Hydrologic effects of the expansion of rubber (*Hevea brasiliensis*) in a tropical catchment

Maite Guardiola-Claramonte,[1]* Peter A. Troch,[1] Alan D. Ziegler,[2] Thomas W. Giambelluca,[3] Matej Durcik,[1] John B. Vogler[4] and Michael A. Nullet[3]

[1] *Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ, USA*
[2] *Geography Department, National University of Singapore, Singapore, Singapore*
[3] *Geography Department, University of Hawai'i at Mānoa, Honolulu, HI, USA*
[4] *University of North Carolina, Charlotte, NC, USA*

ABSTRACT

This study investigates basin-scale hydrologic implications of the replacement of forest-dominated land cover by rubber plantations in Montane Mainland Southeast Asia. The paper presents a new method for estimating the water demand of rubber and consequently water losses to the atmosphere through rubber evapotranspiration (ET). In this paper we argue that rubber ET is energy-limited during the wet season, but during the dry season water consumption is mostly governed by environmental variables that directly affect rubber phenology, namely, vapour pressure deficit, temperature and photoperiodicity. The proposed ET model is introduced into a hillslope-based hydrologic model to predict the basin-scale hydrologic consequences of rubber replacing native vegetation. Simulations suggest greater annual catchment water losses through ET from rubber dominated landscapes compared to traditional vegetation cover. This additional water use reduces discharge from the basin, or its storage. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS   rubber (*Hevea brasiliensis*); phenology; evapotranspiration; land use change; crop factor; China

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INTRODUCTION

Rubber (*Hevea brasiliensis*) seedlings, known as 'Wickham base', were introduced to Singapore and Ceylon from Amazonia in 1877 (Priyadarshan *et al.*, 2005). Since then rubber has expanded throughout all of South and Southeast Asia, where it is now grown in countries such as Indonesia, India, Malaysia, China, Vietnam, Philippines, Myanmar, Bangladesh, Cambodia, and Thailand. Since the early 1980s, rubber research institutions have studied productivity and adaptability of *Hevea* clones to relatively cold and dry environments (Gururaja Rao *et al.*, 1990; Vijayakumar *et al.*, 1998; Priyadarshan *et al.*, 2001). Clones are now adapted to overcoming dry periods and lower temperatures without important loss of latex yield (Chandrashekar *et al.*, 1998; Rodrigo, 2007). Using new genotypes, rubber plantations have now expanded to 27°N latitude and up to 1100 m in elevation (Priyadarshan *et al.*, 2005), well beyond the native environment of 10°N/S of the equator and 400 m above mean sea level (AMSL) (Priyadarshan *et al.*, 2005).

Rubber was first introduced in South China (including Xishuangbanna, Yunnan province) in the early 1950s (Chapman, 1991). At that time rubber replaced large extensions of tropical rain forest occurring naturally below 800 m (Li *et al.*, 2007). The increase in rubber plantations at lower elevations shifted agricultural activities to higher elevations (Li *et al.*, 2007). In recent years, the use of cold resistant rubber clones have been substituting rain forest that grows up to 1100 m in elevation (Shanmughavel *et al.*, 2001; Li *et al.*, 2007, 2008), expanding the rubber plantations and the agricultural lands to higher elevations. Currently there are more than 400 000 ha of rubber in Xishuangbanna (Qiu, 2009) and over 500 000 ha throughout Montane Mainland Southeast Asia (MMSEA) (Ziegler *et al.*, 2009b).

Despite the large extension of land covered by rubber, the environmental and socioeconomics impacts of rubber expansion have only recently been explored at various scales (Xu *et al.*, 2005; Liu *et al.*, 2006; Li *et al.*, 2007, 2008). It is now recognized that land-cover transitions to rubber monocultures may result in significant losses of aboveground (Bunker *et al.*, 2005) and belowground (Guo and Gifford, 2002) carbon stocks and biodiversity (Li *et al.*, 2008; Ziegler *et al.*, 2009a, b). Vegetation dynamics, as well as possible differences in growth rates, leaf turnover and decomposition rates of rubber, might induce changes in carbon stocks and carbon exchange rates. Furthermore, the methods of plantation management for rubber (land terracing, control of understory growth, etc.) and harvesting (latex extraction) may further alter carbon dynamics in ways that are currently unknown.

* Correspondence to: Maite Guardiola-Claramonte, Department of Hydrology and Water Resources, University of Arizona, 1133 E. James E Rogers Way, Tucson, AZ 85721, USA.
E-mail: maite.guardiola@gmail.com

Table I. Parameter values used for the K_{rubber}.

	Temperature[a] (°C)	Vapour pressure deficit[b] (kPa)	Photoperiod[a] (h)
Maximum	28	3·5	11
Minimum	10	1·2	10

[a] Derived from Priyadarshan and Clément-Demange (2004).
[b] Derived from Priyadarshan (2003).

