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RESEARCH ARTICLE

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Does fluctuation of meteorological conditions across years influence stand transpiration of *Tectona grandis* plantation?

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Abstract

Tectona grandis (teak) is widely planted as high-quality timber in the seasonal tropics, yet detailed data on its seasonal water use and the effect of climatic fluctuations on its transpiration behaviour are limited. We measured sap flux density (SFD) using Granier's sap flow sensors for three wet and two dry seasons in the years 2012, 2014, and 2015 (wet season only) in 7 to 14 trees and made a calibration of Granier's equation for teak to calculate SFD for estimating whole-tree water consumption and stand-level transpiration. We also characterized the effects of daily rainfall, vapour pressure deficit, and photosynthetically active radiation on the daily SFD of individual trees. We found a large fluctuation in rainfall in the wet seasons of 2012 to 2015 (1,159 mm in 2012, 778 mm in 2014, and 727 mm in 2015). Total wet and dry season stand-level transpiration were 824 and 501 mm in 2012 and 446 and 214 mm in 2014, respectively, whereas the wet season transpiration of 2015 was 358 mm. Namely, reduced wet season rainfall reduced the total stand-level transpiration of teak at the study site. Most variations in daily SFD were due to differences in meteorological conditions, that is, day-time mean vapour pressure deficit, photosynthetically active radiation, and daily rainfall associated with the seasons of particular year. We also established models to estimate the stand-level transpiration of a teak plantation. The findings of the present study could be useful for forestation program and hydrological management in tropical regions with seasonal drought.

KEYWORDS

photosynthetically active radiation, rainfall fluctuation, sap flux density, timber plantation, vapour pressure deficit, water use

1 | INTRODUCTION

Climate models predict increasing frequency and severity of droughts in tropical regions (Awange, Khandu, Schumacher, & Forootan, 2016; Corlett, 2016; Van Loon & Laaha, 2015). Meanwhile, the demand for wood products will increase the land areas covered by timber plantations (Andréassian, 2004; Brandt, Nolte, & Agrawal, 2016; Rudel, Defries, Asner, & Laurance, 2009), which consume large amounts of water and cause significant reductions in stream flow, particularly in tropical and subtropical regions with seasonal drought (Jackson et al., 2005; Rodríguez-Suárez, Soto, Perez, & Diaz-Fierros, 2011; Sun et al., 2006), exacerbating the effects of droughts (Corlett, 2016; Lima, Laprovitera, Ferraz, Rodrigues, & Silva, 2012). Appropriate species selection for timber plantations may reduce their impact on stream flow (Dierick, Kunert, Köhler, Schwendenmann, & Hölscher, 2010; Pryde, Holland, Watson, Turton, & Nimmo, 2015). More information about the water-use of timber species is required to plan commercial plantations with more sustainable utilization of soil water (Aparecido, Miller, Cahill, & Moore, 2016; Murgue, Therond, & Leenhardt, 2015). Whole-tree water use is correlated with tree size (diameter at 1.3-m height;

DBH), proportion of sapwood area, and leaf area index (LAI), which determine the total transpiration surface of a tree (Ma et al., 2008; Wei et al., 2016). Leaf phenology strongly affects transpiration through its effect on LAI (Dünisch & Morais, 2002; McJannet, Fitch, Disher, & Wallace, 2007). Deciduous species, which drop all leaves in the dry season, may use substantially less water than evergreen species during the dry season. If this is the case, they may be preferable for plantation in areas with strongly seasonal climates to reduce plantation impact on stream flow during the dry season.

Transpiration at the level of plantation stands depends on the sum of daily variations in transpiration, which are substantially determined by meteorological factors that vary at similar time scales (Dammeyer, Schwinning, Schwartz, & Moore, 2016; Whitley et al., 2013; Zhang, Guan, Shi, Yamanaka, & Du, 2015), by stand quantitative parameters such as stand density and tree size, and by qualitative characteristics such as species. Of the meteorological factors, daily rainfall is important for supplying water to the soil, which eventually supplies water for transpiration, whereas daily vapour pressure deficit (VPD) and daily photosynthetically active radiation (PAR) determine transpirational demands (Banin et al., 2014). When ground water is plentiful, daily transpiration may be controlled by VPD and PAR (Chen et al., 2011; Siddiq & Cao, 2016; Zeppel, Murray, Barton, & Eamus, 2004), but as ground water becomes scarce, rainfall inputs may drive transpiration (Fischer, Armstrong, Shugart, & Huth, 2014). Tree transpirational responses to increasing water stress are nonlinear (Lens et al., 2011; Meinzer, Johnson, Lachenbruch, McCulloh, & Woodruff, 2009; Novick et al., 2009; Tyree & Sperry, 1989). Therefore, daily observations through multiple seasons are necessary to disentangle the effects of rainfall, VPD, and PAR on daily, seasonal, and annual transpiration (Llorens et al., 2010; Tan et al., 2013).

