

Throughfall under a teak plantation in Thailand: a multifactorial analysis on the effects of canopy phenology and meteorological conditions

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Abstract Valuable teak (*Tectona grandis* Linn. f.) plantations cover vast areas throughout Southeast Asia. This study sought to increase our understanding of throughfall inputs under teak by analyzing the abiotic and biotic factors governing throughfall amounts and ratios in relation to three canopy phenophases (leafless, leafing, and leafed). There was no rain

during the brief leaf senescence phenophase in our study. Leveraging detailed field observations, we employed boosted regression tree (BRT) analysis to identify the primary controls on throughfall amount and ratio during each canopy phenophase. Whereas throughfall amounts were always dominated by rainfall magnitude (as expected), throughfall ratios were governed by a suite of predictor variables during each phenophase. The BRT analysis demonstrated that throughfall ratio in the leafless phase was most influenced (in descending order of importance) by air temperature, rainfall amount, maximum wind speed, and rainfall intensity. Throughfall ratio in the leafed phenophase was dominated by rainfall amount. The leafing phenophase was an intermediate case where rainfall amount, air temperature, and vapor pressure deficit were most important. Our results highlight the fact that throughfall ratios are differentially influenced by a suite of meteorological variables during each canopy phenophase. Abiotic variables, such as rainfall amount and air temperature, trumped leaf area index and stand density in their effect on throughfall ratio. The leafing phenophase, while transitional in nature and short in duration, has a detectable and unique impact on water inputs to teak plantations. Further work is needed to better understand the biogeochemistry of leaf emergence in teak plantations.

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Introduction

Throughfall, water originating from interception by plant surfaces and subsequently routed downward through the canopy, or passing through the canopy unobstructed, has been the

subject of intense study (e.g., as reviewed by Levia et al. 2011). Some research has focused on the effects of meteorological conditions (e.g., Llorens et al. 2003; Nanko et al. 2006; Tanaka et al. 2011), while other studies have focused on the canopy structural characteristics which govern throughfall water and solute inputs (e.g., Stogsdill et al. 1989; Staelens et al. 2006; Macinnis-Ng et al. 2012). Additional research has sought to better understand the spatiotemporal variation or temporal persistence of throughfall in forested ecosystems (Robson et al. 1994; Keim et al. 2005; Staelens et al. 2006; Zimmermann et al. 2009; Kato et al. 2013). Another suite of studies have investigated collector requirements, collector types, and/or experimental design to best estimate throughfall inputs (e.g., Kimmins 1973; Ritter and Regalado 2010; Shinohara et al. 2010; Zimmermann and Zimmermann 2014). All of these studies have collectively yielded valuable insights into the hydrology and biogeochemistry of forests and plantations around the world and how we might more accurately and precisely measure throughfall inputs.

Throughfall varies greatly at the within-stand scale (Levia and Frost 2006; Zimmermann and Zimmermann 2014). Factors accounting for large variations in throughfall within particular forest stands include stand density (Stogsdill et al. 1989; Raat et al. 2002); plant area index (Peterson and Rolfe 1979); wind direction from lateral rain shadows (Levia and Frost 2006); throughfall amount (Vrugt et al. 2003), which is largely controlled by event magnitude; and event intensity (Loescher et al. 2002). The coefficient of variation of throughfall tends to decrease with increasing amount of rainfall and increase with the complexity of canopy structure (Loustau et al. 1992; Carlyle-Moses et al. 2004; Carlyle-Moses et al. 2014; Zimmermann and Zimmermann 2014). Tropical forests are especially noteworthy in this regard given their complicated three-dimensional canopy structure which has been found to have a significant effect on canopy interception (Herwitz and Slye 1995). In an old-growth tropical forest, for example, Loescher et al. (2002) noted an increase in spatial variability of throughfall with rainfall intensity. Tropical deciduous forests and plantations are of particular interest with respect to throughfall inputs as their canopy structure changes drastically over a given year during leafless, leafing, leafed, and leaf senescence phenophases, concomitant with drastic changes in the rainfall regime for events occurring between dry and wet seasons. Such differences in canopy complexity raise questions as to which factors most influence throughfall inputs during leafless, leafing, or leafed canopy phenophases.

Teak (*Tectona grandis* Linn. f.) is a commercially valuable tropical deciduous hardwood, often grown in plantations throughout Southeastern Asia (Krishnapillay 2000). While teak plantations are more simply structured than some other types of tropical forests, the change in canopy structure among leafless, leafed, and leafing phenophases may lead to different factors that account for throughfall amounts. In this regard, the

leafing phenophase may be of particular importance from both hydrological and biogeochemical perspectives because it may represent a “hot moment” of biogeochemical reactivity in teak plantations. Fresh foliar surfaces have a distinct leaf chemistry from fully leafed or aging and senescing foliage (Bringe et al. 2006) which could impact biogeochemical cycling, especially if throughfall water inputs are affected by different factors than other times of the year.

Using multifactorial boosted regression tree (BRT; Elith et al. 2008) analysis, this study seeks to examine the relative influence of various biotic and abiotic factors on throughfall inputs in a teak plantation. We specifically seek to better understand the effects of canopy phenophase on throughfall amount through a multifactorial analysis of meteorological conditions and stand density during leafed, leafless, and leafing phenophases (there is no rain during leaf senescence in these teak plantations). This research is the first to employ BRT and canopy phenology with throughfall inputs. Insights from our analyses are useful to better understand the relative importance of the factors that govern throughfall inputs with respect to canopy leaf state, with direct ramifications for the biogeochemistry of these valuable teak plantations.

Study area

Field experiments were conducted in a nearly flat and even-aged teak plantation with a mostly homogeneous canopy structure in Mae Mo district, Lampang province, northern Thailand (18° 25' N, 99° 43' E; 380 m asl). The Mae Mo teak plantation was established circa 1968 with a stand density of 440 trees ha⁻¹ in 2005 and 433 trees ha⁻¹ in 2012 as a consequence of tree mortality.

