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Evapotranspiration of rubber (*Hevea brasiliensis*) cultivated at two plantation sites in Southeast Asia

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Key Points:
- SE Asian rubber plantations maintain very high annual evapotranspiration (ET)
- Access to deep soil water enables rapid refoliation after leaf drop and high late dry season ET
- Spatially rubber evapotranspiration increases linearly with increasing net radiation

Supporting Information:
- Supporting Information S1

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Abstract To investigate the effects of expanding rubber (*Hevea brasiliensis*) cultivation on water cycling in Mainland Southeast Asia (MSEA), evapotranspiration (*ET*) was measured within rubber plantations at Bueng Kan, Thailand, and Kampong Cham, Cambodia. After energy closure adjustment, mean annual rubber *ET* was 1211 and 1459 mm yr^{-1} at the Thailand and Cambodia sites, respectively, higher than that of other tree-dominated land covers in the region, including tropical seasonal forest (812–1140 mm yr^{-1}), and savanna (538–1060 mm yr^{-1}). The mean proportion of net radiation used for *ET* by rubber (0.725) is similar to that of tropical rainforest (0.729) and much higher than that of tropical seasonal forest (0.595) and savanna (0.548). Plant area index (varies with leaf area changes), explains 88.2% and 73.1% of the variance in the ratio of latent energy flux (energy equivalent of *ET*) to potential latent energy flux (LE/LE_{pot}) for midday rain-free periods at the Thailand and Cambodia sites, respectively. High annual rubber *ET* results from high late dry season water use, associated with rapid refoliation by this brevideciduous species, facilitated by tapping of deep soil water, and by very high wet season ET, a characteristic of deciduous trees. Spatially, mean annual rubber *ET* increases strongly with increasing net radiation (R_n) across the three available rubber plantation observation sites, unlike nonrubber tropical ecosystems, which reduce canopy conductance at high R_n sites. High water use by rubber raises concerns about potential effects of continued expansion of tree plantations on water and food security in MSEA.

1. Introduction

The influence of land cover change, especially deforestation, on water flows is one of the most important and longstanding topics of hydrological research [*Hoover*, 1944; *Hibbert*, 1965; *Bosch and Hewlett*, 1982; *Bruijnzeel*, 2004]. Decades of observations and model simulations have shown that forests generally support high evapotranspiration (*ET*) and produce lower annual stream discharge than other land covers, but might enhance dry season flows [*Brown et al*., 2013; *Beck et al*., 2013]. Globally, land cover change, dominated by conversion of natural vegetation to cropland, has led to increased runoff, partly as a result of reduced *ET* [*Sterling et al*., 2013]. In recent years, however, reforestation for a variety of purposes has led to a slowdown in the loss of tree cover and even a reversal in some regions [*Meyfroidt and Lambin*, 2011]. While numerous perceived benefits are associated with tree planting [*Malmer et al*., 2010], negative effects of increased tree cover on water resources have been observed. For example, expansion of tree plantations in Australian catchments resulted in streamflow reductions, especially for ephemeral streams, leading to a greater number of zero-flow days [*Zhang et al*., 2012]. However, the possible effects of expanding tree cover on water resources are not always clear [*van Dijk and Keenan*, 2007], especially in the tropics, where estimates are often extrapolated from extratropical data [*Malmer et al*., 2010] because of the paucity of tropical research results [*Wohl et al*., 2012].