Tectona grandis (teak) is a valuable timber species (Palanisamy, Gireesan, Nagarajan, & Hegde, 2009; Restrepo & Orrego, 2015) that occurs naturally in seasonal tropical Asia, mainly between 12 and 25°N and between 75 and 104°E, through India, Myanmar, Laos, and Thailand (White, 1991). This tree has been successfully cultivated in plantation forests in numerous of tropical countries in Asia, Africa, and the Neotropics (Bermejo, Canellas, & San Miguel, 2004; Hedegart, 1976; Keogh, 1979). Teak plantation is ranked third by area in tropical hardwood species, covering a total of 5.7 million hectares in the tropics (Ball, Pandey, & Hirai, 2000; Kraenzel, Castillo, Moore, & Potvin, 2003; Pandey & Brown, 2000). Teak is a deciduous species that could offer an alternative to evergreen timber species in seasonally dry tropical regions because it may consume less water during the dry season when stream flows are most restricted (Tanaka et al., 2009; Vico et al., 2015; Yoshifuji et al., 2006). Despite the importance of teak as a timber species, detailed data on its stand-level water use and annual variation in its transpiration with respect to meteorological fluctuations are limited.

We investigated the whole tree water use of a mature teak plantation in southern China. We aimed to understand the seasonal and annual variations in transpiration of teak in 3 years with fluctuating meteorological conditions, and to develop models for estimating the stand-level transpiration of teak. The study had the following objectives: (a) to estimate the stand-level transpiration of a teak plantation at the northern edge of the tropics and (b) to investigate the effect of various meteorological conditions (VPD, PAR, and rainfall) across 3 years on the sap flow of teak.

2 | MATERIALS AND METHODS

2.1 | Study site

The study was conducted in a teak plantation stand in Xishuangbanna Tropical Botanical Garden (XTBG; 21°54′N, 101°46′E, 580 m asl), in the south of Yunnan Province, Southwest China. This region has a tropical monsoon climate with a pronounced dry season from November to April. The mean annual precipitation is 1,560 mm, approximately 80% of which falls during the wet season (May to October). The mean annual temperature of the study site is 21.7°C (Cao, Zou, Warren, & Zhu, 2006). The teak plantation stand was 60 years old, spanning an area of 100 m × 45 m, with trees planted in rows at a distance of ~ 4 m from one another. The mean DBH of trees in the plantation was 31 cm, whereas the mean tree height was 16 m and, the stand basal area was 38 m^2/ha with a stocking density of 450 trees/ha (see Table S1 in the Supporting Information for details of individual trees). We obtained climatic, data such as air temperature (°C), relative humidity (%), PAR (μ mol · m^{-2} · s^{-1}), and rainfall (mm), from the Tropical Rainforest Ecosystem Station of XTBG, located ~900 m away from the teak stand. VPD was calculated from air temperature and relative humidity (Campbell & Norman, 1998).

2.2 | Estimation of sap flow

In the 2012 wet season, we selected seven teak trees with a DBH range of 17 to 55 cm for sap flow measurements in a plantation stand of teak in XTBG (see Table S1). In the 2015 wet season, we added seven more trees with a similar DBH range to increase the data. Sap flux density (SFD) was measured in the outer 2 cm of sapwood using home-made thermal dissipation sap flow sensors (Granier, 1987). Each sensor consisted of two probes containing copper-constant thermocouples. The upper sensor was heated using a constant current source of 0.2 W, and the lower sensor remained at the trunk temperature (reference probe). All sensors were connected to a data logger (CR-1000, Campbell) with a multiplexer (AM 16/32, Campbell). Each tree was equipped with two sensors fixed directionally opposite to each other. For trees with a DBH of more than 40 cm, SFD was estimated using 3- and 4-cm-long sensors. The sensors were protected by aluminium foil to prevent mechanical damage and solar radiation. Data were scanned every 30 s and recorded in 30 min averages by data loggers. Sap flow data from the sensors was checked for accuracy by plotting them against the hourly values of VPD and by comparing them with the data recorded from sensors that were replaced due to malfunctioning of the old sensors.

Grainer's equation (1987) is most-often used to calculate SFD (g m^{-2} s^{-1}), but recent studies have shown that the original equation is not universal and should be calibrated to estimate the sap flow of some tree species, especially of ring-porous species (Bush, Hultine, Sperry, Ehleringer, & Philips, 2010; Hultine et al., 2010; Siddiq, Chen, Zhang, Zhang, & Cao, 2017; Taneda & Sperry, 2008). Teak has a ring-porous xylem; thus, we calibrated the equation using excised branches from seven different teak trees with a branch diameter range of 3.82 to 9.55 cm, accordance with Bush et al. (2010) and Hua-Xiu et al. (2016), and generated an equation as shown in Figure 1 for estimating the SFD of teak. Further details about the calibration measurements are provided in Siddiq et al. (2017).