Mean (± 1 SD) stem diameter at breast height (dbh, 1.37 m) was 22.4 \pm 7.3 cm ($n=308$) in November 2005. The mean (± 1 SD) height of trees in the plantation was 19.9 \pm 3.5 m ($n=308$) in November 2005. The understory was moderately dense and composed of various herbaceous plants and shrubs. Soil at the plantation was classified as loamy Paleustults (Thai classification) or Ultisols (US Department of Agriculture Soil Taxonomic Classification), with 35.5 % sand, 43.5 % silt, and 21.0 % clay, and a total porosity of 35–40 %. The majority of fine and coarse roots were detected in the top 40 cm of soil (Kume et al. 2013).

The climate is dominated by the Asian Monsoon, with two distinct seasons: a wet season occurring from ~May–October and a dry season spanning from ~November–April. Mean annual rainfall was 1230.9 mm (1986–2010). Rainfall is concentrated during the leafless, leafing, and leafed phenophases. There was no rain in the short leaf senescence phenophase during our study.

Mean annual temperature was 25.4 °C (2001–2010), with a minimum monthly mean of 21–22 °C in December–January, and a maximum monthly mean of 29.5 °C in April.

Materials and methods

Field methods

Meteorological data acquisition

A 40-m-tall scaffold tower was constructed in the study area for conducting micrometeorological measurements. Incident solar radiation above the canopy (R_s , $W\ m^{-2}$) was measured with a pyranometer (CMP21, Kipp & Zonen, Delft, The Netherlands). Air temperature (T_a , °C) and relative humidity above the canopy were measured with an air temperature and humidity sensor (HMP45A, Vaisala, Helsinki, Finland) at a height of 39 m. All these meteorological data were recorded as 10-min averages on dataloggers (CR10X and CR1000, Campbell Scientific, Logan, UT, USA). Wind speeds above the canopy (U) were measured at a 39-m height using cup anemometers (AC750, Makino Instruments, Tokyo, Japan), and its 10-min averages were recorded by dataloggers (CR23X, Campbell Scientific, Logan, UT, USA). Solar radiation was also measured beneath the teak canopy (S_b , $W\ m^{-2}$) at a height of approximately 0.5 m in a throughfall measurement plot (plot A, described later) using a pyranometer (CMP21).

Rainfall and throughfall measurements

Throughfall (TF) measurements were conducted in a 40-year-old teak stand in Mae Mo plantation (Fig. 1a–c) from March to October 2006, using an array of TF collectors. Each collector consisted of a HDPE funnel (20.0- and 21.0-cm diameters) connected to a larger HDPE vessel. Throughfall volumes were measured daily with a graduated cylinder and converted to a depth equivalent by dividing by the horizontal cross-sectional area of the funnel.

TF was measured in four plots with different stand densities and locations (Fig. 1a–c). In plot A (400 m^2 , approximately 50 m from the scaffold tower), the teak trees had a stand density of 499 trees ha^{-1} . Thirty TF collectors were randomly placed on the forest floor of plot A in stationary positions throughout the experiment. To the east, plots B, C, and D (600 m^2 each, approximately 500 m from the scaffold tower) were located collaterally (Fig. 1b). Plots B, C, and D were roughly 100 m from a second open site for rainfall measurement (open site (OP), Fig. 1b). Stand densities of planted teak in plots B, C, and D were 434, 291, and 463 trees ha^{-1} , respectively. In each of the three plots, 20 TF collectors, comprising ten fixed and ten roving collectors, were used throughout the study. Each of the three plots was divided into six quadrats (each measuring 10 $m \times 10\ m$) (Fig. 1c). The ten fixed collectors of each plot were linearly arranged along the northwestern margin of each plot at 1-m intervals (Fig. 1c). The ten roving collectors of each plot were also arranged in linear fashion at 1-m intervals which shifted monthly to ensure

full coverage of each plot over time (Fig. 1c). Total throughfall sampling area for plot A and the other three plots, respectively, was approximately 1.04 and 0.69 m^2 . Daily plot-scale TF was calculated by averaging 30 TF collectors and 20 TF collectors, respectively, for plot A and the other three plots.

