the pine plantation relative to the Banksia woodland was ascribed to its higher stem density. However, the lower  $T_f$  in our plantation relative to other studies was most likely resulted from the higher evaporation rates during rainfall events, which caused more intercepted rainfall water back to air and thus reduced throughfall through the canopy.

## 4.2. Stemflow

The stand-scale  $S_f$  accounted for a fairly low percentage of  $P_g$ , 0.4% and 1.0% of  $P_g$  for BW and PP, respectively. The steep branches of pine trees have a greater access of rainfall to the trunks than the



**Fig. 7.** Sensitivity analyses of canopy parameters *S*, *c*, *p*<sub>t</sub> and *S*<sub>t</sub>, and climatic parameters  $\overline{E}$  and  $\overline{R}$  in the RGAM model on the predicted interception loss. Analyses were based on the average changes observed from two forest stands.

low-angled branches of Banksia trees and possibly caused higher stemflow for PP (Herwitz, 1987). The stemflow for PP was much lower than the other reported values, e.g., 2.7% by Singh (1987), 4.9% by Meng et al. (2001) and 5.9% by Li et al. (2007) with stem density of 1500–5000 tree ha<sup>-1</sup>, but it was closer to 0.88% by Shi et al. (2010) and 0.5% by Ghimire et al. (2012) found in pine forests with similar smaller stem density (600–800 tree ha<sup>-1</sup>). This indicated that the lower stemflow fraction can be possibly explained by the low stem density in our plantation.

## 4.3. Interception loss

The  $E_i$  for BW (16.4% of  $P_g$ ) was similar to the only reported value (average = 15% of  $P_g$ ) by Farrington and Bartle (1991). The observed  $E_i$  for PP (22.9% of  $P_g$ ) was slightly higher than the earlier observations in pine forests with low stem density, e.g., averaged 15% in a Pinus pinaster plantation by Farrington and Bartle (1991), 17.6% in a young pine Pinus palustris stand by Bryant et al. (2005), 14.2% in a natural Pinus armandii stand by Shi et al. (2010), and 19.4% in a planted pine forest reported by Ghimire et al. (2012). It is possible that the higher interception was due to the higher stand density in our study and higher evaporation rates during rainfall resulting from active advection of sensible heat at the coastal areas (van der Molen et al., 2006). The higher percentage of  $E_i$  for PP was expected, as  $E_i$  appears to be generally higher in coniferous forests than in broadleaf forests due to conifers' higher canopy storage capacity and the enhanced sensible heat transfer above the canopy caused by larger laminar boundary conductance from smaller leaves (Oke, 1992; Valente et al., 1997; Carlyle-Moses, 2004). Since the local climate and the canopy cover (e.g., LAI) were similar in both forest stands, the higher  $E_i$  by the pine planation was thus ascribed to its larger canopy storage capacity and smaller aerodynamic resistance at canopy surface as a result of its greater tree height (Valente et al., 1997).

#### 4.4. Canopy parameters

The *S* estimate of 1.31 mm for PP compared favorably with observed values in coniferous forests, ranging from 0.3 mm to 3.0 mm (Llorens and Gallart, 2000). For broadleaf forests, the *S* values generally vary from 0.4 mm to 1.5 mm (Deguchi et al., 2006). The low *S* value (0.45 mm) for BW and estimated *S* value in the lower range for PP were consistent with the lower canopy coverage

for both study plots. Similar to the finding by Hörmann et al. (1996), we found a decreasing trend in *S* with increasing wind speed, which is, however, contrary to the results of Klingaman et al. (2007). The decrease in *S* was because the captured rain droplets were shaken down from the canopy leaves by winds, which did not happen to the leafless stands of Klingaman et al. (2007).