As in other areas in the developing tropics, land cover change in Mainland Southeast Asia (MSEA), including Thailand, peninsular Malaysia, Cambodia, Laos, Myanmar, and the southern part of Yunnan, China, had until recent decades been dominated by activities associated with forest clearing, especially logging and shifting agriculture [*Fox et al*., 1995]. In the last few decades, subsistence cultivation has given way in many areas to commercial agriculture [*Fox*, 2012], often in the form of tree plantations such as rubber [*Li and Fox*, 2011; *Ziegler et al*., 2009a, 2009b, 2011; *Mann*, 2009; *Manivong and Cramb*, 2008], fruit and nut orchards, oil palm, and paper pulp species, and reforestation for conservation and carbon storage [*Fox et al*., 2014]. Commercial tree plantations are already displacing forests, and much of the projected expansion of rubber cultivation is likely to be at the expense of forests, including protected areas [*Warren-Thomas et al*., 2015]. Rubber cultivation is currently leading the expansion of tree plantations in MSEA [*Li and Fox*, 2011; *Fox and Castella*, 2013], driven by spiraling global demand for rubber and the consequent 10-fold increase in the market price of natural rubber latex over the 10 year period ending in February 2011 (www.indexmundi.com/commodities, accessed 20 June 2015). While commodity prices can fluctuate (May 2015 rubber price was 70% below its February 2011 peak), expansion of rubber cultivation over the past decade has been explosive, and rubber is likely to continue to be one of the fastest growing land cover types in MSEA over the coming decades due to projected increases in demand [*Warren-Thomas et al*., 2015]. The locus of new rubber plantations represents a northward and in some cases upward shift from the traditional rubber growing areas of lowland Malaysia and southern Thailand into areas throughout the region with more seasonal rainfall regimes and lower annual minimum temperatures. With the development of rubber clones appropriate for higher latitude/elevation environments such as Xishuangbanna, a district along the southern border of Yunnan, China, a new "non-traditional" rubber cultivation region began to emerge [*Ziegler et al*., 2009a]. In recent decades, the extent of rubber cultivation in nontraditional rubber growing areas of MSEA has increased by more than a million hectares [*Ziegler et al*., 2009a; *Qiu*, 2009].

The unbridled expansion of rubber in some areas is raising concerns about impacts on biodiversity [*Li et al*., 2007] and ecosystem services [*Hu et al*., 2008], including water cycling [*Guardiola-Claramonte et al*., 2008; *Ziegler et al*., 2009a] and carbon storage [*Li et al*., 2008; *Ziegler et al*., 2012; *Fox et al*., 2014]. *Tan et al*. [2011] called rubber plantations in Xishuangbanna "water pumps" because of their high *ET* rates compared with natural forest. *Guardiola-Claramonte et al*. [2008] found high rates of root-water extraction during the mid to late dry season under rubber as compared with other vegetation in Xishuangbanna. Their findings suggest that the high annual *ET* of rubber might be explained by species-specific biological control enabling high water use in the dry season. However, estimates of rubber transpiration based on sap flow measurements have not found unusually high water use rates [*Isarangkool Na Ayutthaya et al*., 2011; *Kobayashi et al*., 2014].

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 the findings of *Guardiola-Claramonte et al*. [2010], the replacement of native and other nonrubber vegetation by rubber in MSEA may have significant negative consequences for water resources in the region. To improve understanding of the potential impacts of expanding rubber cultivation on water fluxes, the objectives of this study were to: (1) determine annual *ET* of rubber plantations at representative sites in MSEA, in order to compare *ET* of rubber plantations with those of other tree-dominated land covers to assess whether rubber is exceptional in its water use traits; (2) determine the roles of phenological and environmental controls on the annual cycle of *ET* and elucidate the mechanisms promoting high annual *ET*; and (3) evaluate the environmental controls that give rise to spatial differences in rubber *ET* in MSEA. To address these objectives, field research stations were established in two rubber plantations in the region. Eddy covariance and related measurements were made at each site beginning in 2009. Herein, we report results from approximately two years of measurements at each site.

2. Methods

2.1. Study Sites

Observations were conducted at two monoculture rubber plantation stands in mainland SE Asia; Som Sanuk, Bueng Kan Province, NE Thailand beginning in February 2009, and the Cambodian Rubber Research Institute (CRRI) plantation in Kampong Cham Province, central Cambodia beginning in September 2009. Study site characteristics are given in Table 1. Herein, we present *ET* estimates for March 2009 to June 2011 at Som Sanuk and for late September 2009 to January 2012 at CRRI. Annual values are given for two years at each site: March 2009 to February 2011 at Som Sanuk and calendar years 2010–2011 at CRRI. Data presented for leaf area extend to December 2012 at Som Sanuk and September 2013 at CRRI to allow better understanding of the annual leaf area cycle. See supporting information Text S1 for more details on the study sites.