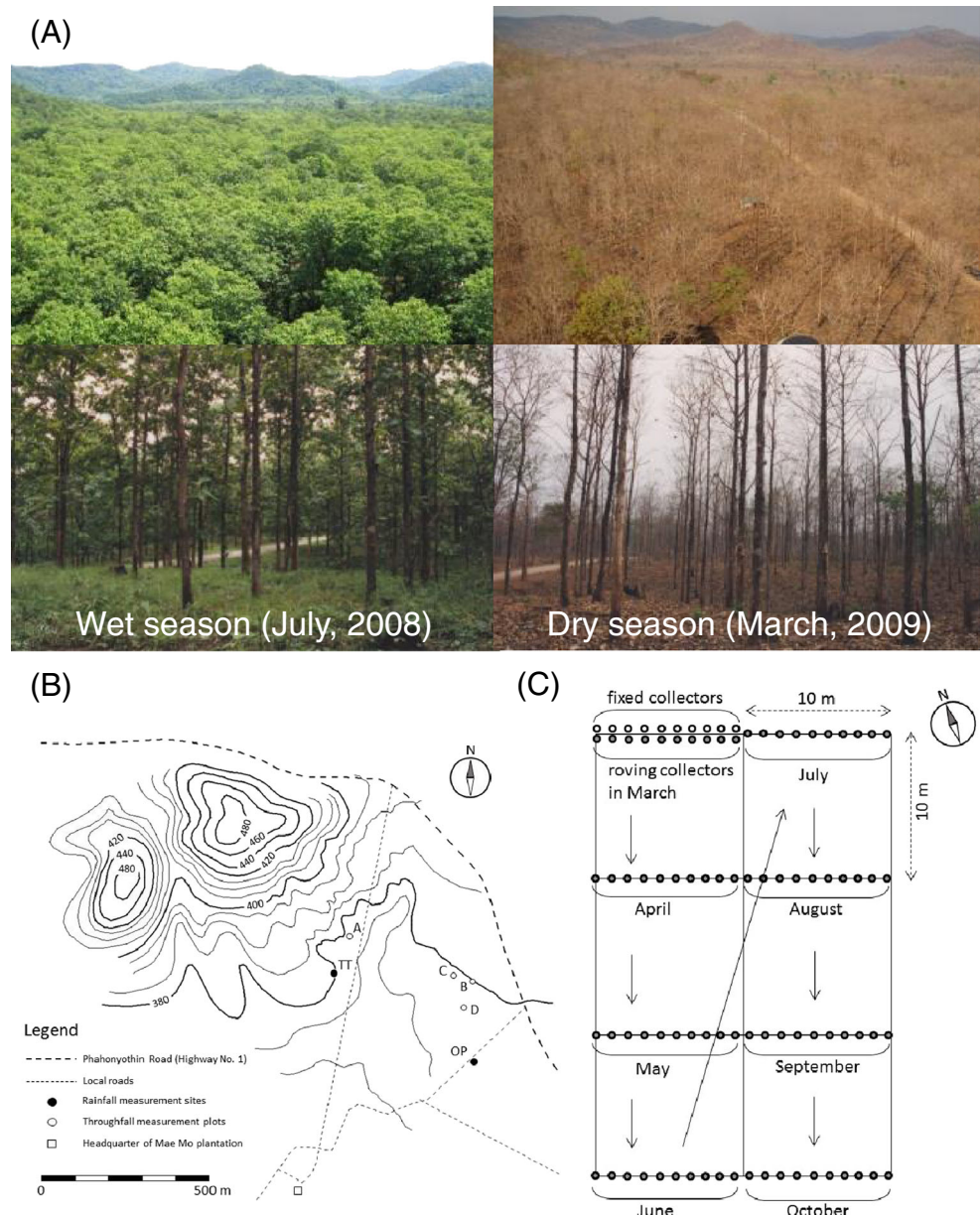
The presence of spatial autocorrelation for TF amount among TF collectors was examined since prior work has found spatial autocorrelation among TF collectors over short distances (Keim et al. 2005; Staelens et al. 2006). We also found that TF amounts were autocorrelated over short distances (less than several meters). The test for autocorrelation also revealed that TF variation at our site had a spatial scale roughly equal to that of crown size. Because our plots (20 $m \times 30\ m$ each) included 23 crowns on average and the sampling networks were spread over the plots, the averaged TF values guaranteed that we had adequate coverage at both intra- and inter-crown spatial scales over each plot. We make no statement regarding statistical significance of results between or among TF collectors. Therefore, the degrees of freedom did not enter into our calculations.

Rainfall measurement was conducted at the top of the tower (TT) and a nearby OP (Fig. 1b). At TT, rainfall was collected using a 20-cm-diameter brass funnel, originally designed as an outer frame of a tipping-bucket rain gauge (No. 34, Ota Keiki Seisakusho Co, Ltd., Tokyo, Japan). For rainfall measurement at OP, a 20-cm-diameter collector with a galvanized funnel similar in design to the TF collectors was employed. Incident rain was measured with graduated cylinders on a daily basis and the volume was converted to a depth equivalent. Considering the high spatial variability in daily rainfall prevalent over the study site, we used daily rainfall at TT for analysis of TF in plot A. Likewise, we used OP rainfall for analyzing TF in plots B, C, and D. In order to monitor temporal distribution of the daily rainfall with a 10-min resolution, at both TT and OP, we used a tipping-bucket rain gauge (No. 34, Ota Keiki Seisakusho Co, Ltd., Tokyo, Japan) connected with a datalogger (Hobo Event, Onset, MA, USA). A discrete rainfall event was defined by measurable rainfall followed by a dry period of at least 6 hours. Rainfall duration (R_d) was defined as total 10-min intervals where the tipping-bucket rain gauge detected rainfall occurrence. Event duration (E_d) was defined as the total minutes of rainfall including dry periods without rain. Hence, $E_d > R_d$.

Canopy phenophase and leaf area index

For examining throughfall in relation to canopy phenophase, we divided the total study period into three phases according to canopy phenology of teak. From a graphical investigation of leaf area index (LAI) time series (shown later), leafless, leafing, and leafed phenophases were determined to occur in the following time periods: March to April, May, and from June to October, respectively.

Fig. 1 **a** Changes in canopy phenophase of the study site in the Mae Mo teak plantation. Shown are photographs taken from above and beneath the canopy in both the wet and dry seasons, **b** contour map in and around the study site with the locations of rainfall measurement sites (*solid circle*) and throughfall measurement plots (*open circle*) denoted, and **c** positions of the ten fixed throughfall collectors (*open circle*) and ten monthly roving throughfall collectors (*solid circle*) for plots B, C, and D



Daily LAI ($\text{m}^2 \text{m}^{-2}$) was determined from the following equation as

$$\text{PAI} = \text{LAI} + b = -1/k \ln(R_t) \quad (1)$$

where the silhouette area index of leaves plus stems and branches (plant area index, PAI, $\text{m}^2 \text{m}^{-2}$) can be estimated by Beer's law (Holst et al. 2004), b is an empirical constant representing the contribution of stems and branches to radiation extinction, k is the extinction coefficient, and R_t is radiative transmittance defined as S_b/R_s . Once the parameters b and k are determined, the temporal variation in LAI can be calculated by Eq. (1) with continuous monitoring of R_t (Maass et al. 1995; Holst et al. 2004; Wang et al. 2004). In the current study, we

used parameters $b=1.03$ and $k=0.52$, both of which were determined by regressing periodic data of LAI estimated from litterfall collection and R_t observations for plot A in this study (Yoshifuji et al. 2011, 2014). We assumed that daily LAIs at plots B, C, and D were equal to that at plot A where the above coefficients were obtained. This assumption is valid since a comparison of R_t time series between the three plots and plot A indicated no significant difference in R_t (Yoshifuji et al. 2011).

Data analysis

Influential predictor factors for estimating throughfall inputs were evaluated by boosted regression tree analysis. BRT combines machine learning methods and regression analysis.