With respect to hydrology, rubber is blamed to be the cause of the dramatic downward trend in fog frequency between the mid-1950s and the mid-1980s (Liu, 1990; cited in Wu *et al.*, 2001). Wu *et al.* (2001) showed that surface runoff increased by a factor of three, and soil erosion increases by a factor of 45 as a result of conversion from tropical forest to monoculture rubber in Xishuangbanna. With regard to rubber water consumption, extensive field observations in Xishuangbanna suggest that rubber is depleting the subsurface water resources, as significant deep root water uptake occurs during leave flushing coinciding with the driest and hottest period of the year (Guardiola-Claramonte *et al.*, 2008). In addition, rubber trees have been referred to as 'water pumps', as they are associated with water depletion in the basins where they are grown (Qiu, 2009). However, more research is needed to verify these claims and to fully understand the hydrological consequences of extensive land-cover conversion to rubber at basin scale (Monteny *et al.*, 1985; Gururaja Rao *et al.*, 1990; Sen *et al.*, in progress; Ziegler *et al.*, 2009b).

In this paper we first develop a new model to estimate rubber evapotranspiration (ET) by accounting for observed patterns of rubber root water uptake as affected by plant's phenology. In particular, the method considers vegetation dynamics and corresponding water needs (evaporative demand). The proposed method is next introduced into a basin-scale hydrologic model to assess and quantify the hydrological impacts of rubber expansion at scales beyond the stand level.

TRADITIONAL APPROACH TO ESTIMATE ET

Water losses through ET constitute a major component in the water cycle, mostly determined by available energy, water (through soil moisture or groundwater), the drying power of the air, land cover and vegetation characteristics. In humid tropical sites, when enough soil moisture is available, ET is mostly limited by atmospheric demand, with net radiation being the strongest driver for ET (Fisher *et al.*, 2009). Conversely, during water limited conditions, plants show different strategies to regulate water use, mostly through stomata regulation that is triggered by atmospheric vapour pressure deficit (VPD), temperature and radiation.

Hydrologic models simulate atmospheric water demand using equations such as Penman–Monteith (Monteith *et al.*, 1965) to calculate maximum, unstressed ET (ET_{max}, commonly referred to as potential ET). ET_{max} is usually calculated either neglecting stomatal/canopy resistance, r_c, (suggesting open water or wet canopy evaporation), or assuming a minimal value of canopy stomatal resistance to represent a known crop or vegetation type. These equations perform best when estimating latent heat flux during periods when water availability is not limiting. During dry periods, when vegetation reduces water consumption by either closing its stomata or shedding its leaves, maximum ET can be adjusted by either considering variable stomata conductance explicitly (Stewart, 1988), or by modifying ET_{max} by factors (often referred as crop factors) that reflect changes in soil water availability (f_θ in Equation (1)) (Thornthwaite and Mather, 1955; Teuling *et al.*, 2007; Vivoni *et al.*, 2008) or changes in leaf cover (f_{vi} in Equation (1)), such as Leaf Area Index (LAI) or normalized vegetation index (NDVI) (Vivoni *et al.*, 2008) used as surrogate measures of the dynamics of vegetation cover, i.e. by setting ET_a, the actual ET to be:

$$ET_a = ET_{max} f_\theta f_{vi} \qquad (1)$$

This is a traditional approach, but it only represents different vegetation dynamics by means of LAI variations, and assumes that ET is always directly related to soil moisture. However, it does not properly represent rubber ET, because it neglects the increased water use during the dry season when both soil water content and canopy cover are minimal (Guardiola-Claramonte *et al.*, 2008). Consequently, in an effort to better represent rubber plant water uptake we seek to define rubber plant water needs in terms of plant phenology.

RUBBER PHENOLOGY AND WATER NEEDS

Rubber is a (brevi-)deciduous tree because it sheds its leaves for a short 2 to 4-week period but retains full foliage throughout the rest of the year. Rubber trees undergo highly synchronous shedding that has been associated with photoperiod (day length), with complete abscission of leaves occurring around the equinox (Guardiola-Claramonte *et al.*, 2008). Leaf flushing in rubber trees happen at the midst of the hottest and driest period in Xishuangbanna, weeks before the arrival of the rainy season. Flushing leaves during the dry season imply that the tree must have access to sufficient reserves of water for the following leaf expansion (Elliot *et al.*, 2006; Williams *et al.*, 2008). Guardiola-Claramonte *et al.* (2008) used extensive field observations of root zone soil moisture to show that significant deep root water uptake takes place during leave flushing of rubber trees. While shedding reduces transpiration (Priyadarshan and Clément-Demange, 2004), simultaneous root water uptake increases stem water potential that is needed for subsequent leaf flushing. Importantly, the water is extracted from the soil column (i.e. basin storage), but is not released to the atmosphere until new

foliage is grown. Rubber, as a deciduous tree, has therefore a very different phenology to the native vegetation which is mostly evergreen.