Table 1. Study Site Characteristics

Characteristic	Som Sanuk, Thailand	CRRI, Cambodia
Coordinates	18°12′N, 103°25′E	11°57′N, 105°34′E
Elevation (m)	210	57
Terrain	Slightly undulating	Very gently sloping
Average slope (°)	<1	<1
Year planted	1991	2004
Tower height (m)	26.5	30.0
Fetch (m)	>500	>500
Clone	RRIM-600	RRIC-100
Spacing (m)	7×2.5	6×3
Planted tree density (trees ha^{-1})	567	555
Tree density at start of obs. (trees ha^{-1})	525	431
Mean canopy height at start of obs. (m)	19.0	11.4^a
Mean stem diameter at 1.7 m (cm)	18.9 ± 3.0	13.3 ± 2.3
Mean stem diameter growth rate (cm yr^{-1})	0.6	1.8
Understory	Sparse	Abundant
Tapping initiation date	1997	Nov 2010
Tapping interval (tapping days|rest days)	2|1	1|2
Fertilizer application frequency (yr^{-1})	2	2^b
Fertilizer type	50/50 manure & N-P-K: 20-10-12	N-P-K: 15-15-15
Herbicide use	None	Annual
Dry season	Oct–Apr	Nov–Apr
Wet season	May–Sep	May–Oct
Cool season	Nov–Jan	Nov–Jan
Annual rainfall – project year 1 (mm)	2215	1332
Annual rainfall – project year 2 (mm)	2020	1545
Mean ann. temperature – project yr 1 (°C)	26.2	28.0
Mean ann. temperature – project yr 2 (°C)	26.0	27.0
Wind - dry season (dom. direction|freq.)	NE (57%)	NE (72%)
Wind - wet season (dom. direction|freq.)	SW (42%)	S (82%)

[a] Increased from this height in February 2010 to 12.9 m in March 2011.
[b] Applied during first 4 years after planting only.

2.2. Instrumentation and Data Analysis

2.2.1. Eddy Covariance Variables

Latent energy flux (*LE*) and sensible energy flux (*H*) were estimated via the eddy covariance (EC) technique. A three-dimensional sonic anemometer (CSAT3, Campbell Scientific, Logan, UT, USA) and an open-path infrared gas analyzer (IRGA, model LI-7500, LiCor, Lincoln, NE, USA) were mounted to the meteorological towers at 26.5 and 30.1 m above the ground, at Som Sanuk and CRRI, respectively. The orientation of the CSAT3 and LI-7500 sensors were changed seasonally toward the prevailing wind direction (southwest in wet season, north in dry season) to limit turbulence effects caused by the tower structure. The 10 Hz eddy covariance measurements were stored using a Campbell Scientific CR3000 data logger for post processing, and all other variables (see below) were stored at a 30 min interval using a Campbell Scientific CR23X data logger. The code to process the EC data was adapted from that of *Noormets et al.* [2007] and *Baldocchi et al.* [1988] [also see *Giambelluca et al.*, 2009a]. Details of the flux calculations are given in supporting information Text S2.

The 30 min fluxes were filtered using the LI-7500 output diagnostic index (*AGC*) that responds to the presence of water droplets on sensor windows. The flux data were also filtered for gross energy balance anomalies (*EBA*). We defined the variable $EBA = R_n - G - LE - H$, where G is soil heat flux. Fluxes estimates were excluded for any 30 min period for which $EBA < -200$ or $EBA > 400$ W m^{-2}. Tower interference was evaluated and determined to be negligible (see supporting information Text S3).

2.2.2. Meteorological Variables

Time series of 30 min rainfall, net radiation (R_n), air temperature (T_a), relative humidity (*RH*), wind speed (*WS*), and wind direction (*WD*) were also measured. See supporting information Text S4.

2.2.3. Soil Moisture

At Som Sanuk, soil moisture was measured using six water content reflectometers (CS616, Campbell Scientific) placed in the soil profile at the following depths and orientations: 0.04 m horizontal, 0.04–0.34 m vertical, 0.48–0.75 m vertical, 0.80 m horizontal, 1.50–1.80 m vertical, and 2.20–2.50 m vertical. At CRRI, soil moisture was measured using five CS616s placed in the soil profile at: 0.04 m horizontal, 0.35–0.65 m vertical, 1.05–1.35 m vertical, 2.03–2.33 m vertical, and 3.08–3.38 m vertical. In addition, five ML2X ThetaProbe

(Delta-T Devices, Burwell, UK) soil moisture sensors were installed horizontally at depths of 0.05, 0.10, 0.20, 0.30, and 0.50 m. The time series of integrated profile soil moisture at each site was obtained by assigning depth ranges to each sensor, with the boundaries of each layer delineated at the midpoint between successive sensors.

