ENERGY BALANCE AND EVAPOTRANSPIRATION CHARACTERISTICS OF RUBBER TREE (*HEVEA BRASILIENSIS*) PLANTATIONS IN XISHUANGBANNA, SOUTHWEST OF CHINA

LING, Z.[1,2,3] – SHI, Z. T.[2*] – GU, S. X.[3,4] – PENG, H. Y.[5] – FENG, G. J.[1] – HUO, H.[1]

[1]*Kunming University, Kunming, 650214 Yunnan, China*

[2]*College of Tourism and Geographic Sciences, Yunnan Normal University, Kunming, 650500 Yunnan, China*

[3]*State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan, 430072 Hubei, China*

[4]*Yunnan Institute of Water & Hydropower Engineering Investigation, Design and Research, Kunming, 650021 Yunnan, China*

[5]*Institute of Land & Resources and Sustainable Development of Yunnan University of Finance and Economics, Kunming, 650221 Yunnan, China*

**Corresponding author*
e-mail: shizhengtao@163.com

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Abstract. Rubber tree (*Hevea brasiliensis*) is important economic agroforestry with high water demand during its growth. Evapotranspiration as the main component of water and energy balance in forest ecosystem which is a vital link between its ecological and hydrological processes. Therefore, it is of extreme significance to study the energy balance and evapotranspiration of rubber plantations for in-depth study of the regional water vapor cycle, scientific and efficient management of water resources. Based on the meteorological and energy data measured by the Bowen ratio system in 2016 at Xishuangbanna, the energy balance and evapotranspiration characteristics of rubber plantations were analyzed by Bowen ratio-energy balance. The result showed that: (1) The daily variations of net radiation (R_n), latent heat flux (LE), sensible heat flux (H) and soil heat flux (G) in rubber plantation were high value in rainy season and low in dry season; (2) The annual ET of the rubber plantation was 1035.91 mm, the average daily ET was 2.83 mm/d in 2016. The ET was about 114%-140% of precipitation in the dry season which indicated that ET of rubber plantation was mainly dependent on the volumetric soil water content (VWC); (3) The dominant environmental factors were R_n, vapour pressure deficit (VPD) and VWC which affect ET of rubber plantation.

Keywords: *tropical deciduous trees, Bowen ratio, Montane Southeast Asia, humid tropics, land-cover change, evapotranspiration*

Instruction

Evapotranspiration (ET) is a complex process involving soil, vegetation and atmosphere. It is one of the most important elements in the water cycle and energy balance of ecosystem and a key factor in the regional water balance as well. The ET of rubber plantation is also related to the water cycle and energy balance of its ecosystem.

In the past few decades, over 200,000 ha of rubber plantations have been established in Xishuangbanna (Ziegler et al., 2009; Mann, 2009). With the rising natural rubber prices, growing population and land management policies, the monoculture rubber plantations gradually replace natural forests and expand into “unsuitable areas” where

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high altitudes in the mountain. Numerous potential negative ecological and environmental consequences of converting primary and secondary forests into rubber plantations have been suggested: reduce in biodiversity (Ling et al., 2020; Monkai et al., 2018; Ahrends et al., 2015); decrease of total biomass carbon; acceleration of erosion (Guillaume et al., 2016; Liu et al., 2015; Zhang et al., 2006) and excessive water consumption (Ma et al., 2019; Liu et al., 2013; Zou et al., 2020; Martius et al., 2004; Qiu, 2009; Xu et al., 2014; Liu et al., 2015). The local population seriously begins to face rare water shortages during the dry season (Li, 2016; Zhou et al., 2011; Qiu, 2009). The research on the ET characteristics of rubber plantation was attracted increasing attention (Tan et al., 2011; Giambelluca et al., 2016; Lin et al., 2018).

Our research is motivated by the concern that if rubber does maintain high annual ET rates as found by Tan et al. (2011) and as suggested by Guardiola-Claramonte et al. (2010). The replacement of native and other non-rubber vegetation by rubber in Xishuangbanna may have significant negative consequences for water resources in the region.

To enhance the understanding of the energy cycle and ET processes of rubber plantation in Xishuangbanna, we used the Bowen ratio-energy method to study the ET of the rubber plantation ecosystem based on field monitoring data. The objectives of this study were to:(1) analyzed the characteristics of the fluxes of the rubber plantation ecosystem at different time scales; (2) determined annual ET of rubber plantations at representative sites in Xishuangbannna, in order to compare ET of rubber plantations with natural forests which dominated land covers to assess whether rubber is exceptional in its water use traits; (3) discussed the roles of phenological and environmental controls on the annual cycle of ET and elucidate the mechanisms promoting high annual ET.

Materials and methods

Site description

Our study site was located in Bubeng Village (21°34′10″N, 101°35′24″E), Mengla County, Xishuangbanna, Southwest of China, as shown in *Figure 1*. The climate included dry season (November - April the next year) and wet season (May - October) which is strongly seasonal. While dry season can be divided into cool-dry season (November - February the next year) and hot-dry season (February - May) (Zhang, 1963). The multi-year (1970-2017) mean annual precipitation was 1599.5 mm, and approximately 85% of the rainfall occurs during the rainy season. The annual average sunshine hours 1853.4 h. The annual average temperature was 21.5 °C and the monthly values range from 18 to 22 °C. The main soil type of study area is mainly brick red loam.