SFD for each individual tree was calculated as the average of data from the two sensors installed in opposite azimuths. Sapwood was distinguishable from heartwood owing to its distinct yellow colour, but because teak is a ring-porous species, the whole sapwood area may not be active in conducting water. Therefore, active sapwood area was determined by injecting a dye solution at DBH on the opposite sides of stems into the sapwood of 15 live trees with a similar DBH range to the trees being measured for SFD, as well as into seven branches cut from the trees, and then moved to a laboratory. After 24–48 hr, a couple of cores were collected from the trees at above the site of dye injection. Active sapwood area was determined by the distance travelled by the dye on the portion of sapwood from its outer part where the dye was injected. In the laboratory, the dye solution was injected to the branch sapwood under pressure (0.02 to 0.06 MPa). The stained portion of sapwood in each branch was considered to be the active sapwood of the sample. Most trees had sapwood depth approximately 2 cm, especially those with a DBH of less than 40 cm. For trees with a DBH of more than 40 cm, SFD was estimated using 3- and 4-cm-long sensors, as mentioned above. SFD from these sensors was then multiplied with the sap wood area of the concerned length to estimate whole-tree transpiration.

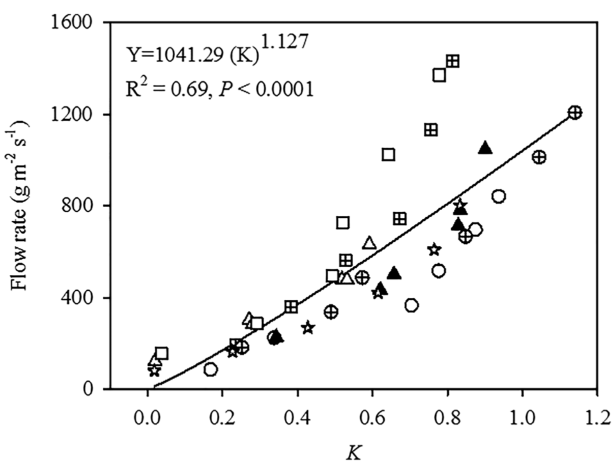

FIGURE 1 Relationship of flow rate with the temperature difference between heated and non-heated sensors from the calibration measurements in seven branches of seven trees (indicated with different symbols), with six measures at different pressures for each branch

Sap flow measurements were conducted from the beginning of the wet season of 2012 until the beginning of wet season of 2013 and from the beginning of the wet season of 2014 until the end of wet season of 2015. Thus, the measurements covered three wet and two dry seasons.

2.3 | Whole tree water use and stand transpiration

Daily whole-tree water use (kg/day) was calculated by multiplying tree SFD by the active sapwood area, that is, the part of the sapwood stained by perfusion with a dye.

We used power models to estimate the relationship between DBH and whole tree water use (kg/day) for each wet and dry season. From these values we were able to estimate total stand transpiration using the DBH estimates for all trees in the stand. Stand-level water use was estimated based on the survey of four 20-m × 20-m plots in the teak plantation stand. The mean canopy height and DBH in the surveyed plots ranged from 16 to 18 m, and 28 to 35 cm, respectively, with 13–17 trees in each plot. In all the plots, only six trees had a DBH of <10 cm. All trees with a DBH of >10 cm were measured for diameter. We developed separate wet and dry season regression models of whole-tree water use from the measured trees, then extrapolated water use for unmeasured trees in the plots. Stand-level daily transpiration (mm/day) was estimated using the following formula (Kumagai, Tateishi, Shimizu, & Otsuki, 2008; Wullschleger, Hanson, & Todd, 2001):

$$E = \frac{1}{A_{\text{plot}}} * \sum_{j=1}^{n} WU_j,$$

where E is the stand daily transpiration (mm/day), WU_j is the daily water use of tree j (kg/day), and A_{plot} is the plot area (m^2). Daily stand-level transpiration (mm/day) was integrated to estimate the seasonal and annual stand-level transpiration.

2.4 | Data analysis

We compared seasonal and annual differences in climatic factors (rainfall, VPD, and PAR), individual tree SFD, and stand-level transpiration using t tests. Next, we used mixed-effect models to test whether daily VPD, PAR, and rainfall affect daily SFD, and whether the effects are altered by season and year. Because we did not measure soil water content regularly, we used an exponential time lag of rainfall (lagged rainfall) to represent the effect of rainfall on soil water content, using the following formula:

$$\text{Lagged rainfall}_t = (1 - \alpha)\ \text{lagged rainfall}_{t-1} + \alpha\ \text{rainfall}_{t.}$$

The value of α can be increased to increase the relative contribution of new rainfall events. This also changes the shape of exponential decay, providing a simple method for modelling exponential water loss from the soil. Soil water decay is commonly represented in mechanistic models using exponential decay processes, because this appears to be a reasonable representation of soil water drying

(Guswa, Celia, & Rodriguez-Iturbe, 2002; Li, Boisvert, & De Jong, 1998; Wang & Singh, 2017).