The brevi-deciduous response of rubber (i.e. short shedding, and subsequent flushing during the hottest and driest season) is common in drier seasonal tropical forest of Thailand (Williams *et al.*, 2008) and the Indian monsoon forest (Elliot *et al.*, 2006), but has not yet been reported for the moister rainforests in Xishuangbanna. In the Thai forests', deciduous trees show a wide range of leaf exchange patterns with most species partially flushing their leaves during the late dry season (Elliot *et al.*, 2006; Williams *et al.*, 2008). It is believed that trees will show different phenology depending on the local water balance during the dry season, with the degree of deciduousness increasing with rising water stress (Elliot *et al.*, 2006; Yoshifuji *et al.*, 2006). Leaf abscission in these dry forests has also been associated either with photoperiod or the start of the rainy season (Elliot *et al.*, 2006; Williams *et al.*, 2008), similar to the leaf shedding of rubber trees (Guardiola-Claramonte *et al.*, 2008). A common characteristic for these deciduous tropical forests (and also rubber) is the high degree of synchronicity that seems to arise when leaves shed for short periods of time.

In summary, rubber is a (brevi-)deciduous tree that has now replaced mostly evergreen vegetation in the basin, which shows strong synchronicity for flushing and shedding, with important root water uptake associated with these two processes.

ESTIMATING RUBBER ET

The scientific community has given little attention to parameterizing rubber ET (Monteny *et al.*, 1985) or quantifying the basin-scale hydrological implications of the extensive conversion of native vegetation to rubber monoculture (Gururaja Rao *et al.*, 1990; Monteny *et al.*, 1985). Rodrigo *et al.* (2005) developed a model to compute rubber boundary layer conductance based on LAI and wind speed as a first step towards estimating rubber ET. While the model improved estimates of rubber ET with the Penman–Monteith equation, the authors state that the model would perform better if phenological information would be added (Rodrigo *et al.*, 2005).

Recently, some land surface models have introduced phenology information in an attempt to better predict vegetation dynamics and their interactions with climate (Foley *et al.*, 1998). A recent study by Jolly *et al.* (2005) proposed a generalized, bioclimatic index that depends on minimum temperature, VPD and photoperiod to predict foliar phenology. A similar approach was already used by Stewart in 1988 to estimate changes in surface conductance for ET estimation within different ecosystems. The Jarvis–Stewart conductance model (Stewart, 1988) relates temperature, VPD, radiation, and soil moisture to canopy/stomatal conductance (the inverse of r_c). In a similar context, the phenology variables such as minimum temperature, VPD and photoperiod have been used to

adjust stomata conductance to better represent mesquite ET in a riparian ecosystem (Serrat-Capdevila *et al.*, in review) with satisfactory results.

We propose using a factor (K) that depends on these three phenology variables as they have already shown to correlate with ET, and water demand and have, therefore, the potential to improve ET estimates for different vegetation types and climate conditions. Herein, we propose the phenology coefficient, that depends on phenology ($K_{phenology}$) to estimate ET (ET_{rubber}) as follows:

$$ET_{rubber} = ET_{max}K_{phenology}$$

$$K_{phenology} = f_T f_{VPD} f_{DL} \qquad (2)$$

and f_T, f_D, and f_{DL} are ET reduction functions associated with the three environmental variables ($f = 1$ when the vegetation is fully active and $f = 0$ when inactive; Thornthwaite and Mather, 1955). Applying the $K_{phenology}$ to directly modify ET_{max} avoids the need for stomata conductance measurements. Extensive research on rubber trees has shown dependence of rubber yields on the $K_{phenology}$ environmental variables (Priyadarshan, 2003), and strong relationships between rubber yield and ET (Priyadarshan and Clément-Demange, 2004). Therefore, we hypothesize that the same environmental conditions also inform the rubber's water consumption and we can define the K_{rubber} to estimate its water demand. A similar concept to the phenology coefficient is the crop coefficients, used to extensively in agriculture to adjust maximum ET for a specific crop (Allen *et al.*, 1998).

The ET reduction functions in Equation (2) are represented by linear ramp functions controlled by minimum and maximum bounds. These parameters of the ramp functions are chosen from literature reviews, as well as from extensive field observations (Guardiola-Claramonte *et al.*, 2008) to fit the specific water demand for rubber (Figure 1 and Table 1):