The characteristics of the rubber plantation were shown in *Table 1*. The rubber plantation study site was transformed from the original tropical monsoon forest with a slope length of about 300 m. Rubber trees were planted 2-3 m in rows of mixed spacing between 4 - 6 m. Understory with a small amount of shrubs and weeds.

Table 1. *Characteristics of the plant structure and the study site*

Planting year	Location	Altitude (m)	Slope (°)	Plot area (m × m)	Diameter at breast height (cm)	Tree height (m)	Planting density (trees/ha)
1992	21°34′10″N 101°35′24″E	726	22	200×200	20 ± 2	11.58 ± 2.3	300 ± 50

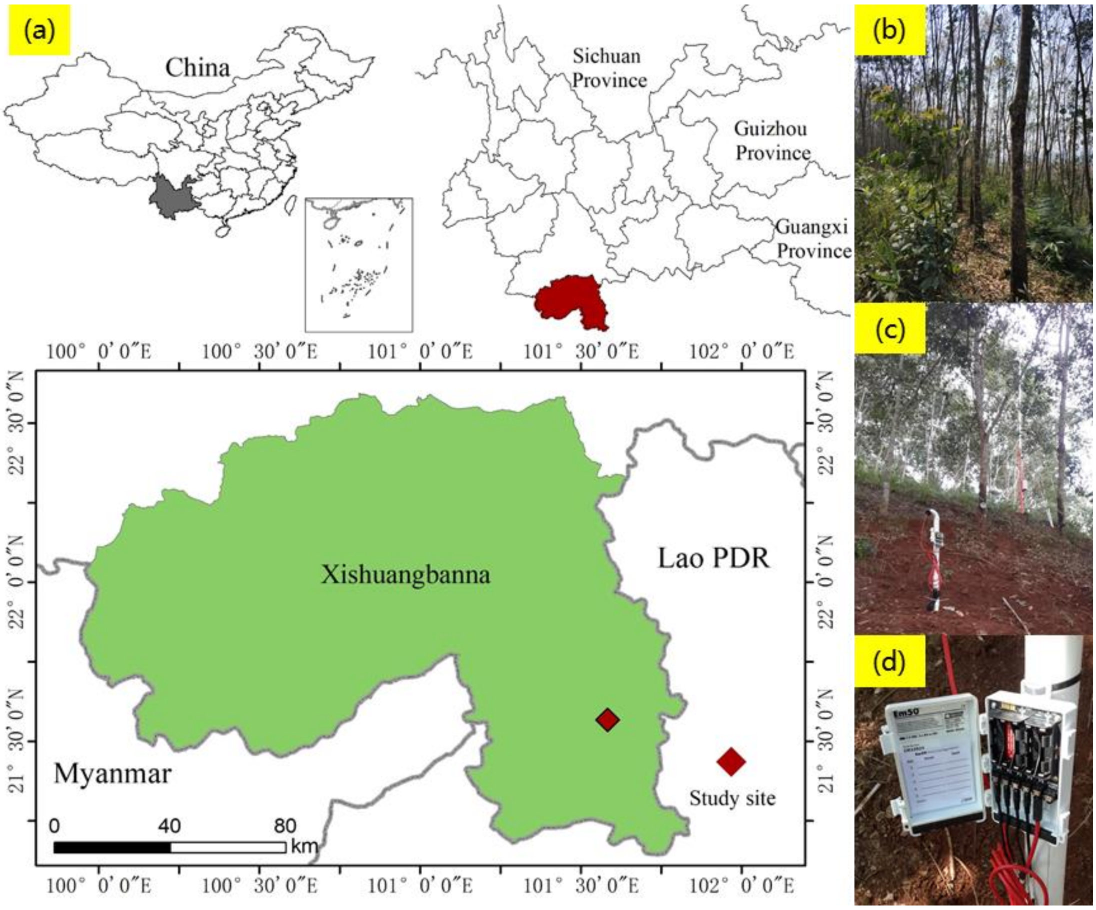

Figure 1. *The study site of Rubber Plantation (indicated by a solid square; 21°55'39"N; 101°15'55"E) in Xishuangbanna, Yunnan Province, Southwest China. (a) Location of area; (b) observed rubber plantation; (c) Bowenby system; (d) EM50 monitor sensor*

Methods

Meteorological measurements

Environmental variables including precipitation (Pe, mm), air temperature (Ta, °C) and net radiation (R_n, $MW \cdot m^{-2}$) were measured by sensors mounted on a 15-m-tall automatic weather station system sensor (WS-BR06, USA) that was established in Bubeng in 2016. The water vapour pressure deficit (VPD, hPa) was calculated from Ta and relative humidity (RH, %), which were monitored by air humidity sensor (SKH2060, Vaisala, Finland). Volumetric soil water content (VWC, %) was measured by a depth profile at each site using time domain reflectometers (ECH2O 5TE, Pullman, Washington, USA) at a depth of -10 cm, -20 cm, -30 cm, -40 cm. All meteorological data were collected using a data logger (CR1000, Campbell Sci., USA) every 30 min, as shown in *Table 2*.