We used daily SFD against daytime-only mean VPD because nighttime SFD is also partially affected by daytime response (Fan, Ostergaard, Guyot, Fujiwara, & Lockington, 2016; Forster, 2014; Siddiq & Cao, 2018). Our regression model used SFD data from individual trees; therefore, tree identity was included as a random variable into the model. Finally, because we were interested in how variable these relationships were from year to year, we included year as a predictor, which was multiplied onto VPD, PAR, and lagged rainfall. All predictors were standardized prior to modelling. The data distribution of SFD was exponential but included zero values; therefore, SFD was log (x + 1) transformed to generate homogeneous residuals. Our full model was as follow.

$$\text{SFD} = (\text{VPD} + \text{PAR} + \text{lagged rainfall}) \times \text{Year} + (1|\text{TreeID}) + \varepsilon.$$

Separate models were run for the wet and for the dry season data. We also ran models with different lagged rainfall values, using α = .1,.2,.3, .4,.5,.6,.7, .8, and.9, and chose the α value that maximized the F value of the regression model. We used analysis of variance type II SS to separate the variation explained by VPD, PAR, and lagged rainfall, as well as their interactions with year.

3 | RESULTS

3.1 | Whole-tree water use and stand transpiration

We found that Granier equation underestimated the SFD of teak approximately 8 times (Figure S1 in the Supporting Information). The calibrated equation for teak is shown in Figure 1. Dye infusion indicated that the active sapwood was substantially thinner than the visually determined sapwood. DBH strongly predicted sap wood area (Figure 2a; R^2 = .88) and whole-tree water use (Figures 2b and 2c; $R^2 \geq .70$). The mean whole-tree daily water use ranged from 2.0 to 226.59 kg/day during the three wet season (Figure 2b and Table S1) and from 4.0 to 170 kg/day in the dry seasons of 2012 and 2014 (Figure 2c). The estimated total stand-level transpiration in the wet seasons of 2012, 2014, and 2015 was 824, 446, and 358 mm, respectively. The estimated total stand-level transpiration in two dry seasons (November to April) of 2012 and 2014 was 501 and 214 mm, respectively. The estimated annual stand transpiration from June 2012 to May 2013 was 1325 mm and that from June 2014 to May 2015 was 660 mm.

3.2 | Interannual and seasonal variations in meteorological factors

The daily patterns of rainfall, VPD, and PAR during study period are shown in Figures 3a–3l. During study period, total rainfall was 1,540.6 mm (1,159 mm in wet season and 381.6 mm in dry season) from June 2012 to May 2013, 1,145.2 mm (778 mm in wet season and 367.2 mm in dry season) from June 2014 to May 2015, and