The method has several important advantages: the predictor variables can be of any type (numeric, binary, or categorical), it is insensitive to outliers, it can accommodate missing data using surrogates, and interaction predictors are modeled automatically (De'ath 2007; Elith et al. 2008). A similar approach using BRT in other studies of forest ecosystems was performed by Martin et al. (2011), Aertsens et al. (2012), Cools et al. (2014), and Nanko et al. (2014).

The response variable in our two BRT analyses was either throughfall amount or throughfall ratio within a given canopy phenophase—leafless, leafing, and leafed. A total of 456 daily TF readings were included in both BRT analyses (114 individual daily TF readings from each of the four study plots) for throughfall amount and throughfall ratio, respectively. The following 14 variables served as predictors: gross incident rainfall amount (P_r), R_d , E_d , maximum rainfall intensity (I_n), antecedent dry period (ADP), T_a , mean wind speed (U), maximum wind speed (U_{max}), incident solar radiation (R_s), vapor pressure deficit (D), leaf area index (LAI), determination of daytime/nighttime rainfall (day/night), prevailing wind direction (WD), and stand density (D_n). Vapor pressure deficit was calculated from T_a and relative humidity.

If the daily TF reading was produced by >1 rainfall event, T_a , U , R_s , and D in the dataset were averaged over the duration of all events. Because the BRT analyses using throughfall ratio as the response variable yielded more valuable insights as to which variables govern throughfall inputs into teak plantations as a function of canopy phenophase than throughfall amount, our data analysis efforts focused on throughfall ratio.

BRT was built by means of R software using the “gbm” package version 2.1 (Ridgeway 2013) and its extensions developed by Elith et al. (2008). Models were fitted using the `gbm.step` function and a Gaussian response type (aimed at minimizing squared error), with most effective settings for tree complexity and learning rate, respectively, set as follows for the three canopy phenophases investigated: three and 0.004 in the leafless, four and 0.009 in the leafing, and five and 0.01 in the leafed. The bag fraction was set to 0.5 according to recommendations by Elith et al. (2008) for small datasets. We set the minimum number of trees to 1000. As output, the BRT analysis provides the relative influence (RI) of the predictor variables in the model, based on the number of times that this variable was selected for splitting, weighed by the squared improvement to the model as a result of each split, and averaged over all trees. The RI of each variable is scaled so that the sum adds to 100, with higher numbers indicating stronger influence on the response. Individual predictor effects indicate how much the response is affected by certain predictor values and are visualized in partial dependence plots (PDPs).

Significant differences ($p < 0.05$) among the predictor variables in each of the three canopy phenophases were first examined via Kruskal-Wallis nonparametric ANOVA.

Planned comparisons among the canopy phenophases were then conducted with Tukey-Kramer's test ($p < 0.05$) to identify which phenophases differed from each other. Since day/night and WD were categorical predictor variables, neither the Kruskal-Wallis test nor the Tukey-Kramer test was used to determine significant differences for those two variables among phenophases.

Results

Rainfall and meteorological characteristics among three canopy phenophases

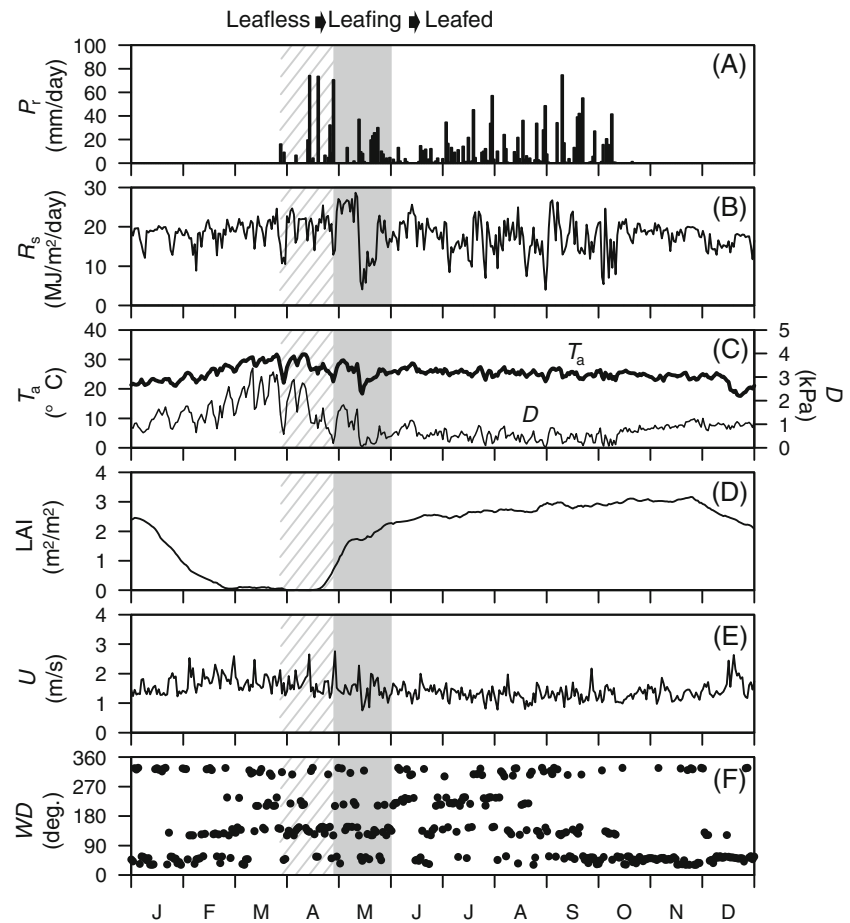
Over the course of our field observation period in 2006, a total of 120 discrete rainfall events occurred and 114 daily TF readings were recorded. Total gross rainfall amount was 1741 and 1749 mm at TT and OP, respectively. Total throughfall amount among the study plots ranged from 1556 to 1632 mm, while the throughfall ratio ranged from 0.89 to 0.93 (Table 1). The four experimental plots had similar throughfall ratios, despite differences in stand density. Plot C had a relatively lower throughfall ratio during the leafless phase (0.89) than either the leafing or leafed canopy phenophases (0.95 and 0.94, respectively).