- Temperature (T): *Hevea* trees suffer cold damage when temperatures fall below 5 °C or remain below 10 °C for a prolonged period of time. On the other hand, rubber yield reduces when temperatures are above 28 °C. Assuming that changes in rubber yield and ET are triggered by the same temperature thresholds (Priyadarshan and Clément-Demange, 2004), we propose minimum and maximum bounds of 10 °C and 28 °C (Priyadarshan *et al.*, 2001).
- Vapor Pressure Defect (VPD): Rubber closes its stomata when VPD rises above 3·5 kPa, with the largest latex flow occurring when deficit is below 1·2 kPa (Priyadarshan, 2003). As the stomata close, transpiration is reduced, thus ET is inversely proportional to VPD between values of 1·2 and 3·5 kPa.
- Photoperiod or daylength E (DL): *Hevea* needs sunny environments with 2000 h of sunshine per year (with at least 6 h/day in all months) (Priyadarshan, 2003). We use the values of active and non-active vegetation suggested by Jolly *et al.* (2005), in which the lower bound
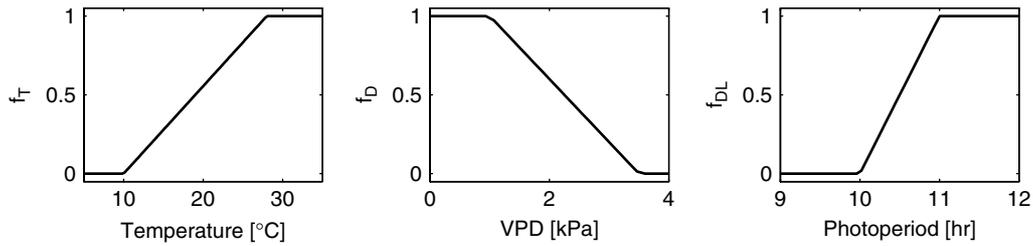
Figure 1. Stress functions for the three environmental variables used in the k_{rubber} to protect rubber phenology, temperature, vapor pressure deficit and photoperiod or daylength.

also corresponds to the day length during the spring equinox. According to the proposed photoperiod index, vegetation starts to become active when day length is longer than 10 h, and is fully active for days of 11 h sunshine or more. These bounds are confirmed with albedo observations in a rubber plantation (Guardiola-Claramonte *et al.*, 2008).

It is important to recognize that our model for estimating ET of rubber trees does not depend on LAI or NDVI, which are manifestations of vegetation responses to different environmental stresses rather than a driver of vegetation dynamics. These vegetation indices might be proposed as a surrogate for the purpose of calibrate K_{rubber}. However for some parts of the year rubber tree water demand is not related to either LAI or NDVI, because root water uptake has been observed during rubber shedding when LAI is minimal (Guardiola-Claramonte *et al.*, 2008). In addition, K_{rubber} does not include soil moisture as one of the environmental stressors that affects vegetation dynamics, given that flushing of new leaves occurs in the midst of the driest and hottest season. Instead, we assume that enough water is available either in the surface soil layers or in deeper layers, as was observed in Xishuangbanna (Guardiola-Claramonte *et al.*, 2008).

EXPERIMENT SITES

Our study uses hydrological and meteorological data collected at two experimental sites in MMSEA: (1) Nam Ken (Xishuangbanna, China), where rubber expansion is now occurring but where only limited hydro-meteorological data were recorded between 2004 and 2008; and (2) Pang Khum experimental watershed (PKEW) in northern Thailand, where hydro-meteorological data have been collected since 1996. Measurements at Nam Ken are used to characterize rubber phenology and verify the K_{rubber} and subsequently ET_{rubber} (Equation (2)). The long time series of hydrological data collected in PKEW are used for calibration and validation of the catchment-scale hydrological model to study the hydrological implications of land-cover conversion to rubber.

Nam Ken (69 km^2) is located in the Chinese prefecture of Xishuangbanna (22°N, 101 °E), next to the Myanmar border (Figure 2). The elevation in the basin ranges from 800 m to over 2000 m AMSL, and mean

Figure 2. Location of the experimental catchments Nam Ken and PKEW in the SEA region.

annual precipitation and temperature are 1380 mm and 20 °C, respectively. Nam Ken is characterized by a monsoon-dominated climate, where most of the precipitation falls between May and October. During the dry season monthly precipitation usually is below 50 mm/month and often absent. Rubber was introduced at low elevation areas in the late 1970s. With the development of lower temperature resistant clones, rubber has been planted up to 1100-m AMSL, covering by 2005 about 16% of the total basin area. Rubber expansion has occurred largely at the expense of traditional agriculture and forest. A micrometeorological station was installed in a 15-years-old rubber plantation in May 2004 and removed in February 2007. Measurements of four radiation components (incoming shortwave and long wave radiation, reflected shortwave radiation and emitted long wave radiation), wind speed, air temperature, relative humidity, and precipitation above the canopy were recorded hourly at this site. In addition, soil heat flux was measured at the soil surface together with soil moisture at three different depths (surface, 1 and 2-m depth). Albedo is defined as the ratio of reflected to incoming shortwave radiation. Daily albedo values are calculated by averaging the hourly radiation from 10:00 to 14:00 local time.