2.2.4. Plant Area Index

Plant area index (*PAI*, m^3 m^{-3}) estimates were obtained using a plant canopy analyzer (LAI-2000 or LAI 2200, Li-Cor, Lincoln, NE) at both sites at irregular time intervals over the course of the study. Note that the lowest rings of the LAI-2000 and LAI-2200 were masked to minimize the contributions of tree stems and branches. Emphasis was placed on sampling *PAI* frequently during leaf shedding and flushing periods, and periodically throughout the year to approximate the annual cycle of foliage accumulation and loss throughout the study period. Data were collected at a height of approximately 1.2 m above the ground and at 6 m intervals at Som Sanuk and 5 m intervals at CRRI along transects oriented diagonally with respect to tree rows; the interval was selected as 1 m less than the row separation, which with the diagonal transect, resulted in even sampling across the planting rows. In addition, at Som Sanuk only, daily *PAI* was estimated based on measurements of photosynthetically active radiation above (PAR_A) and below (at 2 m above the ground) the canopy (PAR_B). PAR_A was estimated using the relationship between solar radiation (CNR1, Kipp, and Zonen) and PAR (LI-190, LI-COR, Lincoln NE) for the period when the PAR sensor was less than 1 month old, before significant calibration drift occurred. PAR_B was measured with a line quantum sensor (model SQ-321, Apogee Instruments, Logan, UT, USA). In homogeneous vegetation, *PAI* can be estimated using a relationship derived from the Beer-Lambert Law [*Monsi and Saeki*, 1953, 2005; *Law and Waring*, 1994]:

$$PAI = -\frac{\ln\left(\frac{PAR_B}{PAR_A}\right)}{k} \tag{1}$$

where the extinction coefficient $k = G/cos(\beta)$, G is the leaf inclination distribution function, defined as the cosine of the angle between the solar zenith and the normal to the mean leaf orientation, and β is the solar zenith angle. To mitigate foliar clumping effects [*Ryu et al*., 2010], only periods when the solar zenith angle was near one radian were used. Thus, for each day, one morning and one afternoon sample were averaged. Because *PAI* estimates derived from this method are affected by variations in diffuse light content due to cloud cover, wet season values are considered to be more uncertain than dry season values. Note that *PAI* measurements exclude understory vegetation, which was very sparse at Som Sanuk and substantial at CRRI (see supporting information Figure S1).

To develop a continuous time series of *PAI* at each site, points between measurements were estimated based on LAI2000 and LAI2200 measurements for the same time of year in previous or later years, variations in albedo, *PAI* estimates derived from the ratio of below to above-canopy PAR measurements (at Som Sanuk only), and visual observations; the time series lines were smoothed using a cubic spline.

2.2.5. Soil Heat Flux

The 30 min time series of soil heat storage (G, W m^{-2}) was calculated from the output of four plates (model HFP01, Hukseflux) placed at a depth of 0.08 m, the averaged soil temperatures (T_{soil}, K) of two 4-probe sensors (model TCAV, Campbell Scientific) installed at depths of 0.02 and 0.06 m, and the volumetric soil moisture of one horizontally oriented reflectometer (CS-616, Campbell Scientific) at a depth of 0.04 m. The variable G represents the sum of soil heat flux at 0.08 m (F) and heat storage in the 0.08 m soil layer above the heat flux plates (M), which are given as:

$$\mathrm{G} = \mathrm{F} + \mathrm{M} \tag{2}$$

$$F = \frac{SHF_1 + SHF_2 + SHF_3 + SHF_4}{4} \tag{3}$$

$$M = \frac{dT_{soil}}{dt} D(\rho_b C_s + \rho_w \theta C_w) \tag{4}$$

where SHF_j is the soil heat flux (W m^{-2}) measured at 0.08 m depth by sensor j, dT_{soil} is the change in temperature in the upper 0.08 m soil layer (K) during the time interval dt (1800 s), D is the depth of soil heat flux plates (0.08 m), ρ_b is site-specific soil bulk density of the upper 0.08 m of soil (kg m^{-3}), C_S is the specific heat for mineral soil (840 J kg^{-1} K^{-1}), ρ_w is the density of water (approximated as 1000 kg m^{-3}), θ is the volumetric soil moisture content of the upper 0.08 m soil layer, assumed equal to the 0.04 m horizontal soil moisture sensor value ($m^3\ m^{-3}$), and C_W is the specific heat of water (4186 J $kg^{-1}\ K^{-1}$). Site-specific ρ_b was determined to be 1295 kg m^{-3} at Som Sanuk and 1138 kg m^{-3} at CRRI, based on the average oven-dry mass of eight and six samples of known volume at Som Sanuk and CRRI, respectively.