The RGAM model was confirmed to be fairly insensitive to stemflow parameters  $S_t$  and  $P_t$  due to their small contributions to the total  $E_i$ , as shown in other studies (e.g., Valente et al., 1997; Limousin et al., 2008; Shi et al., 2010; Ghimire et al., 2012). The *c* was not highly sensitive to the model compared with studies by Gash et al. (1995) and Limousin et al. (2008), but it was in agreement with the results of Dykes (1997), Deguchi et al. (2006).

## 4.5. Mean rainfall intensity

The sensitivity analysis revealed that the RGAM model was mostly and highly sensitive to changes in climate parameters  $\overline{R}$ and  $\overline{E}$ , which agrees well with the work by Loustau et al. (1992), Limousin et al. (2008). The median rainfall intensity  $(2.76 \text{ mm h}^{-1})$  observed here was also comparable to what was reported in other tropical and subtropical regions, generally ranging from 2.5 to 5.0 mm  $h^{-1}$  (Van Dijk and Bruijnzeel, 2001; Limousin et al., 2008; Ghimire et al., 2012). Earlier investigations have shown that the separation time between two rainfall events did not significantly affect the resulted total  $E_i$  (Klaassen et al., 1998; Wallace and McJannet, 2006). Wallace and McJannet (2006) found that the uncertainty in rainfall intensity only brought less than 10% of the modeled  $E_i$ . The separation time in our study (at least 6 h dry period between successive rainfall events) was thus considered to be reasonable and would not sensibly affect the resulted E<sub>i</sub>.

#### 4.6. Mean met-canopy evaporation rate

The calculated  $\overline{E}_{PM}$  using PM equation were 0.19 mm h<sup>-1</sup> and 0.22 mm h<sup>-1</sup> for BW and PP, within the range of 0.07–0.70 mm h<sup>-1</sup> found for most (sub)tropical forests (Carlyle-Moses and Price, 2007). The  $\overline{E}_{PM}$  for BW and PP were approximately half of the corresponding  $\overline{E}_{TF}$  obtained from regression method, while the  $\overline{E}_0$  was closer to corresponding  $\overline{E}_{TF}$ . The optimized  $\overline{E}_0$  in our study (0.34 mm h<sup>-1</sup> for BW and 0.35 mm h<sup>-1</sup> for PP) was slightly higher than the optimized values in subtropical montane forests (0.25–0.30 mm h<sup>-1</sup>) by Ghimire et al. (2012), but much lower than those reported in the tropical coastal and montane rainforests (average = 0.72 mm h<sup>-1</sup>, range = 0.44–1.20 mm h<sup>-1</sup>) by Wallace and McJannet (2008).

Similar discrepancies between  $\overline{E}_{PM}$  and  $\overline{E}_{TF}$  have been reported in other rainfall interception studies (Wallace and McJannet, 2008; Holwerda et al., 2012) and the possible causes of this difference were discussed below. First, one-dimensional evaporation models like PM equation may be no longer valid for these sparse forests because the forest sparseness tends to enhance the turbulence and thus evaporation (Holwerda et al., 2012). Second, the assumed zero plane displacement height and roughness heights used to derive  $r_a$  in the PM equation can be questionable (Brutsaert, 1979; Verseghy et al., 1993). It is also possibly that PM equation fail in these coastal areas because of high advection of sensible heat from the nearby ocean during rainfall (van der Molen et al., 2006). Finally, the discrepancy between  $\overline{E}_{PM}$  and  $\overline{E}_{TF}$ can be caused by the difficulty in accurately measuring very high relative humidity during rainfall (Wallace and McJannet, 2008) and the evaporation of rain droplets splashed from tree canopy (Murakami, 2006).