Detailed soil characterization showed rubber tree roots concentrated mostly within the first 1·1 m, but roots have been observed throughout the 2·25-m soil profile. For further information about Nam Ken please refer to Guardiola-Claramonte *et al.* (2008).

PKEW (93 ha) is located near the village of Pang Khum (19°03′N, 98°39′E), in Chiang Mai province, Thailand (Figure 2). Characterized by a monsoon-type of climate, PKEW receives over 90% of the total annual precipitation (1200–1300 mm) between mid-May and October. The basin has been continuously monitored since 1996 for energy and water fluxes with two micrometeorological towers measuring precipitation, air temperature, relative humidity, incoming and reflected radiation, and wind speed. We used data from 1998 to 2005 (8 years). For this period of time, soil moisture has also been measured at three different depths (surface, 1 and 2 m) in several locations. The basin presents a mosaic of agriculture fields, fallow fields and secondary forest. PKEW basin, with 8 years of hydrologic forcing data, stream flow, and detailed soil and vegetation characterizations, constitutes an ideal reference basin to calibrate hydrologic models for tropical catchments, prior to the expansion of rubber in the region. There are numerous publications using PKEW data. Among the most relevant for further details about the basin please refer to the following ones: Giambelluca, 1996; Giambelluca *et al.* 1996; Ziegler and Giambelluca, 1997; Ziegler *et al.* 2000, 2001, 2004; Cuo *et al.*, 2006.

Time series of LAI and surface reflectance for Nam Ken rubber and forest were downloaded from NASA's (National Aeronautics and Space Administration) MODerate resolution Imaging Spectroradiometer (MODIS) Land Products MOD15A2 and MOD09A1. MOD15A2 measures LAI composites every 8 days at 1-km resolution; MOD09A1 provides an estimate of the surface spectral reflectance from Bands 1–7 at 500-m resolution at 8-day resolution. The spectral reflectance from MOD09A1 is similar to surface spectral reflectance as it would be measured at ground level in the absence of atmospheric scattering or absorption. The images were filtered and only high quality and cloud-free images were selected for analysis. After filtering, to fill gaps in the time series, a piecewise cubic Hermite interpolation interval with a 1 day time step was used to derive a continuous

data series of LAI and surface reflectance. Annual average LAI series for PKEW and Nam Ken were derived by averaging daily values for 9 years of data (Figure 3). Surface reflectance was used to calculate NDVI (Huete *et al.*, 2002).

HILLSLOPE-STORAGE BOUSSINESQ SOIL MOISTURE HYDROLOGIC MODEL

The hillslope-storage Boussinesq soil moisture model (hsB-sm) solves the energy and water balance of the root zone, computes saturated subsurface flow from all hillslopes of a catchment, and allows return flow generating saturation excess overland flow. Vertical exchange fluxes (groundwater recharge and capillary rise) between the root zone and the groundwater table are derived from a parametrization based on the steady-state Darcy equation (Bogaart *et al.*, 2008). Subsurface flow and groundwater table dynamics are computed using the hillslope-storage Bousinesq equation (Paniconi *et al.*, 2003; Troch *et al.*, 2003). These simplifications allow the model to be computationally efficient, and yet physically based. Maximum ET is computed using the Penman–Monteith equation for a coniferous type of vegetation. Actual ET values depend on root zone soil moisture conditions as well as root fraction and LAI (Teuling and Troch, 2005). This traditional approach (Equation (1)) uses a ET reduction function which parameters are saturated water content (θ_{sat}), critical water content (θ_c) and wilting point (θ_w) (Table II). To introduce the phenology coefficient into the

Table II. Major HsB-SM parameter values used for all the baseline simulations in PKEW.

Soil	Vegetation
$K_{sat} = 35$ cm/day[a]	Root zone depth: 1 m
$\theta_{residual} = 0 \cdot 1$[b]	Vegetation height: 4·2 m
$\theta_{saturated} = 0 \cdot 37$	Light efficiency: 0·3
$\theta_{critical} = 0 \cdot 21$	Root fraction: 0·4
$\theta_{wilt} = 0 \cdot 11$	
Total soil depth: 4 m	
Drainable porosity: 0·3	

[a] The hydraulic conductivity within the root zone is assumed to be equal to K_{sat}, but the value decreases with depth below the root zone, where the horizontal hydraulic conductivity of the Bousinesq aquifer decreases exponentially with depth.
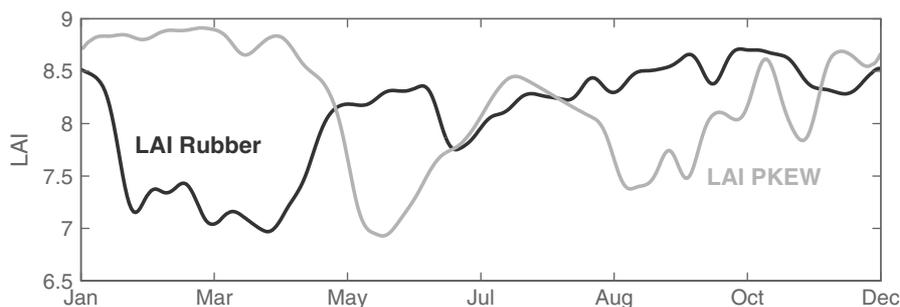[b] θ volumetric water content.