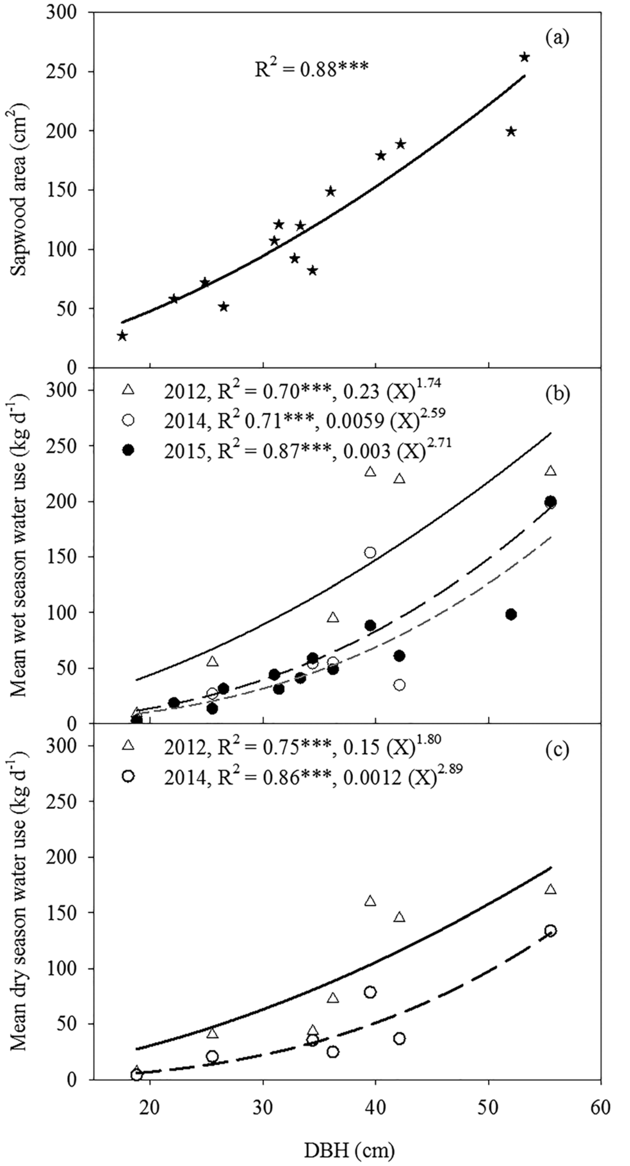

FIGURE 2 Relationship between diameter at 1.3-m height (DBH) and (a) sapwood area, (b) mean wet season daily water use, and (c) mean dry season daily water use. For all the relationships a power function $Y = a(X)^b$ was fitted. *** p < .0001

727 mm in the 6 months of the wet season from June to October 2015 (Figures 3a–3c). The average daytime VPD was significantly higher (p < .05) in the wet season of 2012 (0.97 ± 0.03 kPa) than in the wet seasons of 2014 (0.86 ± 0.03 kPa) and 2015 (0.81 ± 0.02 kPa). There was no significant difference in daytime mean VPD between the dry seasons of 2012 (1.04 ± 0.04 kPa) and 2014 (1.06 ± 0.04 kPa; Figures 3d–3f). The average daily PAR in the wet season of 2014 was 744.26 ± 209.10 μmol · m^{-2} · s^{-1}, which was significantly higher (p < .05) than that in the wet seasons of 2012 (613.60 ± 220.44 μ mol · m^{-2} · s^{-1}) and 2015 (587.06 ± 181.31 μ mol · m^{-2} · s^{-1}). The average daily PAR in the dry season of 2012 was 580.59 μmol · m^{-2} · s^{-1} (±147.72), which was significantly lower (p < .05) than that in the 2014 dry season (662.11 μmol · m^{-2} · s^{-1} ± 164.99; Figures 3g–3i). Day-time mean