Energy flux measurements

The canopy tower was 20 m tall were constructed at Bubeng village for micrometeorological and energy flux measurements. The latent heat flux (LE) and sensible heat flux (H) were measured using the Bowen ratio system. Wind speeds was all sampled and stored at 10 Hz on a data logger. All variances and covariances required for the Bowen ratio flux estimates were computed over a 30-min averaging interval.

The ratio of mean annual LE + H to mean annual available energy (A), which was estimated as R_n - G, was 0.71 for the whole observation period. Whereas, LE + H accounted for only 58% and 65% in the wet and cool-dry seasons in Xishuangbanna influenced by fog drops. We used “Bowenby ratio closure” method for closing the canopy surface energy balance for each 30-min interval (Wilson., 2002; Twine et al., 2000).

In this study, the meteorological data and energy flux data were processed by coordinate correction, wild point rejection, data interpolation and data quality analysis to eliminate abnormal value of rubber plantation due to uncontrollable factors (Falge et al., 2001; Baldocchi et al., 2001; Liu et al., 2014).

Table 2. *Sensor parameters and installation of WS-BR06 automatic weather station system*

Sensor	**Model**	**Installation height (m)**	**Unit**	**Observation interval/min**
Data logger	CR1000	0.5		30
Wind speed and direction sensor	05103L	15	m/s	30
Heat flux plate	HFP01	15		30
Global radiation	Long wave radiation sensor	14.5	U mol/(sm^{-2})	30
Net solar radiation	CNR4	14.5	W m^{-2}	30
Tipping-bucket rain recorder	TE525MM	15	Mm	30
Air temperature sensor	SKH2060	14.5	℃	30
Air humidity sensor		14.5	%	30
Canopy temperature sensor		11	℃	30

Leaf area index measurements

The Leaf area index (LAI) was measured using plant canopy analyzer (LI-COR, Lincorn, USA) at irregular time intervals over the course of the study at an interval of 6 to 5 m at study site, along transects oriented diagonally with respect to tree rows.

Calculation of energy-balance

According to the principle of energy conservation (Tang et al.,1996; Maruyama et al., 2019; Li et al., 2021):

$$R_n = \lambda ET + H + G \tag{Eq.1}$$

where R_n is the net radiation, W·m^{-2}; λET is the latent heat flux, W·m^{-2}; λ is the latent heat of vaporization, J/kg, generally taken as 2.45 MJ/kg; ET is the evapotranspiration; H is the sensible heat flux, W·m^{-2}; G is the soil heat flux, W·m^{-2}.

According to the boundary diffusion theory, the diffusion of water vapor and heat on the evaporation surface can be described by the following equation:

$$\lambda ET = -\lambda_\rho K_w \left(\frac{0.622}{P}\right)\frac{\partial e}{\partial z} \tag{Eq.2}$$

$$H = -\rho C_p K_h \frac{\partial T}{\partial z} \tag{Eq.3}$$

where ρ is the air density, kg/m^3; P is the atmospheric pressure, kPa; C_p is the specific heat of air at constant pressure, J·kg^{-1} K^{-1}; K_w and K_h are the turbulent exchange coefficients for λ ET and H transport, respectively, m^2/s; $\partial e/\partial z$ is the water vapor pressure gradient, k Pa/m; and $\partial T/\partial z$ is the temperature gradient, °C /m.

If $K_w = K_h$ and quote the Bowen ratio β is the ratio of H to λET, we obtain:

$$\beta = \frac{H}{\lambda ET} = \frac{PC_p K_h}{0.622\lambda K_w} \bullet \frac{\Delta T}{\Delta e} = \gamma \frac{\Delta T}{\Delta e} \tag{Eq.4}$$

where ΔT is the temperature difference between the two heights (upper layer temperature - lower layer temperature), °C; Δe is the water vapor pressure difference between the two heights (upper layer humidity - lower layer humidity), k Pa; γ is the humidity counting coefficient, k Pa/°C, for:

$$\gamma = \frac{PC_p}{0.622\lambda} \tag{Eq.5}$$

Then, λET and H can be written as:

$$\lambda ET = \frac{R_n - G}{1+\beta} \tag{Eq.6}$$

$$H = \frac{\beta(R_n - G)}{1+\beta} \tag{Eq.7}$$

Results and discussion

Characteristics of dynamic variation of meteorological factors in rubber plantation

Xishuangbanna is influenced by the southwest monsoon where with more sunny weather and high temperature in March and April (the late hot-dry season) but with more cloudy rainy days in June. As shown in *Figure 2,* the annual rainfall was 1565.5 mm including 1241.5 mm in the rainy season in 2016. The average temperature of 22.1 °C. The VPD reached maximum value in April which about 1.48 kPa and minimum value about 0.36 kPa in December.