2.2.6. Biomass and Air Layer Heat Storage

The 30 min time series of sensible heat storage in the biomass is a function of temporal change in temperature, mass, and specific heat of each major component of the above ground biomass of the rubber trees:

$$S_{bio} = \sum \frac{dT_{bio\_i}}{dt}(C_i BM_i) \tag{5}$$

where S_{bio} is the change in sensible heat stored in the biomass per unit ground area (W m^{-2}), i indicates the different components of the aboveground biomass (main stems, branches, and leaves), dT_{bio_i} is the change in temperature of biomass component i (K) during the time interval, dt (1800 s), C_i is the specific heat of biomass component i (J $kg^{-1}\ K^{-1}$); and BM_i is the fresh biomass (including water content) of component i (kg m^{-2}). Details of the biomass energy storage estimates are given in supporting information Text S5.

The change in stored energy in the air layer under the EC sensors (S_{air}; W m^{-2}) was estimated, including changes in stored sensible and latent heat (S_{air_h} and S_{air_LE}, respectively). S_{air_h} was estimated from field measurements of T_a using shielded thermocouples at heights of 3, 9, and 15 m on the tower at Som Sanuk; and at heights of 3, 5, and 7 m on the tower at CRRI, and the temperature sensors (HMP45C) at the top of each tower. No humidity measurements were made within the canopy; therefore, the top-of-tower HMP45C humidity time series was used as an approximation. For each 30 min period, the change in stored energy was estimated as

$$S_{air} = S_{air\_h} + S_{air\_LE} \tag{6}$$

$$S_{air\_h} = z\frac{dT_a}{dt}\left[\left(C_p \rho_{dry\_air}\right) + (C_{wv} q)\right] \tag{7}$$

$$S_{air\_LE} = z\frac{dq}{dt}\lambda \tag{8}$$

where z is the depth of the air layer (27 m at Som Sanuk and 30.1 m at CRRI), dT_a is change in mean air layer temperature (K) during the time interval dt (1800 s), C_p is specific heat of dry air at constant pressure (1004 J $kg^{-1}\ K^{-1}$), ρ_{dry_air} is the dry air density (kg m^{-3}), C_{wv} is the specific heat of water vapor (J $kg^{-1}\ K^{-1}$), q is the water vapor density (kg m^{-3}), and λ is the latent heat of vaporization (J kg^{-1}), estimated as a function of air temperature.

2.2.7. Gap Filling

Data gaps created by missing observations and filtering of data during quality control procedures, e.g., removal of poor quality data associated with wet sensor conditions, lead to problems in data analysis and aggregation. For example, because of the pronounced diurnal cycle in most variables, averaging the remaining values in a time series with many gaps can produce severely biased results. Therefore, it is preferable to implement gap-filling techniques, in which missing values are replaced with estimates to produce a time series as close to serially complete as possible [*Falge et al*., 2001]. The 30 min time series of *LE* and *H* flux for each site were gap-filled using regressions of each flux variable with available energy ($A = R_n - G - S_{bio} - S_{air}$). Initially, one regression was performed for each month of the year, combining data for the same month in different years. Subsequently, months with very similar relationships were merged. For Som Sanuk, grouping resulted in five "seasons": January, February, March–October, November, and December. For CRRI, six separate seasons were used: January, February, March, April, May–November, and December. For all instances of a missing value of *LE* or *H*, during a time interval when *A* was available, the estimated value derived from the appropriate regression was substituted to fill the gap. This procedure increased the number of 30 min *LE* estimates from 34,249 to 37,301 at Som Sanuk, raising the proportion of data available from 83.7 to 91.2%, and from 35,228 to 37,743 at CRRI, increasing available data from 86.0 to 92.2%. Gap-filled data were used to calculate the mean of each 30 min period in each month, from which monthly means (or sums) were obtained. Monthly means were used to calculate annual values.