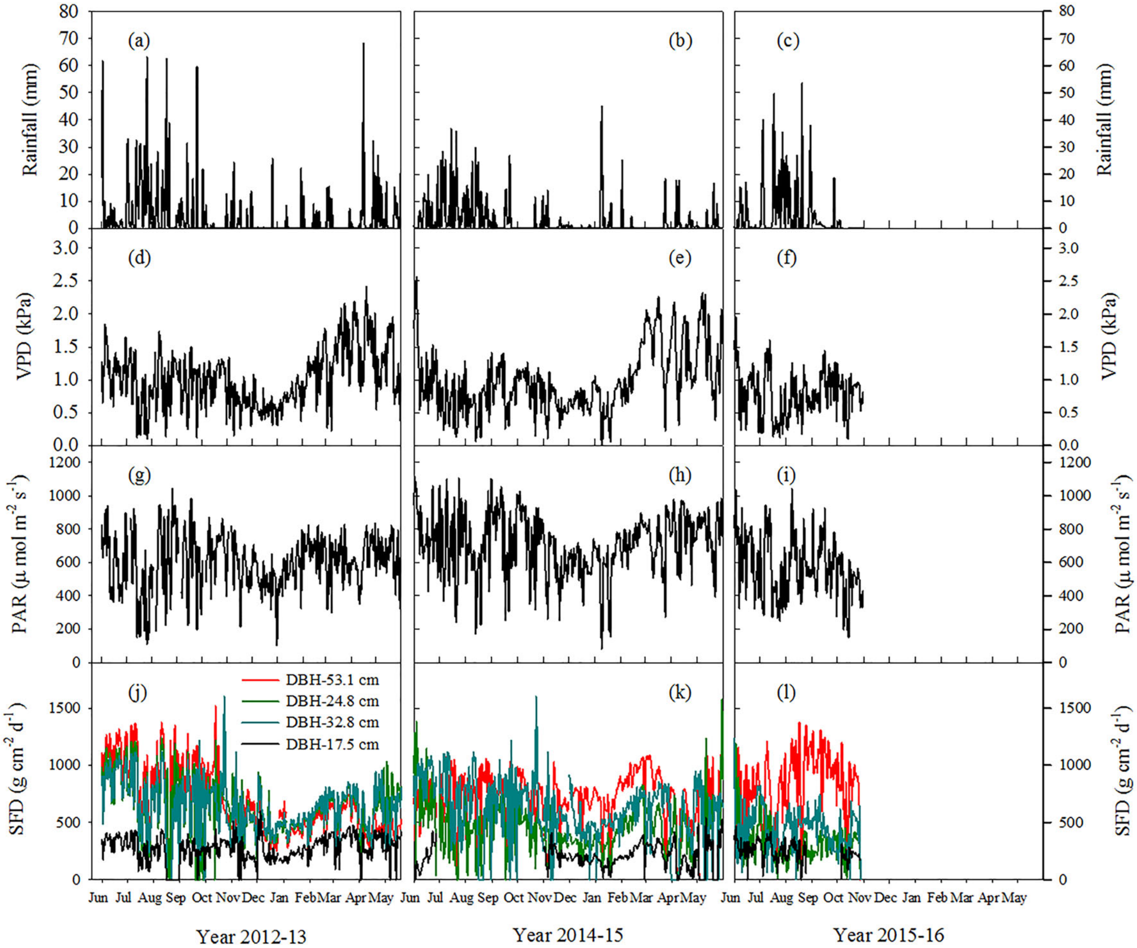

FIGURE 3 Time series showing the (a–c) total daily rain fall, (d–f) mean daytime vapour pressure deficit (VPD), (g-i) daytime mean photosynthetically active radiation (PAR), and the representative daily integrated sap flux density (SFD) during the study period of two and a half years. (j-l) Tg indicates *Tectona grandis* trees with the mentioned diameter at 1.3-m height (DBH)

VPD and mean PAR were strongly correlated with each other during the wet and dry seasons across the years but uncorrelated with lagged rainfall (Table S2).

3.3 | Seasonal response of SFD to VPD, PAR, and lagged rainfall

Representative tree SFDs across three wet and dry seasons are shown in Figures 3j–3l. We regressed hourly mean VPD and PAR against hourly SFD in the wet and dry seasons of 2014 (as a representative year) and found a significant relation between mean VPD and mean SFD with a coefficient of determination (R^2) range of.86 to.64 across trees in the wet season and dry seasons, whereas the relationship between hourly mean PAR and SFD was weaker than that with VPD and this relationship of PAR and SFD even not significant in the dry season. The coefficient of determination for PAR ranged from.40 to.07 across trees in the wet and dry seasons respectively (Figure 4).

Our analysis of variance type II SS analysis of the mixed-effect model predicting SFD as a function of VPD, PAR, lagged rainfall, and year (Table 1) indicated that there were different response patterns between the wet and dry season data. The maximum F value for wet season data was obtained using α = .1 and that for dry season data was obtained using α = .9. The estimated marginal R^2 (calculated using fixed effects only) and conditional R^2 (calculated using fixed effects plus the variation due to different trees) indicated that the explanatory power of the models was greater for dry season data than for wet season data and that more than half of the explained variation in the data was due to differences in SFD between individual trees.

In wet season data, SFD variation was explained by all the main effects and interactions tested, with Year explaining most variation, followed by VPD, PAR, and lagged rainfall playing smaller roles. The model coefficients (see Table S3) indicated that wet season SFD was much greater in Year 2012 than in 2014 or 2015 (t = −3.57 and t = −4.88, respectively). In dry season data, terms involving lagged rainfall explained a much greater portion of variation in SFD, but again, most variation was explained by the main effect of year, with VPD and PAR also being important. PAR and lagged rainfall explained much more variation than VPD. SFD in 2014 was substantially lower than 2012 (t = −4.94).

In agreement with the regression model results, we found a strong positive relation between wet season rainfall and stand transpiration