The monthly average R_n increased to the maximum value in April and May was 98.6 W·m^{-2}, and then started to decrease to minimum was 49.3 W·m^{-2} in December. The VWC of each soil layer remained high values were 0.37 to 0.22 cm^3/cm^3 in the rainy season and reduced with the depth of the soil layer increased. In dry season, the VWC decreased to the lowest value when it was consumed by rubber tree. The T_{asoil} was 17.3 °C which was lowest in January and February, and high from June to September average value up to 25.2 °C. The T_{asoil} in the 0-20 cm layer of the rubber plantation was more sensitive by environmental changes. The periodic defoliation of the rubber plantation led to large fluctuations in LAI within the year. The LAI was 0.75 ± 0.072 m^2/m^2 in the dormant defoliation period from January to February up to 2.87 ± 0.11 m^2/m^2 in the first canopy leaf period. Then the mean LAI reached a maximum value was 4.26 ± 0.45 m^2/m^2 in the second canopy leaf period. The monthly average value of meteorological factors in rubber plantation as shown in *Table 3*.

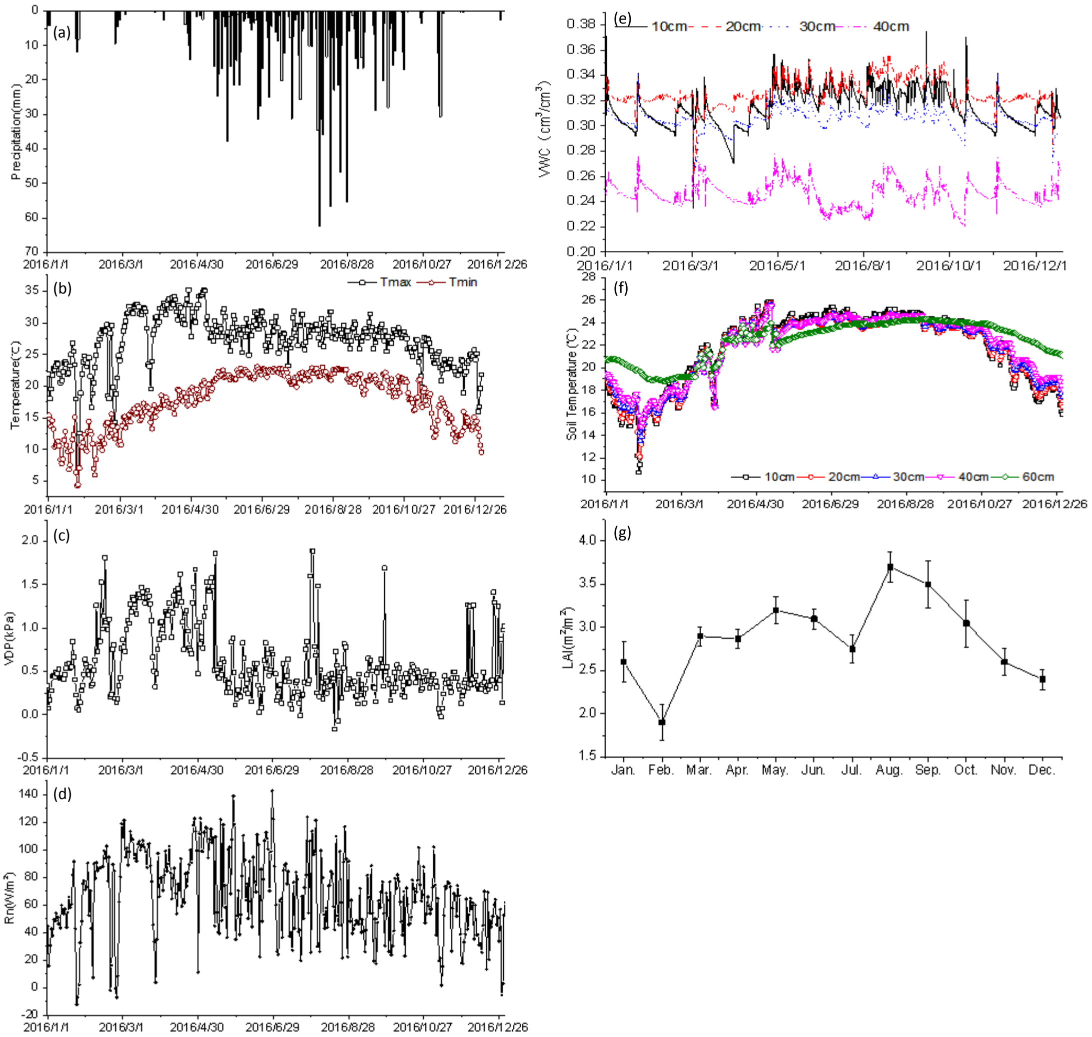

Figure 2. *Variation characteristics of meteorological factors in rubber plantation. (a) Rainfall outside the plantation; (b) the temperature; (c) saturated vapor pressure difference; (d) net radiation; (e) soil moisture content; (f) soil temperature; (g) leaf area index*