Rain occurred during all three canopy phenophases examined (Fig. 2). The leafless phase began 30 March, with the leafing phase starting 30 April and the leafed phase commencing 1 June (Fig. 2). The leafed phenophase was the longest, whereas the leafing phenophase was the shortest, lasting only 4 weeks (Fig. 2). After the onset of rainfall, LAI gradually

Table 1 Observed rainfall (P_r , mm) and throughfall depths (TF, mm) and throughfall ratio for all events and for events occurring during each canopy phenophase (leafless, leafing, and leafed) at the four study plots (plots A, B, C, and D) with different stand densities (see text for details)

Canopy phenophase	Plot	Plot			
		A	B	C	D
Overall ($n=114$)	P_r (mm)	1741	1749	1749	1749
	TF (mm)	1594	1556	1632	1590
	Ratio	0.92	0.89	0.93	0.91
Leafless ($n=18$)	P_r (mm)	359	367	367	367
	TF (mm)	322	328	329	339
	Ratio	0.90	0.89	0.89	0.92
Leafing ($n=12$)	P_r (mm)	239	232	232	232
	TF	222	206	220	217
	Ratio	0.93	0.89	0.95	0.93
Leafed ($n=84$)	P_r (mm)	1143	1150	1150	1150
	TF (mm)	1050	1023	1083	1034
	Ratio	0.92	0.89	0.94	0.90

Fig. 2 Climate data of **a** daily rainfall (P_r), **b** daily total solar radiation (R_s), **c** daily mean air temperature (T_a : *thick solid line*) and daily mean vapor pressure deficit (D : *thin solid line*), **d** leaf area index (LAI), **e** daily mean wind speed (U), and **f** daily mean wind direction (WD). *Hatched columns* represent the leafless phenophase. *Shaded columns* represent the leafing phenophase. *Unshaded columns* represent the leafed phenophase



increased with leaf budding and expansion, reaching a maximum LAI of $3.16 \text{ m}^2 \text{ m}^{-2}$ on November 26 (Fig. 2d). Approximately 360 mm of rainfall was recorded for 18 days during the leafless phase, compared to roughly 235 mm for 12 days in the brief leafing phase, and around 1150 mm for 84 days in the leafed phase (Table 1). Throughfall ratios were similar for all three canopy phenophases, differing only a few percent (Table 1).

Meteorological conditions during rainfall differed most notably between the leafless phenophase and the leafing or leafed phenophases. The leafless phase had relatively higher P_r , R_d , ADP, I_n , U , U_{\max} , and D and lower E_d and R_s than the either the leafing or leafed phenophases (Table 2). The leafing and leafed phenophases experienced more similar meteorological conditions, but the leafing phase had relatively higher E_d and R_d than the leafed phase (Table 2).

Significant differences were observed for some variables among the three canopy phenophases (Table 2). Specifically, phenophase variations in U , U_{\max} , R_s , D , and LAI were statistically significantly different. T_a did not show a significant difference among phenophases. One third of the rainfall occurred in daylight hours in the leafless phase, compared to 47–50 % of rainfall in the leafing and leafed phenophases.

Influence of predictor variables for throughfall generation in the leafless phenophase

BRT created the RI of the predictor variables for throughfall ratio and amount (Fig. 3). For throughfall amount, P_r was the most influential variable in the leafless phase (Fig. 3d). The RI of P_r was more than 70 %. It indicates that throughfall amount was mainly determined by P_r . On the other hand, T_a was the most influential variable for throughfall ratio in the leafless phase (Fig. 3a). P_r was the second most influential variable, followed by U_{\max} (Fig. 3a). These results indicate that throughfall ratio in the leafless phase was determined by rainfall amount and water behavior in canopies which is influenced by both air temperature and wind speed.

PDPs show the individual effect of each predictor to the throughfall ratio (Fig. 4). T_a , with the highest RI, showed a staged negative correlation with throughfall ratio in leafless phase (Fig. 4a1). When $T_a > 24 \text{ }^\circ\text{C}$, the throughfall ratio was lower than that for temperatures $< 22 \text{ }^\circ\text{C}$. P_r , with the second highest RI, showed a negative correlation with throughfall ratio for lower magnitude events with $< 25 \text{ mm day}^{-1}$ of rainfall (Fig. 4a2). A staged negative correlation was observed between throughfall ratio and U_{\max} (Fig. 4a2). More

Table 2 Predictor variables utilized in the boosted regression trees analysis

Variable	Unit	Leafless ($n=12$)		Leafing ($n=18$)		Leafed ($n=84$)	
		Mean	± 1 SD	Mean	± 1 SD	Mean	± 1 SD
Rainfall (P_r)	mm day ⁻¹	<i>30.4</i>	29.9	13.0	16.5	13.7	16.3
Event duration (E_d)	Min	225.0	204.9	294.4	436.9	266.2	433.3
Rainfall duration (R_d)	Min	120.0	90.5	108.3	132.8	90.2	137.9
Maximum rainfall intensity (I_n)	mm h ⁻¹	<i>16.3</i>	16.8	7.0	7.0	7.4	8.5
Antecedent dry period (ADP)	Day	2.8 ^a	2.5 ^a	1.8	1.7	1.6	1.0
Air temperature (T_a)	°C	23.4	2.9	23.7	2.0	24.2	1.6
Mean wind speed (U)	m s ⁻¹	2.9	1.7	1.8	0.8	1.6	0.7
Maximum wind speed (U_{max})	m s ⁻¹	4.8	2.2	3.5	1.8	3.1	1.8
Solar radiation (R_s)	W m ⁻²	37.7	70.1	116.2	182.9	101.2	128
Vapor pressure deficit (D)	kPa	0.5	0.7	0.2	0.2	0.2	0.3
Leaf area index (LAI)	m ² m ⁻²	0.2	0.2	1.9	0.4	2.7	0.2
Day/night	–	3, 9		7, 11		42, 42	
Wind direction (WD) ^b	–	NE		E		N	
		Site plot					
		A	B	C	D		
Stand density (D_n)		499	434	291	463		

Values in italics indicate significant differences among phenophases ($p < 0.05$, Tukey's test)

^a Antecedent dry period of first rainfall event was removed from statistic

^b Wind direction indicates the most frequent wind direction during the period

windy conditions (>5.5 m s⁻¹) reduced the throughfall ratio more so than when mean U_{max} was <4.5 m s⁻¹. In summary, lower T_a , P_r , and U_{max} tended to produce higher throughfall ratios during the leafless phenophase.