Figure 3. Nine-year (2000–2009) daily average of LAI for PKEW (grey line) and for Nam Ken rubber plantations (black line). These are the LAI time series in the baseline simulation (scenario B), and the scenario C, respectively.

model, the ET formulation has been replaced by Equation (2).

Model forcing data include precipitation, net radiation, wind speed, temperature and relative humidity. Table II summarizes main vegetation and soil parameter values used for a baseline model simulation to reflect existing (observed) conditions in the catchment of PKEW. This baseline run will be compared to model simulations accounting for rubber land use.

BASIN-SCALE WATER BALANCE SIMULATIONS

Because of the limited access to direct ET_{rubber} measurements in Nam Ken, to support our K_{rubber} and ET_{rubber} predictions, we derived estimates of root water uptake for two dry seasons (2005 and 2006) from detailed soil moisture profiles. Root water uptake has been normalized by estimated maximum ET ($\lambda = ET/ET_{max}$), providing direct information of the rubber phenology coefficient. Figure 4 shows the K_{rubber} closely following the λ values, confirming the representation of rubber water uptake when using the K_{rubber}. Second, we consider rubber water demand to be a function of energy availability during the rainy season, where there is no water or temperature limitation on rubber phenology or water use. During this season, K_{rubber} is proportional to vegetation indices, namely, LAI and NDVI, as showed in Figure 4, where K_{rubber} closely follows the same pattern as NDVI and LAI.

The hydrologic model hsB-sm is calibrated and validated using the long term observations at PKEW. Soil and vegetation parameter values required to set up hsB-sm have been based on *in situ* measurements, remote sensing observations and values taken from prior modelling applications in the basin (Table II; Cuo *et al.*, 2006). After manual calibration, minimizing the difference between observed and simulated discharge, soil moisture, runoff coefficient (ROC) (the ratio of annual discharge vs annual precipitation) and the Horton index (ratio of water vaporization to catchment wetting; Troch *et al.*, 2009) using the first 4 years of data from PKEW, hsB-sm was validated using the entire 8 years of daily observation data. The calibrated model run, representing a mosaic of traditional land cover in MMSEA in PKEW, is referred to as the baseline simulation or scenario B (scenario A refers to the observations at PKEW). This baseline scenario (which uses the traditional ET approach) is compared in the next paragraph with two rubber simulations: a first model run in which rubber ET has been approximated using also the traditional modelling approach (i.e. Equation (1), scenario C, using rubber LAI, leaving the rest of soil parameters constant), and a second model run in which the ET_{rubber} with K_{rubber} index are used (scenario D). The three different models runs and the overall water balance performances are summarized in Table III and Figure 5. There is a good agreement between the baseline simulation and observations in PKEW with regard to discharge, ET, ROC and the Horton index (Table III). Furthermore, based on ROCs and exceedance probability curves, the agreement between observed and simulated stream flow distributions are considered reasonable (Figure 6; Table III), with the exception for low flows in 1999 and 2001. Overall, the model adequately simulated the major water balance components in PKEW, with a small overestimation of ET and underestimation of discharge of only about 17 mm year^{-1} (Table III).
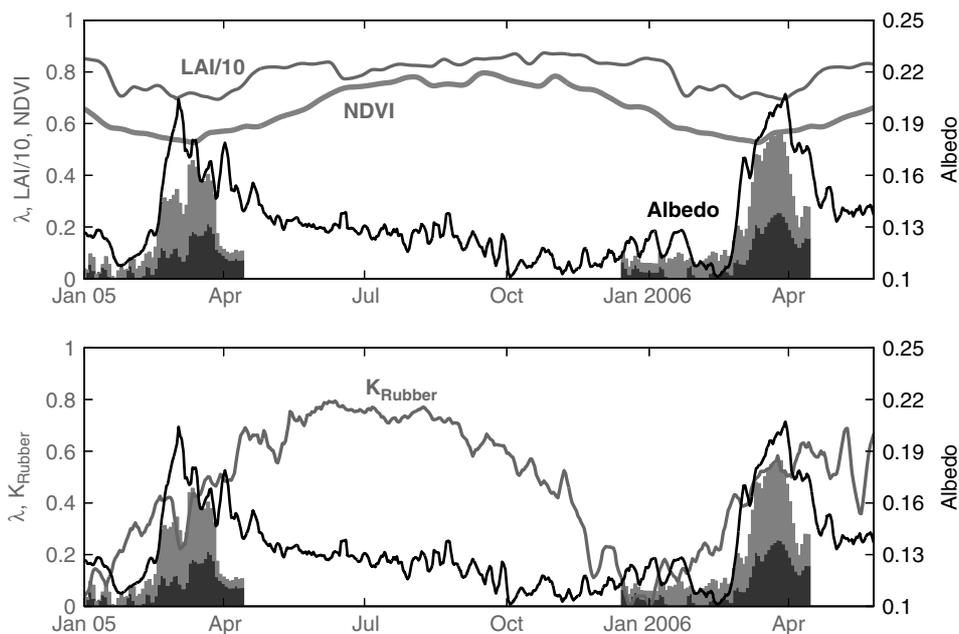