Table 3. *Monthly average value of meteorological factors in rubber plantation*

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Pe (mm)	77.7	34.5	35.4	58.9	186.3	188.7	193.3	431.0	172.6	69.6	92.0	25.5
Tmax (℃)	21.1	23.5	29.6	32.1	30.6	29.1	27.9	28.9	28.3	27.8	24.9	22.7
Tmin (℃)	10.5	11.6	15.2	17.5	20.2	21.9	21.8	21.9	21.3	20.4	17.1	13.5
VDP (kPa)	0.41	0.70	1.09	1.14	0.81	0.45	0.48	0.44	0.44	0.41	0.32	0.59
Rn ($W\cdot m^{-2}$)	47.70	67.24	89.29	81.77	89.59	82.45	63.79	66.38	52.26	61.39	52.25	44.81
VWC (cm^3/cm^3)	0.297	0.293	0.289	0.290	0.301	0.305	0.300	0.308	0.306	0.296	0.295	0.292
Tsoil (℃)	17.34	17.39	19.60	22.78	23.64	24.03	24.21	24.39	24.12	23.62	21.63	19.26
LAI (m^2/m^2)	2.6±0.23	1.9±0.21	2.9±0.11	2.87±0.11	3.2±0.16	3.1±0.12	2.75±0.16	3.7±0.18	3.5±0.27	3.05±0.27	2.6±0.16	2.4±0.12

Rubber plantation energy flux distribution

Diurnal variation of evapotranspiration in rubber plantations

According to *Equation 1*, the daily variation in R_n, G, H and LE in the rubber plantation were all showing a ‘single-peaked’ curve. R_n is the driving factor of ET in forest ecosystem. The daily average changes of R_n in rubber plantation were shown in *Figure 3a*. The change of H (*Fig. 3b*) was most similar to R_n, but lagged behind R_n.

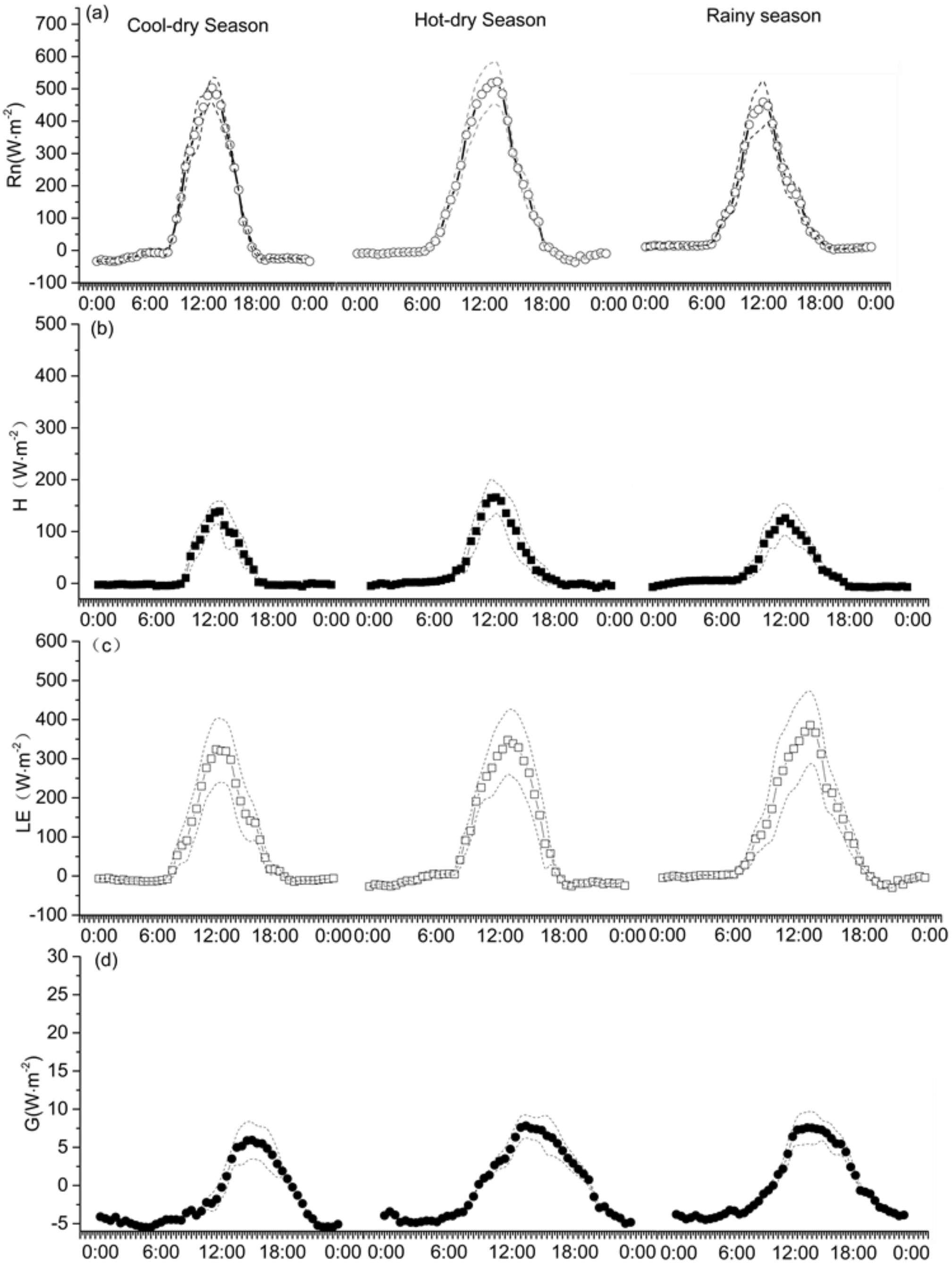

Figure 3. *Diurnal variations of ecosystem ET (represented by latent heat flux), sensible heat flux (H), net radiation (R_n), soil heat flux (G) in the cool-dry season, hot-dry season and rainy season. Solid circles are the means of all available 30-min data in each of the three seasons. Dash lines represent the standard deviation of the 30-minute data*

The intermittent of LE makes its changes rough but almost synchronous with the R_n. The LE appeared that in the rainy season was larger than the hot-dry and the cool-dry season which indicated the rubber plantation use much more energy for water vapor transport in the rainy season than in the dry season.