Influence of predictor variables for throughfall generation in the leafing phenophase

The RI plots of the BRT analysis indicate that P_r was the most influential variable for determining throughfall amount during leafing phase (Fig. 3e), similar to the leafless phase. The next most influential variables affecting throughfall amount were R_d and E_d (Fig. 3e). These findings demonstrate that throughfall amount was almost entirely determined by rainfall amount and duration. As for the throughfall ratio, P_r was also the most influential variable during the leafing phase (Fig. 3b). T_a and D were also found to have a notable influence on throughfall ratio in the leafing phenophase with a RI score of >10 % each (Fig. 3b). The analysis indicates that throughfall ratio in the leafing phase was determined by rainfall amount and evaporative demand to atmosphere.

PDPs indicate that P_r , the highest RI, showed a negative correlation with throughfall ratio when rain was <2 mm (Fig. 4b1). The individual effect of P_r was not obvious for larger magnitude rainfall >10 mm. As for T_a and D , although

sudden decreases of throughfall ratios were observed around 23 °C in T_a (Fig. 4b2) and around 0.07 kPa in D , higher T_a and D had lower throughfall ratios on the whole (Fig. 4b2, b3). The sudden decreases were created by two rainfall events with the two lowest throughfall ratios, around 0.35 and 0.7. Consequently, lower P_r , T_a , and D tended to produce higher throughfall ratios during the leafing phase.

Influence of predictor variables for throughfall generation in the leafed phenophase

The RI plots indicate that P_r was the most influential variable for determining throughfall amount during the leafed phenophase (Fig. 3f), as was the case with the other phenophases. RI of P_r scored more than 95 %, indicating that throughfall amount in the leafed phase was almost completely determined by rainfall magnitude. As for throughfall ratio, P_r was by far the most influential variable during the leafed phase (Fig. 3c), although D and T_a had some influence albeit smaller than that for the leafing phenophase (Fig. 3b, c). The throughfall ratio in the leafed phase was largely determined by rainfall magnitude.

PDPs indicate that P_r , with the highest RI, showed fluctuation in throughfall ratio when there was <12 mm day⁻¹ (Fig. 4c1). The throughfall ratio showed a positive correlation from 12 to 25 mm day⁻¹ in P_r and was stable for rainfall amounts >25 mm.

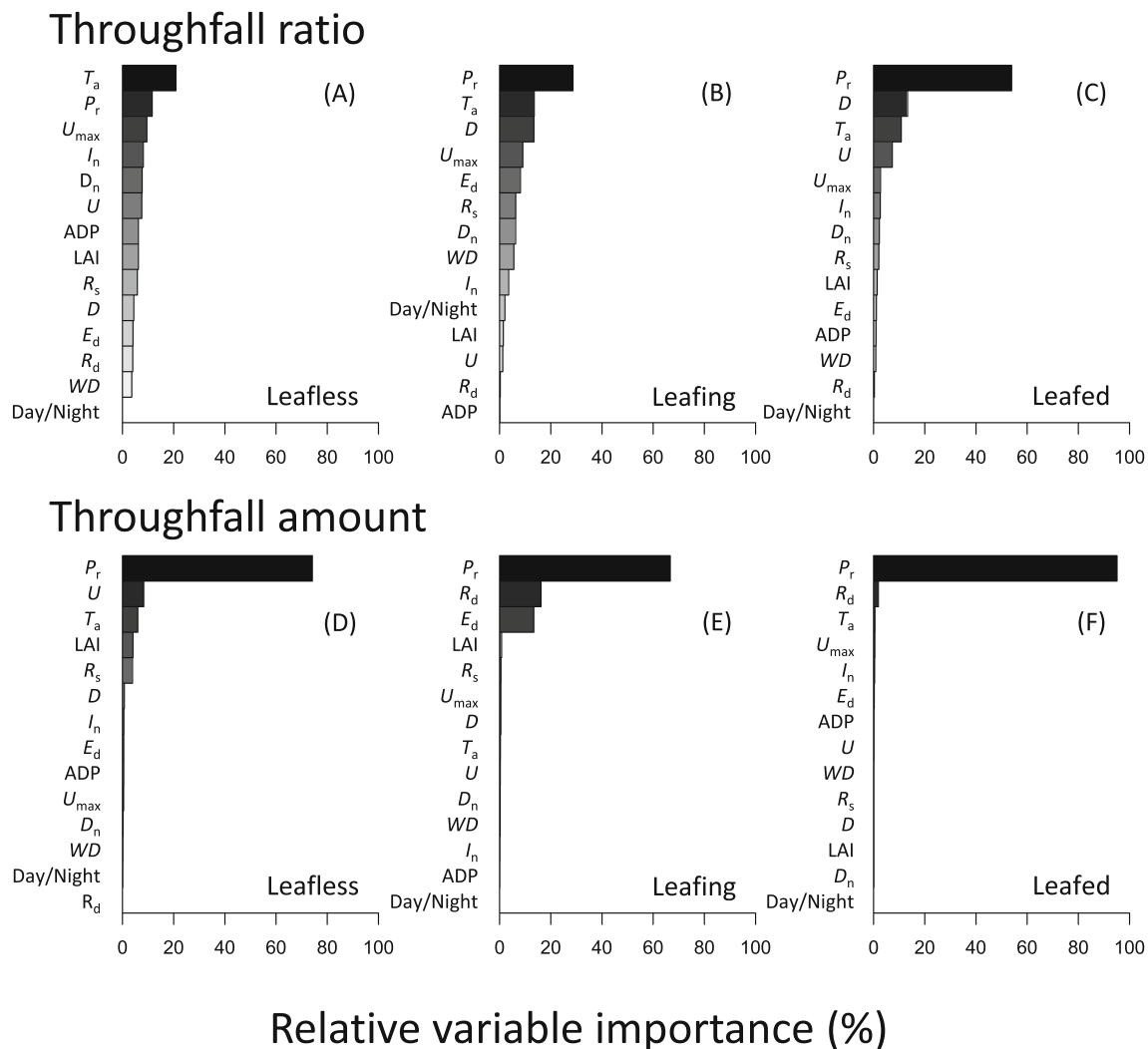


Fig. 3 Relative predictor variable importance (RI, %) for throughfall ratio in **a** leafless, **b** leafing, and **c** leafed phenophases, respectively. RI (%) for throughfall amount in **d** leafless, **e** leafing, and **f** leafed phenophases, respectively