2.2.8. Energy Closure Adjustment

As a test of eddy covariance flux estimates, energy balance closure is commonly evaluated by comparing the sum of estimated turbulent fluxes ($LE + H$) to the available energy (A). For most eddy covariance sites,

$LE + H$ is less than A. For example, at most tropical forest flux tower sites in the Large-Scale Biosphere Atmosphere Experiment (LBA) in Amazonia, energy closure error was in the 20–30% range [*Fisher et al.*, 2009]. While much has been written about the numerous possible sources of energy closure error [*Twine et al.*, 2000; *Wilson et al.*, 2002; *Fisher et al.*, 2009; *Franssen et al.*, 2010; *Leuning et al.*, 2012], it is widely assumed that energy closure error results from underestimation of both LE and H rather than an overestimate of A. Further, it is sometimes assumed that despite underestimation of LE and H, the ratio of H to LE (Bowen ratio) is correctly estimated. This assumption gives rise to the use of the so-called Bowen ratio closure method recommended by *Twine et al.* [2000], in which LE and H are each adjusted by a factor of the inverse of the energy closure ratio to force energy closure. *Kochendorfer et al.* [2012] suggests that a significant source of underestimation of LE and H can be traced to a systematic bias in vertical wind speed measurements from sonic anemometers [also see *Nakai and Shimoyama*, 2012], a finding that supports the use of the Bowen ratio closure method.

Energy balance closure can be evaluated in terms of the ratio of the sum of turbulent fluxes ($LE + H$) to the available energy (A). If assessed at each 30 min time interval, this ratio is very noisy and, therefore, time averaging is needed to smooth it for use in adjusting flux data to force energy closure. At each 30 min time step (i), a centered 1000.5 h (2001 30 min intervals) moving window energy closure ratio (ECR_i) was calculated as:

$$ECR_i = \frac{\frac{\sum_{k=i-1000}^{k=i+1000} LE_k + H_k}{2001}}{\frac{\sum_{k=i-1000}^{k=i+1000} A_k}{2001}} \tag{9}$$

To achieve approximate energy closure, the values of LE and H were adjusted at each time step by a factor of ECR_i^{-1}. The results for LE and H are subsequently summarized with and without the energy closure adjustment.

2.3. Evapotranspiration Response to Environmental Demand

Variations in *ET* are driven, in part, by fluctuating environmental demand, which can be quantified in terms of potential evapotranspiration. To better understand the mechanisms controlling the response of rubber *ET* to environmental demand, as influenced by factors such as soil moisture and leaf phenology, we compared measured *ET* with potential ET at each site.

2.3.1. Analysis of Midday Rain-Free Periods

The response of rubber *ET* to variations in atmospheric demand was analyzed using a subset of data comprised of midday (09:30-14:00 local time), rain-free periods. This allowed us to focus on periods that are most strongly controlled by the physiological traits of rubber trees, i.e., mostly high solar radiation and dry-canopy conditions [see *Kumagai et al.*, 2015].

2.3.2. Potential Evapotranspiration

Evaluation of variations in observed *ET* includes comparison with potential evapotranspiration derived using the Penman-Monteith equation [*Monteith*, 1965] with surface conductance set to infinity:

$$LE_{pot} = \frac{sA}{s + \gamma} + \frac{\rho_a C_p G_a VPD}{s + \gamma} \tag{10}$$

where LE_{pot} is the latent energy flux equivalent of potential *ET* (W m^{-2}), s is slope of saturation vapor pressure versus temperature curve (kPa K^{-1}), A is available energy (W m^{-2}), ρ_a is air density (kg m^{-3}), C_p is specific heat of air at constant pressure (J K^{-1} kg^{-1}), G_a is aerodynamic conductance (m s^{-1}) estimated as u_*^2/u, where u_* is the friction velocity (m s^{-1}), and u is wind speed (m s^{-1}) VPD is vapor pressure deficit (kPa), and γ is the psychrometric constant (kPa K^{-1}). In the form shown (equation (10)), the two terms on the right can be referred to as the energy term (LE_{pot_energy}) and the aerodynamic term ($LE_{pot\_aerodynamic}$), respectively. LE_{pot} and the two component terms were calculated for the midday rain-free periods and analyzed in comparison with observed LE for the same time periods.

2.3.3. Surface Conductance

By inverting the Penman-Monteith equation, surface conductance (G_s; m s^{-1}) can be calculated as:

$$G_s = \frac{G_A \gamma LE}{sA + \rho_a C_p G_a VPD - (s + \gamma) LE} \tag{10}$$

where LE is derived from the eddy covariance measurements. G_s was calculated for the midday rain-free periods for both sites.