During the cool-dry season, LE of the rubber plantation reached a maximum value of 320.25 ± 80.04 $W \cdot m^{-2}$ (*Fig. 3c*) lagging about 1 h behind the R_n. The VPD (*Fig. 2c*) and Ta (*Fig. 2b*) increased faster in the hot-dry season because of clear weather. Substantially, the evapotranspiration increased while the rubber trees inter to leaf flushing period at this time. Then the LE rose up to 347.33 ± 80.79 $W \cdot m^{-2}$ (*Fig. 3c*).

The daily distribution of LE during the rainy season roughly increased with the R_n and H (*Fig. 3 a, c*). The maximum value of LE in the rainy season was 385.45 ± 93.32 $W \cdot m^{-2}$ which was much higher than the maximum value of H (*Fig. 3b*). There were large variations of LE (*Fig, 3c*) and R_n (*Fig. 3a*) (large standard deviations) which was reflected that the ET of the rubber plantation was affected by the variable weather conditions in the rainy season. Although the VPD (*Fig. 2c*) and Ta (*Fig. 2b*) increased rapidly and the ET also rose substantially in the hot-dry season, the maximum value of LE in rubber plantation was still lower than that in the rainy season (*Fig. 3c*). It was due to the reduced soil water moisture and the rose VPD of rubber plantation which produced some limitation on ET of rubber plantation in the dry season (Li, 2010).

G was little seasonal variation in the year. The change of G was similar to R_n but lag behind R_n. G showed less variation in the rainy season than dry season in rubber plantation. It means there were more energy for ET in the rainy season than dry season.

As shown in *Figure 4*, The Bowen ratio ranges from 0.48 to 0.63 in the rainy season (May to October) that the LE of rubber plantation was higher than H; The Bowen ratio ranged from 0.52 to 1.38 in all the dry season but its average was still less than 1. The high values of Bowen ratio appear in January and February that were 1.38 and 1.16, respectively. Because January and February in Xishuangbanna were dry period that the water vapor exchange between the rubber plantation and the atmosphere was reduced. The ET was minimized because of deficit soil moisture and rubber plantation defoliation.

Seasonal variation and annual total evapotranspiration of rubber plantation

We used Bowen ratio-energy balance to estimate the ET of rubber plantation at representative sites in Xishuangbannna. The annual ET was 1035.91 mm and the average daily ET was 2.83 mm/d. The ET of rubber plantation was maximum in rainy season and minimum in cool-dry season, as shown in *Figure 5*.

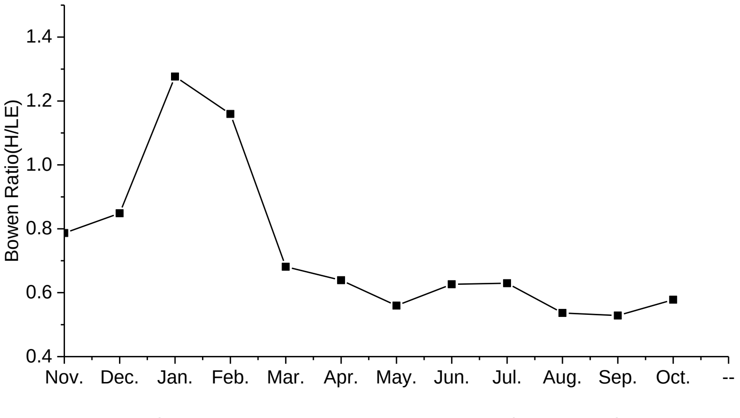

Figure 4. *Trend of monthly mean Bowen ratio of rubber forest ecosystem*

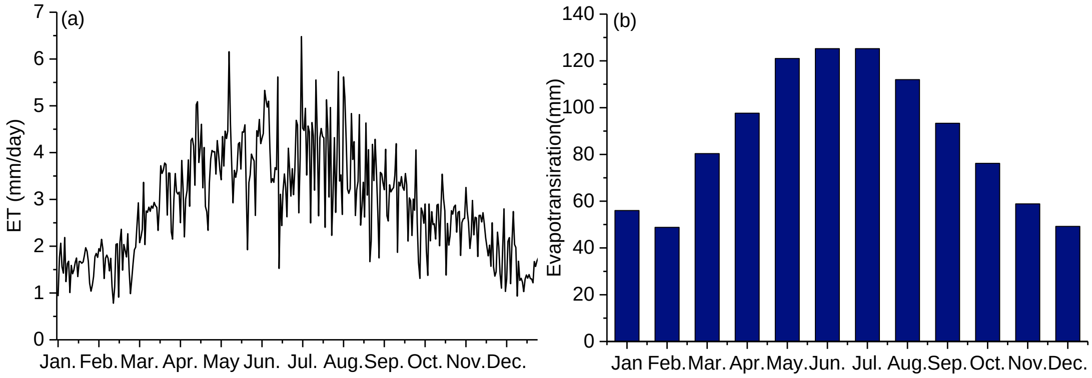

Figure 5. *The trend of daily mean (a) and monthly mean (b) of evapotranspiration ET in rubber plantation*

The ET of the rubber plantation decreased from November to January (early and middle of the cool-dry season) due to the reduced Ta; The Ta reached its minimum value of about 10 °C at the end of December and the beginning of February (*Fig. 2b*). Also, the VPD was very low during this period (*Fig. 2c*). The minimum ET value of rubber trees at the end of the cool-dry season in February when it started to drop leaves.