Comparison of predictor variables for determining throughfall ratio among leafless, leafing, and leafed canopy phenophases

As expected, P_r was the most influential variable for determining throughfall amount among all of the three phenophases (Fig. 3d–f). To unmask the importance of other factors in determining throughfall inputs as a function of canopy phenophase, it was necessary to examine throughfall ratios. For throughfall ratio, the top three influential variables, P_r , U_{max} , T_a , and D , were similar among the three phenophases (Fig. 3a–c) and were important for determining throughfall ratio.

Biotic variables, such as LAI and D_n , were less influential. Rainfall characteristics, such as event duration and intensity, as well as WD and R_s , had less impact on throughfall ratio.

The rank order and individual influence among the top five influential variables were different among the three phenophases. P_r was the most influential variable during the

leafing and the leafed phase and the second during the leafless phase (Fig. 3a–c). The RI of P_r increased from leafless (11.6 %) to leafing (28.7 %) and leafed (54.0 %) phenophases (Fig. 4a2, b1, c1). However, LAI was not so important in determining throughfall ratio (Fig. 3a–c), thereby indicating that throughfall generation is more affected by canopy surface properties than leaf area itself.

The individual influence of P_r on throughfall ratio was markedly different for rainfall amounts greater or lesser than 25 mm (Fig. 4a2, b1, c1). Although P_r with >25 mm day^{-1} had stable throughfall ratios, P_r with <25 mm day^{-1} had fluctuations of the throughfall ratio; in particular, P_r with <5 mm day^{-1} had wide fluctuation. Consequently, the influence of P_r on the throughfall ratio was higher with lower P_r in the leafing and leafed phenophases. In addition, the stable throughfall ratio under higher P_r conditions was lower in the order of the leafless phase (0.86), the leafed phase (0.91), and the leafing phase (0.97) (Fig. 4b1, a2, c1). Precipitation partitioning to

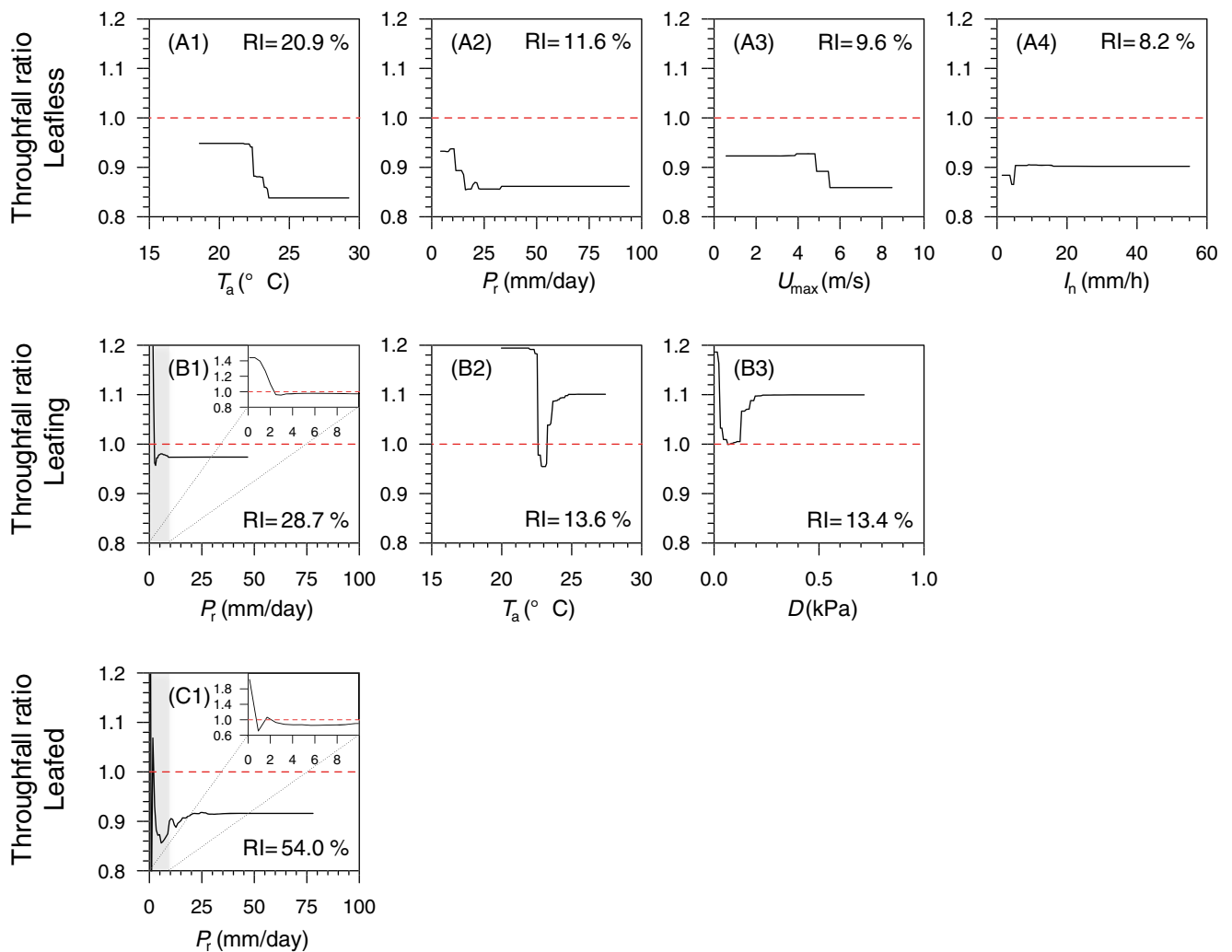


Fig. 4 Partial dependence plots (PDPs) of predictor variables and their effect on throughfall ratio in **a** (1–4) leafless, **b** (1–3) leafing, and **c** (1) leafed phases, respectively. Dashed lines denote that throughfall ratio is 1. To emphasize the relative importance of

individual predictor variables for each canopy phenophase, the PDPs are shown for each phase until the cumulative 50 % of the total explanatory power of throughfall ratio is reached

throughfall by the canopy differed among canopy phenophases and was relatively larger in the leafing phenophase.