Figure 4. The top panel shows average LAI (scaled by a factor of 10) and NDVI from MODIS pixels covering rubber plantations in Nam Ken. The black line represents smoothed hourly *in situ* measurements of albedo, and the bars represent root water uptake (λ) from a 75 to 125 cm soil layer (light grey) and 125 to 225 cm soil layer (dark grey). Albedo values are calculated by averaging the hourly radiation from 10:00 to 14:00 local time. Root water uptake has been normalized by estimated maximum ET as follows: ($\lambda = ET/ET_{max}$), providing direct information of the crop factor. The bottom panel adds the K_{rubber} (light grey line) for Nam Ken climatic conditions.

Table III. Mean observed and simulated values for PKEW basin.

Scenarios	Mean values	ET (mm/year)	Discharge (mm/year)	ROC (−)	Horton index (−)
A	Observations	824[a]	724	0·47	0·69
B	Baseline simulation	841	707	0·46	0·70
D	Rubber LAI	850	698	0·45	0·70
C	K_{rubber}	1052	496	0·32	0·80

[a] Based on the difference between precipitation and discharge, assuming no change in basin water storage.
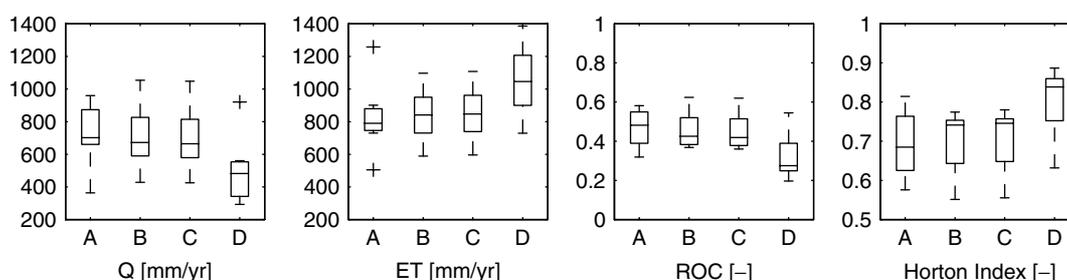

Figure 5. Box plots summarizing the overall water balance. Q is total discharge, ET is total evapotranspiration, and ROC is runoff coefficient. Shown are scenario A: observations; scenario B: baseline simulation; scenario C: rubber simulation using traditional f_θ and f_{LAI}; and scenario D: rubber simulation using the proposed crop factor. The top and bottom ends of the box correspond to the 25th and 75th percentiles of the samples, and the centre line is the median. Whiskers extend from each end of the box to the adjacent values in the data and outliers are data with values beyond the ends of the whiskers, displayed with a cross.

Simulation of rubber conversion using the K_{rubber} showed substantial changes in annual discharge, ET, ROC and the Horton index (Scenario D; Table III; Figure 5). Comparing to the baseline scenario, annual ET is enhanced by 20% and discharge is reduced by 29%. Increase in evaporation decreases the ROC, from 0·46 to 0·32. The Horton index is a measure of rain-use efficiency of the ecosystem present in the catchment (Troch *et al.*, 2009), thus, the observed increase in the Horton index of the basin (from 0·7 to 0·8) indicates that rubber is more efficient in using the plant available water in the root zone. Simulated ET rates agree with earlier estimates of water and energy fluxes in a rubber plantation in Ivory Coast (Monteny *et al.*, 1985). These authors measured ET rates ranging from 3 to 5 mm/day during most of the year and a decrease to 1−3 mm/day during the 2 months prior to leaf fall. Annual total ET rates were larger than 1000 mm/year. This annual ET value is similar to the ET_{rubber} estimates of scenario D (Table III). Also, similar to our findings, ET measurements in a 10-years-old rubber site in Chethackal (9°22′N and 76°50′E) showed a maximum transpiration rate of around 3−4 mm/day during the driest months of the year, right before leaf shedding (Gururaja Rao *et al.*, 1990). These values are also supported by recent flux measurements in northeastern Thailand (T. Giambelluca, unpublished data), that showed average ET of 3·4 mm/day during the dry months of February and March 2009. These ET observations rubber plantations are in line with the K_{rubber} model simulations that indicated an average net increase of ET of 0·59 mm day^{-1} over the baseline simulation.