2.4. Comparison with Estimates Extracted from Global *ET* Analysis

Mueller et al. [2013] mapped the global distribution of *ET* derived from a synthesis of 1985–2005 satellite-based estimates, in situ observations, and estimates from land-surface models. For the locations of our two study sites and the Xishuangbanna site [*Tan et al*., 2011], the 1989–2005 annual *ET* statistics were extracted for the relevant 1°× 1° grid cells. The mapped estimates pertain to the dominant land covers, not necessarily rubber, and therefore offer a means of evaluating *ET* of rubber in relation to that of the typical existing land covers surrounding each study site.

3. Results

3.1. Hydrometeorological Variables

The climate regimes of the two sites have similar characteristics (Figure 1). However, some differences are evident in the measured variables, reflecting the geographical contrasts in latitude and continentality. At both sites, the highly seasonal climate of the Asian Monsoon region is clearly evident in the annual cycles of rainfall, soil moisture, and VPD. The annual range of mean daily temperature is greater than 15°C at the more continental Som Sanuk site, and less than 10°C at CRRI; temperature minima are experienced early in the dry season (∼14–15 and ∼22–24°C at Som Sanuk and CRRI, respectively); maxima occur near the end of the dry season (∼31–33°C at Som Sanuk and ∼30–32°C at CRRI). With its more equatorward location, CRRI generally has higher net radiation than Som Sanuk. On relatively clear days, net radiation follows the annual course of sun angle at both sites. Cloudiness causes more day-to-day variability and attenuates average net radiation during the wet season. Monthly mean net radiation is lowest in December and January (∼100 and ∼130 W m^{-2} at Som Sanuk and CRRI, respectively) and high during April through September (∼140 W m^{-2} at Som Sanuk and ∼160 W m^{-2} at CRRI). Soil moisture variation at the two sites is responsive to the highly seasonal rainfall regime. However, while the deep layers at Som Sanuk responded rapidly to the initiation of rains marking the start of the wet season, with the wetting front reaching below 2 m depth by late May in both study years, soil moisture during 2010 remained near minimum values below 2 m depth at CRRI until late in August.

3.2. PAI

At Som Sanuk, *PAI* reached a maximum of about 5 from July to September, while the annual maximum value increased at CRRI from just over 4 in 2010 to about 4.9 in 2011, 2012, and 2013 (Figure 2). At both sites, for each year, leaf abscission significantly increased around the beginning of January. *PAI* reached a minimum in mid to late January, followed a sharp increase caused by rapid leaf flushing from around the end of January into February. Note that total *PAI* is higher at CRRI than shown in Figure 2 because of the relatively dense understory there (see supporting information Figure S1).

3.3. Energy Balance Closure

The slope and r^2 values of the regression lines for 30 min A versus $LE+H$ (0.84 and 0.92, respectively, at Som Sanuk, and 0.83 and 0.90, respectively, at CRRI; see supporting information Figure S2) indicate reasonably good results, well within the upper half of the range of values achieved at 22 FLUXNET sites: slope: 0.55–0.99; r^2: 0.64–0.96 [*Wilson et al*., 2002]. The ratio of mean annual $LE+H$ to mean annual A was 0.94 for Som Sanuk and 0.88 for CRRI. However, energy closure varied temporally at each site, with ECR_i (see equation (9)) from 0.825 to 1.025 at Som Sanuk and from 0.786 to 0.974 at CRRI. Variations in ECR_i were not strongly related to environmental variables T_a, RH, WS, WD, SM_z, A, LE, or H (max $r^2=0.07$ for $SM_{6\text{-}34\ cm}$ at Som Sanuk; max $r^2=0.04$ for T_a at CRRI).

3.4. Energy Partitioning

The monthly mean diurnal cycles of *LE* and *H* (Figure 3) illustrate the annual cycle in the relative magnitudes of the two variables, with *LE* much higher than *H* through all months except November–February at Som Sanuk and all months except December–March/April at CRRI, periods affected by dry soil and leaf shedding. The Bowen ratio (*H/LE*) remains between about 0.20 and 0.33 during May–October at Som Sanuk, then rises to a January peak of 2.27 (2010) and 3.50 (2011), before dropping rapidly to wet season values. At CRRI, the Bowen ratio is in the 0.17–0.33 range from May to December, rises to 0.80, 1.1, and 1.1 in January 2009, February 2010, and February 2011, respectively.