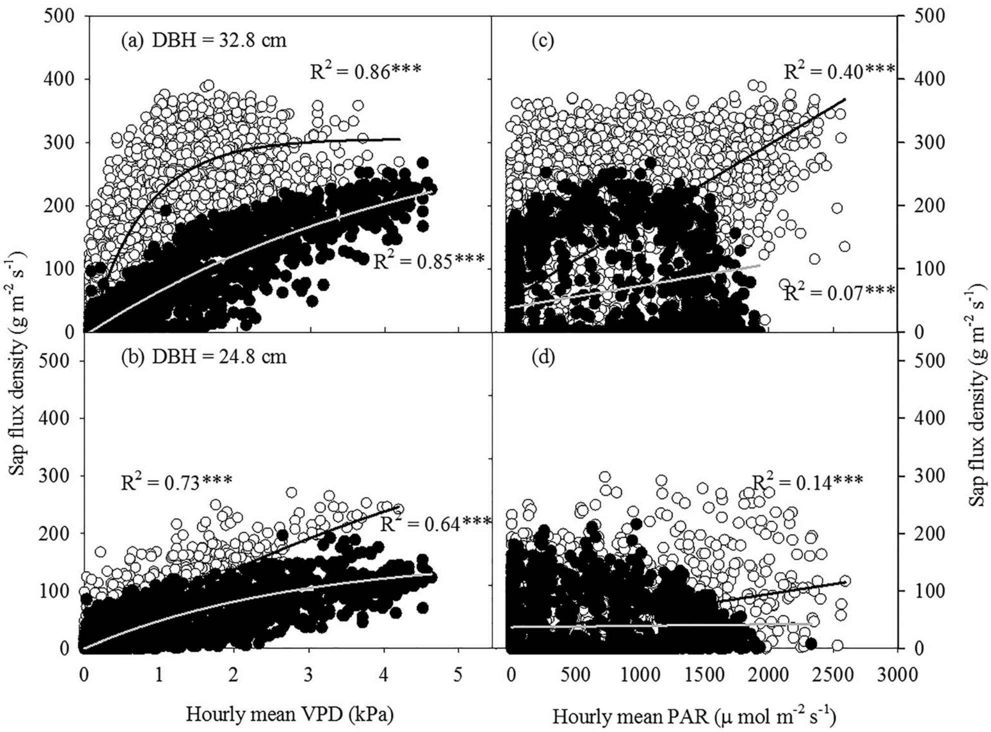

FIGURE 4 A representative response of hourly mean sap flux density (SFD) to (a and b) hourly mean vapour pressure deficit (VPD) and (c and d) hourly mean photosynthetically active radiation (PAR) in the wet (open symbols) and dry seasons (filled symbols) 2014. DBH indicates diameter at 1.3-m height. For panels (a) and (b) an exponential rise to maximum function was fitted and for panels (c) and (d) linear function was fitted to the data. ***, $p < .0001$

TABLE 1 ANOVA type II SS indicating the amount of variation of daily SFD explained by mean VPD, mean PAR, lagged rainfall, and year

	Wet seasons			Dry seasons		
Predictor	**Df**	***F***	***p***	**df**	***F***	***p***
VPD	1	51.84	<.001	1	20.26	<.001
PAR	1	39.06	<.001	1	92.77	<.001
Lagged rainfall	1	16.28	<.001	1	69.29	<.001
Year	2	73.27	<.001	1	560.34	<.001
VPD:Year	2	8.15	<.001	1	1.13	NS
PAR:Year	2	4.95	.007	1	4.07	.044
Lagged rainfall: Year	2	5.52	.004	1	57.53	<.001
R^2 marginal[a]		0.211			0.277	
R^2 conditional		0.508			0.642	

Note. Lagged rainfall is an exponentially lagged value of daily rainfall events that coarsely represents soil water availability. Residual degrees of freedom for *F* tests obtained using Kenward-Rogers approximation.

Abbreviations: ANOVA: analysis of variance; PAR: photosynthetically active radiation; SFD: sap flux density; VPD: vapour pressure deficit.

[a]Marginal and conditional R^2 values for the mixed model were calculated using the *r.squaredGLMM()* function in the *MuMIN* package. NS indicates nonsignificant.

(Figure 5). There was a significant increase in stand-level transpiration in wet season along with an increase in wet season rainfall.

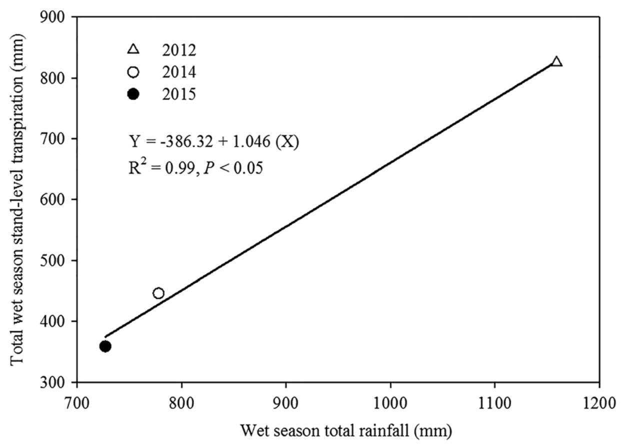

FIGURE 5 Relation between total wet season rainfall across 3 years and wet season stand-level transpiration

4 | DISCUSSION

We aimed to understand the amount of stand transpiration of a teak plantation at the northern edge of the tropics and the impact of varying meteorological conditions on its daily SFD behaviour. We found that the total annual stand transpiration of teak varied from 1,325 mm in 2012 (3.31 mm/day) to 660 mm in 2014 (1.65 mm/day), with associated annual rainfall of 1,541 and 1,143 mm, respectively. Our reported daily stand transpirations across years are in the range of teak annual transpiration (~ 3.6 mm/day) reported by Tanaka et al. (2009). They were lower than those of *Acacia mangium* plantation with a transpiration rate of 3.9 mm/day (Cienciala, Kucera, & Malmer, 2000). Further, our data indicated that teak uses 30–40% less water during the dry season than during the wet season, which could be partly caused by leaf senescence and shedding in the dry season (Figure S3). This finding indicates that teak plantations may place less stress on soil water resource during the dry season (Kobayashi et al., 2014). Because teak is deciduous it may use far less soil water in the dry season than evergreen species.