The Ta and the VPD increased at the begin of the hot-dry season in March which lead to the ET of rubber plantation rise; however, the surface soil water moisture decreased rapidly during this period. So the deeper soil water incontestable supported the increasing ET during the hot-dry season.

The LE has high values accompanied by large fluctuations (large standard deviation, as in *Fig. 3c*) which were mainly related to the extremely variable weather conditions during the rainy season from May to October. In our study, the maximum value of daily ET in rubber plantation was already over 6 mm day^{-1} in the rainy season.

As shown in *Table 4*, the ET was 630.19 mm in the rainy season, 211.67 mm in the cool-dry season, and 194.05 mm in the hot-dry season, accounting for 51%, 114%, and 140% of the seasonal rainfall, respectively.

Table 4. *Annual and seasonal amounts of rainfall and evapotranspiration in rubber plantation*

Year	**Cool-dry (Nov.- Feb.)**			**Hot-dry (Mar.-Apr.)**		
2016	P 185.75	ET 211.67	ET/P 1.14	P 138.30	ET 194.05	ET/P 1.40
Year	**Rainy (May - Oct.)**			**Year**		
2016	P 1241.55	ET 630.19	ET/P 0.51	P 1565.60	ET 1035.91	ET/P 0.66

The amount of fog drops entered the rubber plantation ecosystem can account for about 13% and 2.3% of the rainfall during the cool-dry and hot-dry seasons. The ET in cool-dry and hot-dry seasons would decreased significantly to 100.85% and 137.15%, if we added the retention of fog drops by the rubber plantation canopy in the rainfall water. It shown that fog precipitation plays a very important role in the ET of rubber plantation in the dry season. However, the ET of rubber plantation in Xishuangbanna was still higher than the total precipitation (rainfall + fog precipitation). It can be seen that the recharge of subsurface soil water was another important supplement to the ET water in rubber plantations during the dry season when precipitation was insufficient (e.g., *Fig. 2e*) and the soil water content substantial and continuous decreased during the dry season.

From the changes of soil water content in rubber plantation (*Fig. 2e*), it can be seen that the large consumption of soil water by rubber plantation in the late dry season was one of the reason for the high annual ET. The rubber plantation in Xishuangbanna fell their leaves in February. While the LAI and ET increased rapidly until the beginning of the rainy season in May (*Fig. 2g*). As we known, the average ET of rubber plantation in April can reach about 85% of it was the rainy season (May to October). Although the dry season soil water content was the lowest, the rubber plantation still maintain a high ET in the late dry season. The rubber trees were able to access water which reserved in the deep soil (Kumagai et al., 2015). Therefore, soil water in Xishuangbanna played a very important role in the ET of rubber plantation in the dry season.

In all, the self-regulatory function of the rubber plantation ecosystem for water use was an important reason for its able to survive and develop well in Xishuangbanna where was less precipitation than its original area.

Effects of environmental factors on evapotranspiration in rubber plantation ecosystem

A linear regression of ET and environmental factors for each season in the year was conducted to analyze the key environmental factors affecting seasonal ET in rubber plantation. The equation was:

$$ET = -18.956 + 0.029R_n + 0.082T_{air} - 0.139VPD + 15.233VWC + 0.028T_{soil} + 0.086LAI \quad \text{(Eq.8)}$$

where ET is evapotranspiration, mm day^{-1}; R_n is net radiation, W·m^{-2}; T_{air} is air temperature, °C; VPD is saturated water vapor pressure difference, kPa; VWC is soil water content, m^3/m^3; T_{soil} is soil temperature (20 cm), °C; LAI is leaf area index, m^2/m^2. $R^2 = 0.781$.

According to *Equation 8* the results showed that ET of rubber plantations in Xishuangbanna was mainly affected by R_n ($r = 0.697$, $p < 0.01$), VPD ($r = 0.664$, $p < 0.01$), VWC ($r = 0.616$, $p < 0.01$), T_{air} ($r = 0.549$, $p < 0.01$), T_{air} ($r = 0.549$, $p < 0.01$), LAI ($r = 0.534$, $p < 0.01$) and 20 cm soil temperature T_{soil} ($r = 0.388$, $p < 0.01$).

The results were consistent with Zhang (2016) and Giambelluca et al. (2016) that R_n, VPD and VWC were the dominant environmental factors which affect ET of rubber plantation in each season of year, as shown in *Table 5*. The R was not obvious in the cool-dry season because of the low ET of the rubber plantation and the influence of environmental factors on ET was greatly reduced.

Discussion

The daily change of R_n, G, H, and LE in rubber plantation were similar but with large differences between seasonal change. Energy was used for ET in the rainy season.