#### 4.7. Performance of the RGAM and WiMo models

In terms of the estimation error, the RGAM model generally performed better for BW than for PP. Although the model tended to underestimate  $E_i$ , it produced a reasonably good agreement between the predicted and observed total  $E_i$  using optimized wet-canopy evaporation rates, which confirmed the finding by Ghimire et al. (2012). The RGAM model was found typically underestimating the interception losses, e.g., 2.9% by Valente et al. (1997), 4.3% by Llorens (1997) and 6.2% by Limousin et al. (2008). In our study, the model slightly overestimated the  $E_i$  for some heavy rainfall events, while  $E_i$  for smaller rainfall events tended to be underestimated, which is acceptable since interception losses are most often estimated over a season or a year instead of a single rainfall event. The errors resulting from underestimation of most small rainfall events were considered to be the main factor that caused underestimations of the total  $E_i$ . The obtained Nash-Sutcliffe model efficiency (0.75-0.84) for RGAM model was comparable to the values for a hardwood forest (0.73-0.80) and pine forest (0.44–0.94) by Bryant et al. (2005). The WiMo model also tends to underestimate  $E_i$ , but it performed well with acceptable error (9.4–12.7%) and relatively high Nash–Sutcliffe model efficiency (0.72–0.79). Klingaman et al. (2007) reported a similar Nash-Sutcliffe model efficiency (0.76) for the WiMo model but a lower value (0.50) for the RGAM model.

Compared to the wet season, the underestimation in dry season  $E_i$  by the RGAM model was much higher. The higher underestimates of  $E_i$  during the dry season is probably introduced by overestimation of rainfall intensity during the dry season, when small rainfall events occur more frequently and more actual evaporation is supposed to occur. However, closer errors were found between the dry season and wet season  $E_i$  simulated by the WiMo model, which is possibly because the empirically derived relationship between *S* and  $u_{max}$  can be applicable for both study periods. The relative high Nash–Sutcliffe model efficiency indicates the overall performance of the RGAM and WiMo models are satisfying.

Similar to Ghimire et al. (2012), fixed wet season parameters were used in the RGAM to predict seasonal and annual  $E_i$  in our study. Slight seasonal changes in canopy and climatic parameters can be expected due to changes in LAI and weather patterns, yet it is still possible to obtain satisfying estimates of seasonal and annual  $E_i$  using fixed parameters (Wallace and McJannet, 2008; Ghimire et al., 2012). Firstly, changes in seasonal LAI are small for both forests and the RGAM model is found to be less sensitive to canopy parameters in our study. Secondly, 71% of the annual rainfall in this area occurs during the wet season and the rainfall patterns are similar between wet and dry seasons. Finally, these model parameters may alter the seasonal proportion of interception, but changes in canopy and climatic parameters would compensate each other and the resulted errors in modeled interception using fixed parameters are considered to be minimal, as discussed by Wallace and McJannet (2008).

## 5. Conclusions

Rainfall interception losses were quantified and modeled for a native Banksia woodland (BW) and an exotic pine plantation (PP) situated in subtropical coastal areas of Australia. Over the one-year period, measured throughfall, stemflow and interception loss were 83.2%, 0.4% and 16.4% of annual gross rainfall for BW, respectively. Corresponding values for PP were 76.1%, 1.0% and 22.9%. A higher interception loss in the pine plantation can be explained by its higher canopy storage capacity and lower aerodynamic resistance. The simulated dry season and annual interception losses by the optimized RGAM and WiMo models were close to the observed

values, with an underestimation of 5.2–12.7%. The RGAM is highly sensitive to climatic variables  $\overline{R}$ ,  $\overline{E}$ , and less sensitive to canopy parameters *S*, *c*, but it was found to be fairly insensitive to the stem parameters *S*<sub>t</sub> and *p*<sub>t</sub>. The optimized RGAM model performed slightly better than the WiMo model, but both models appear to be robust and reliable to model seasonal or annual interception losses by Banksia woodland and pine plantation under subtropical coastal conditions. The results indicate increase in interception losses by pine plantations would reduce the rainfall input on the forest floor, but further studies on changes in soil moisture dynamics and tree transpiration are needed to better understand the hydrological effects of exotic pine plantations in these subtropical coastal areas.

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