Because whole-tree daily sap flow was significantly different in the studied wet and dry seasons, we used different models to estimate wet and dry season transpiration (Figure 1b). A reduction of approximately 400 mm in annual rainfall at the present site caused significant reduction in annual transpiration of the teak plantation, supporting the evidence that deciduous trees are sensitive to reduced total rainfall (Allen et al., 2017; Liu, Harper, Dell, Liu, & Yu, 2017). Wet season rainfall was reduced from 1,159 mm in 2012 to 778 mm in 2014 (33%); hence, transpiration was also reduced from 824 mm in 2012 to 446 mm in 2014 (45%). Similarly, there was a 37% reduction in rainfall in 2014 as compared with than in 2012, which resulted in a 56% reduction in transpiration. However, the dry season rainfall in 2014 was reduced by 4% as compared with that in 2012, but the reduction in transpiration was 10% in 2014 as compared with that in 2012. This indicated the strong dependence of teak's stand-level transpiration on annual rainfall, which was supported by the correlation between annual rainfall and annual stand transpiration (Figure 5). Yoshifuji et al. (2006) reported soil moisture as a major determinant of teak transpiration. Large variations in rate of transpiration were observed in their study, indicating the sensitivity of teak plantation to soil moisture availability. Further, teak is a fast growing tree, ~1.5-cm annual diameter increment at present site (unpublished data), and due to its deciduous nature with fully developed canopy for about 8 months, the tree needs to use most of available water during its growing season.

In our study, VPD and PAR explained more variation in daily SFD than daily rainfall in the wet season (Table 1), which indicated that the canopy transpiration of teak is strongly coupled with atmospheric demand and photosynthetic activity. This is consistent with previous findings in tropical forests (Otieno et al., 2014; Phillips, Oren, Zimmermann, and Wright (1999)) and may suggest that VPD controls daily SFD, whereas PAR controls diurnal SFD. The other reason for the stronger effect of VPD and PAR on SFD in the wet season could be the availability of soil moisture, enabling the trees to meet their transpiration demand. The daytime mean VPD in the wet season was ~1.0 kPa, which is within the range of optimum conditions for most of tropical trees with maximum stomatal conductance and transpiration (Hardanto, Röll, Niu, Meijide, & Hölscher, 2017; O'Brien, Oberbauer, & Clark, 2004; Oren et al., 1999). The higher coefficient of determination for the relationship between hourly mean SFD and hourly mean VPD than that between hourly mean PAR could occur because that PAR is zero in the dusk and VPD is still enough to drive the SFD; there is also nocturnal sap flow as well in the tropical trees as well (Siddiq & Cao, 2018).

Variation in SFD during the dry season was also strongly tied to rainfall events (Table 1), more so than during the wet season, suggesting that rare rainfall events in the dry season cause increased SFD of teak species. The day-time mean VPD and PAR remained important drivers of SFD during the dry season (Figure S2). How SFD changes with the level of canopy leaf shedding in teak through the dry season is unclear. Yoshifuji et al. (2011) found that interannual variation in the onset of transpiration of a mature plantation in Thailand was linked with soil water and variation in LAI. Increasing stand transpiration in the year with larger annual rainfall was also reported in a rubber plantation in Cambodia (Kobayashi et al., 2014). The evergreen dipterocarp species exhibited larger stand-level transpiration in the dry season than in the wet season, with greater water use in the species with less reduction in their LAI during the dry season (Siddiq & Cao, 2016). Similarly, another evergreen forest in northern Thailand had its maximum rate of transpiration during the late dry season (Tanaka et al., 2003). In both studies, the observed increased transpiration could be due to the availability of soil moisture near the tree's roots, which enabled these trees to meet their high transpiration demand during the dry season. In our study, teak showed decreased water consumption during the dry season, which could make it a preferred choice for plantation in the seasonal tropics with increasing drought intensity and frequency.

5 | CONCLUSION

This study showed that a mature stand of teak plantation in the northern tropical area transpired a greater amount of water annually when annual rainfall was greater, and, within individual years, transpired far less water during the dry season than during the wet season. The models established for determining wet and dry season whole-tree daily water use in this study can be used to estimate stand transpiration of teak in the seasonal tropical areas. Stand-level estimates of transpiration can help in planning teak plantations based on their seasonal and annual water use. The reduced stand-level transpiration of teak in the dry seasons may make it a preferred plantation choice for reducing catchment water abstraction in seasonal tropical environments.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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