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While the little difference between H and LE consumed in the dry season. There were consistent with the energy flux changes in Hainan rubber plantation studied by Zhang (2016) and similar to the energy flux changes in Xishuangbanna monsoon rainforest studied by Li (2010).

Table 5. *Stepwise regression analysis results of ET and different influencing factors in different seasons*

Season	Factors	R	Regression equation
Cool-dry season	Rn, VPD, VWC, T_{soil}	0.596	$ET=3.769+0.013R_n+0.18VPD-3.15VWC+0.056T_{soil}$
Hot-dry season	Rn, VPD, VWC, T_{soil}, LAI	0.644	$ET=-3.428+0.017R_n+0.4VPD+2.477VWC+0.009T_{soil}+0.62LAI$
Rainy season	Rn, Ta, VPD, VWC	0.743	$ET=-6.506+0.046R_n+0.231Ta+0.516VPD+0.007VWC$
Year	Rn, Ta, VPD, VWC, T_{soil}, LAI	0.781	$ET=-18.956+0.029R_n+0.082Ta-0.139VPD+15.233VWC+0.028T_{soil}+0.086LAI$

Compared with the ET of rubber plantations in Southeast Asia, as shown in *Table 6*. The annual of ET from rubber plantation in our study was 1035.91 mm monitored by Bowenby ratio system which with an average daily ET of 2.83 mm/d. There was little lower which compared to other study regions in Southeast Asia that because it mainly influenced by some factors such as precipitation and age of rubber trees (Lin et al., 2016, 2019). Nobuhiro et al. (2007) studied the ET of rubber plantation in Cambodia was similarly higher than that of evergreen forest by 28%. It indicated that ET of rubber plantation was generally higher than that of natural forest, as shown in *Table 6*.

Table 6. *Comparative study on evapotranspiration between rubber plantations and natural forests in different regions*

	Study area	Location	Annual precipitation (mm)	Annual net radiation (w/m^2)	ET (mm)	ET/P	
Rubber plantation	Xiushuangbanna, China	21°34′10″N, 101°35′24″E	1565.6	125.13	1108.7	0.71	Our study
	Xiushuangbanna, China	21°55′39″, 101°15′55″	1504	123.3	1125	0.75	Tan et al. (2011)
	Som Sanuk, Thailand	18°12’N, 103°25’E	2145	129.5	1211	0.56	Giambelluca et al. (2016)
	CRRI, Cambodia	11°57’N, 105°34’E	1439	151.0	1459	1.01	Giambelluca et al. (2016)
Tropical seasonal forest	Xishuangbanna, China	21°55′39″, 101°15′55″	1534	119.2	927	0.60	Tan et al. (2011)
	Kampong Thom, Cambodia	12°44′ N, 105°28′ E	1600	161.3	1140	0.71	Nobuhiro et al. (2007)
	Chiang Mai, Thailand	19.55 N, 99.5 E	1573	115.7	812	0.52	Tanaka et al. (2003), Igarashi et al. (2015b)
	Kog-Ma, Thailand	18.48 N, 98.54 E	1768		812	0.46	Tanaka et al. (2008)

As *Figure 2e*, the large consumption of soil water in the late hot-dry season was the important reason for the high annual ET of rubber plantation. The rubber plantation fell their leaves in February then quickly entered leaf flushing period in Xishuangbanna. The ET increased with the increasing LAI. Normally, the average ET of rubber plantation in April can reach more than 85% of it was in the rainy season (May-October). Although the soil water content was near the minimum value in dry season, the ET of rubber plantation was high in the late dry season because it can access the water in the deep soil layer.

Guardiola-Claramonte et al. (2008) showed that the use of deep soil water increased after the rubber planation surface soil layer dried out in Xishuangbanna. Gonkhamdee et al. (2010) found that there were amount of fine roots of rubber plantations in deep soil (below 300 cm) in Baan Sila were active only during the dry season. Giambelluca et al. (2016) also suggested that rubber tree extracted more than half of the water from the deeper soil layers by the end of the dry season. In order to maintain a high ET, the distribution of rubber roots respond to the changing of soil water when the surface layer was dry in the late dry season.

Conclusion

The main reasons for the high annual total evapotranspiration of the rubber plantations were not only that it still used a large amount of water to make strong evapotranspiration during the whole rainy season, but also that the rubber plantations rapidly grew leaves and reached a higher LAI in the late cool-dry season after concentrated defoliation; secondly, the rubber plantations had developed roots to utilize the deep soil water reserve to maintain a high evapotranspiration even affected by the soil water content limitation in the late hot-dry season.

With the expansion of the area used to grow rubber plantations in the region, the relatively high ET rates of rubber should use deep soil moisture during the dry season to maintain physiological activity may result in reduced river flow and drier catchments throughout the region. In that case, rubber plantations are rapidly becoming the main emerging land cover in Xishuangbanna has affected or intensified the seasonal drought in the region. It could have impacts on water security.

In summary, we accurately estimate the ET of rubber plantation at typical site using Bowen ratio-energy method. We also analyzed the main environmental factors which affected the ET of rubber plantation at each season. The results provide important data support subsequent studies on ET of rubber plantations.

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