T_a and D were influential variables for determining throughfall ratio, especially T_a during the leafless phenophase. RI of T_a decreased with the phenophase transition, accounting for 20.9, 13.6, and 10.9 % for leafless, leafing, and leafed phenophases, respectively (Fig. 3a–c). The RI of D increased between leafless and leafing and leafed phenophases, constituting 4.4, 13.4, and 13.3 % for leafless, leafing, and leafed phases, respectively (Fig. 3a–c). These results demonstrate that higher T_a and D tended to lower the throughfall ratio (e.g., Fig. 4a1, b2, b3), indicating that higher evaporative demand during rainfall events decrease the throughfall ratio. During the leafless phenophase, rainfall has unfettered access to the woody frames of the teak trees. Thus, intercepted rainwater on the tree branches and stems is subjected to the inherently different surface properties of bark rather than foliar

surfaces. T_a can exert an influence on the surface temperature of branches and stems and was most influential for throughfall ratio during the leafless phase. With bud break, leaf expansion, and eventually full leaf conditions, the proportion of intercepted rainwater on foliar surfaces greatly increased and lower proportions of intercepted water was on woody surfaces. T_a may exert a stronger effect on the surface temperature of woody surfaces (with lower albedo) than foliar surfaces. As such, the influence of T_a on the throughfall ratio decreased for leafing and leafed conditions as compared to leafless conditions, whereas the RI of D increased.

Concluding discussion

Throughfall ratios were found to be remarkably similar among canopy phenophases for the teak plantation studied, differing

at most by only a few percent (Table 1). This finding differs from many deciduous forests in temperate climates where higher throughfall ratios are generally reported for the leafless canopy phenophase than for the leafed phenophase (e.g., Augusto et al. 2002), although this relationship is not universal for all deciduous forest sites (Krämer and Hölscher 2009). Herbst et al. (2008), for a mixed deciduous forest, observed slightly higher wet canopy evaporation rates in the leafless canopy than in the leafed canopy and concluded that an appreciable rainfall interception rate in the leafless period (ca. 20 % of rainfall) may partially account for the difference. Further studies examining seasonal variations in both wet canopy evaporation rates and stemflow production of teak are needed to clarify the biophysical mechanism controlling the nearly identical throughfall ratios between different canopy phenophases in this study.

Our results highlight the importance of canopy phenophase on the hydrology of teak plantations. As expected, our BRT analyses revealed that throughfall amounts were dominated by P_r (Fig. 3d–f). Throughfall ratios, however, were governed by different meteorological factors depending on canopy phenophase (Fig. 3a–c). The leafless phenophase was the most complicated in that it had four different predictor variables (T_a , P_r , U_{max} , and I_n) which exhibited an influence on throughfall ratio to account the first 50 % of the RI, whereas the leafed phenophase had only one predictor variable to account for the first 50 % of RI, namely P_r (Fig. 4). The leafing phenophase represented an intermediate case whereby three predictor variables (P_r , T_a , and D) were needed to reach the first 50 % of RI (Fig. 4). These findings illustrate the intricate role of canopy phenophase on the throughfall ratio.

Variations in the throughfall ratios are partly attributable to the differential exposure of foliar and woody surfaces to incident rainfall, coincident with canopy phenophase, since the behavior of intercepted water is markedly different on foliar and woody surfaces (Herwitz 1987). Indeed, plant surfaces exhibit a wide range of hydrophobicity (Koch and Barthlott 2009). According to the BRT results, rainfall partitioning to throughfall was the largest in the leafing phase. One reason for this finding is that the hydrophobicity of leaves decrease substantially with leaf age, as demonstrated for the adaxial surface of apple leaves (Bringe et al. 2006) as well as the adaxial surfaces of leaves for certain tree species in urban areas of China (Wang et al. 2013). Thus, intercepted rainwater is more easily detached from surfaces of newly unfolded leaves during the leafing phenophase than the leafed phenophase, thereby increasing the probability of increased throughfall (and stemflow if release throughfall is subsequently detained by a branch instead of another leaf or the forest floor). So, while the leafing phenophase is short in duration, the canopy has unique properties at this time of year which can alter throughfall water inputs, as evidenced in our study, and may also influence biogeochemical cycles (Staelens et al. 2007). Emerging leaves

of European beech were documented to release sodium, chloride, and ammonium, leading to TF enrichment of those ions, as opposed to canopy release of base cations (potassium, calcium, magnesium) during leafed conditions (Staelens et al. 2007). More detailed knowledge of the leafing phenophase and the factors that govern TF ratios are therefore important to gain the requisite knowledge to improve ecohydrological and biogeochemical models of wooded ecosystems.

The leafing phenophase, while transitional in nature and short in duration, has a detectable and unique impact on water inputs to teak plantations. Further work, however, is clearly needed to better gauge the importance of the leafing phenophase, as well as the other canopy phenophases, on the biogeochemistry of teak plantations. This is especially relevant and important given the fact that temporal variations in canopy release (or uptake) of particular ions affect the mineral nutrition of higher plants (Marschner 1995) and could possibly create hot moments (as espoused by McClain et al. 2003) of enhanced biogeochemical cycling. Such research results could indeed lead to improved management of and yield from teak plantations.

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