As an alternative estimate for the hydrological effects of rubber expansion, we replaced PKEW's LAI with that observed in stands of rubber in Nam Ken (scenario C in Table III and Figure 5), and using the traditional method to reduce ET based on root zone soil moisture and LAI. This simple, yet traditional, approach resulted in only slightly higher predicted ET rates and lower discharge and ROCs than the baseline simulation (Table III; Figure 6). Importantly, the total average net ET increase predicted is only 0·02 mm day^{-1}, much lower than the prediction when using the K_{rubber} for ET estimate.

Both scenarios (C and D) show similar hydrologic trends (increase in ET and decrease in water storage in the basin) as native vegetation is replaced by rubber. Scenario D shows a stronger trend compared to scenario C. Even though we lack ET measurements on rubber fields to further validate the proposed phenology crop factor, we argue that the actual effects of rubber expansion on the basin-scale water balance is more closely simulated with scenario D. The existing field observations (Guardiola-Claramonte *et al.*, 2008) points to a higher likelihood of our scenario D results. For example, the traditional estimation approach is underestimating ET during periods of low LAI or NDVI. Observations show that these two variables reach minimums during periods of high soil water uplift from deeper soil layers (75-cm to 225 cm deep), as surface soil moisture is too low to support changes in rubber phenology (Figure 5; see also Guardiola-Claramonte *et al.*, 2008). In contrast, the trajectory of the K_{rubber} index correctly follows that of observed deep root water uptake during the dry season (Figure 5). Nonetheless, there is a need to further explore how rubber plantations (through e.g. direct ET and CO_2 fluxes measurements) affect basin-scale water balance components in different environments to provide a final answer.
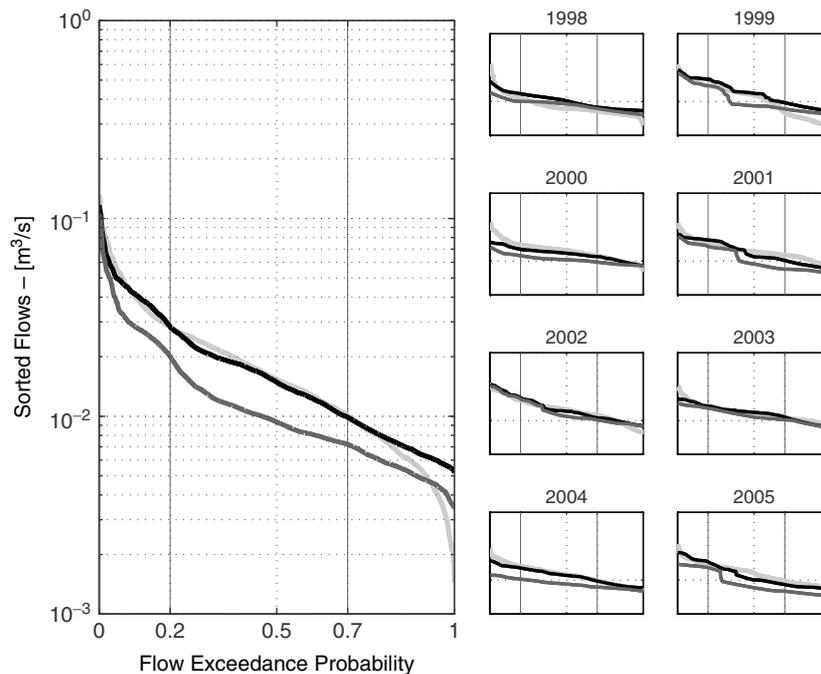
Figure 6. Observed (light grey) and simulated (black) yearly exceedance probability plots for annual and total discharge. Dark grey lines show model results when vegetation is replaced by rubber fields modelled with the K_{rubber} model (Scenario D).

CONCLUSIONS

The ET model proposed in this paper combines the energy-based maximum ET estimate from the Penman–Monteith equation with a phenology coefficient that represents more accurately vegetation response to climatic forcing. In particular for rubber, this allows a more accurate prediction of relatively high water use during dry periods when canopy cover is at a minimum following leaf drop. Hydrological model simulations suggest that the conversion of forest cover to rubber in MMSEA depletes water storage from the subsurface soil during the dry season, increasing water losses through ET, and reducing discharge. Traditional modelling approaches show similar trends, however, the implications of rubber conversion are more conservative. Either estimate align with local beliefs regarding the high water use of *hevea brasilensis*, which could lead to stream desiccation. However, detail field observations points towards a higher likelihood on K_{rubber} modelling estimates. A final answer could only be achieved when additional ET measurements in rubber plantations at different environments are available. In the mean time, the addition of a phenologically based index to tune ET provides a means to more adequately represent effects of climate and land-cover/land-use changes on the partitioning of water balance components.

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