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Local hydrologic effects of introducing non-native vegetation in a tropical catchment

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ABSTRACT

This study investigates the hydrologic implications of land use conversion from native vegetation to rubber (*Hevea brasiliensis*) in Southeast Asia. The experimental catchment, Nam Ken (69 km^2), is located in Xishuangbanna Prefecture (22°N, 101 °E), in the south of Yunnan province, in southwestern China. During 2005 and 2006, we collected hourly records of 2 m deep soil moisture profiles in rubber and three native land-covers (tea, secondary forest and grassland), and measured surface radiation above the tea and rubber canopies. Observations show that root water uptake of rubber during the dry season is controlled by day-length, whereas water demand of the native vegetation starts with the arrival of the first monsoon rainfall. The different dynamics of root water uptake in rubber result in distinct depletion of soil moisture in deeper layers. Traditional evapotranspiration and soil moisture models are unable to simulate this specific behaviour. Therefore, a different conceptual model, taking in account vegetation dynamics, is needed to predict hydrologic changes due to land use conversion in the area. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS Rubber (*Hevea brasiliensis*); root zone water balance; evapotranspiration; land use change; hydrologic change

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INTRODUCTION

Current global population growth and economic development is accelerating land-cover conversion in many parts of the world at an unprecedented rate (Lambin *et al*., 2001). Impacts on the natural environment, such as changes in water and carbon cycles, have been widely reported (e.g. Brontstert, 2004). Land use change not only disturbs the atmospheric concentrations of CO_2, CH_4 and N_2O (Moiser, 1998), but also plays an important role in modifying the hydrological cycle (Huxman and Scott, 2007). There is an urgent need to improve our knowledge about the ecological–hydrological interactions in both natural and disturbed environments to assess the implications of land use change on the hydrological cycle. These interactions and feedbacks can have important consequences for streamflow in humid environments, where connectivity between surface and subsurface hydrology is strong, as well as in arid regions where vegetation changes can affect local to regional water balances (Newman *et al*., 2006; Wilcox *et al*., 2006).

This study follows an ecohydrological approach to understand the hydrological implications of growing non-native rubber in montane mainland Southeast Asia. Towards the end of the 1950s, China introduced rubber in the southern region of Yunnan Province (Chapman, 1991). Since then, native vegetation (mainly primary and secondary forest) has been rapidly replaced by rubber plantations. In 1963 rubber occupied 6130 ha (Jiang, 2003), which increased to 136 782 ha by 1998 (Wu *et al*., 2001) and to about 220 000 ha by 2004 (Li Haitao, personal communication). This increase follows the global demand for natural rubber driven by the economic growth of China and other emerging countries.

Rubber (*Hevea brasiliensis*) is a tree native to the tropical rainforest of the Amazon Basin. Its habitat is characterized by small variations in air temperature (24–28 °C) and precipitation (1500–2000 mm) throughout the year. Rubber's natural habitat extends between 10° north and south of the equator and to at most 600 m above mean sea level (AMSL). However, because of its economic importance, rubber is now cultivated at higher latitudes and altitudes in South America, Southeast Asia and Africa. In these marginally suitable environments (colder and drier), the productive life of rubber, its yield and its growth are reduced (Chandrashekar *et al*., 1998; Devakumar *et al*., 1999).

In general, the effects of introducing a non-native species on the local and regional hydrologic cycle are poorly understood (Newman *et al*., 2006). Our study focuses on a humid environment with a distinctive dry season followed by a strong wet monsoon season. It characterizes root water uptake dynamics of three native vegetation types (tea, secondary forest and grassland) and compares them to rubber tree plantations. Our analysis is

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based on 2 years (2005 and 2006) of hourly soil moisture observations and other hydro-meteorological variables measured in these four land-covers. The research methodology has been designed to answer the following question: *how is the local root zone water balance affected by the introduction of rubber?*

RESEARCH METHODOLOGY

Site description

Climate. Our experimental catchment, Nam Ken (69 km^2), is located in the Xishuangbanna Prefecture (22°N, 101 °E), close to the Myanmar border (Figure 1(a)). The region is characterized by a tropical monsoon climate, with most monsoon storms originating from the Beibu Gulf (southeast) and the Bay of Bengal (southwest). The basin waters drain to the Mekong River (Lancang Jiang in Chinese). Topography strongly affects precipitation and temperature in the basin, creating pronounced altitudinal climate zones. The average precipitation for the entire basin is 1380 mm, ranging from 1100 mm at 800 m to over 1700 mm at 2000 m (Figure 1(c)). In this monsoon-dominated climate, most of the precipitation falls between May and October. Monthly mean precipitation during the wet season often exceeds 200 mm. The rest of the year is mostly dry, with precipitation below 50 mm/month. During part of the dry season the upper basin is characterized by heavy fog, and fog interception accounts for 5% of the total annual precipitation (Liu *et al.*, 2004). Annual mean temperature is approximately 20 °C, with the highest temperatures occurring during the wet season.

Vegetation. Land-cover distribution is different in the upper and lower parts of the catchment (Figure 1(d)). The primary forest, mostly montane rainforest, extends in the higher areas of the basin. Montane rainforest dominates the upper regions of the basin where fog interception compensates for the insufficient precipitation during the dry season to sustain this type of vegetation (Wu and Ou, 1995; Zhang and Cao, 1995; Zhu, 1997; Wu *et al.*, 2001). It is dominated by evergreen species belonging to the following families: Lecythidaceae, Magnoliaceae, Dipterocarpaceae, Lauraceae, Meliaceae and Apocynaceae (Zhang and Cao, 1995; Zhu *et al.*, 2004). Nam Ken has a large extension of disturbed or fragmented forest, called secondary forest (Figure 2(c)), dominated by families such as Fagaceae, Euphorbiaceae, Theaceae and Lauraceae (Zhu *et al.*, 2004; Zhu, 2006). Stands of secondary forest are located adjacent to the primary forest. The lower areas are used extensively for agriculture and rubber cultivation. The primary crops include corn (planted on hillslope swidden fields) and paddy rice (in the proximities of the river). Rice paddies are located in terraces adjacent to the river and the lower river-bedside slopes. Rubber was introduced in the lowest elevation areas in the late 70's, and with the development of more resistant clones, rubber is now planted up to

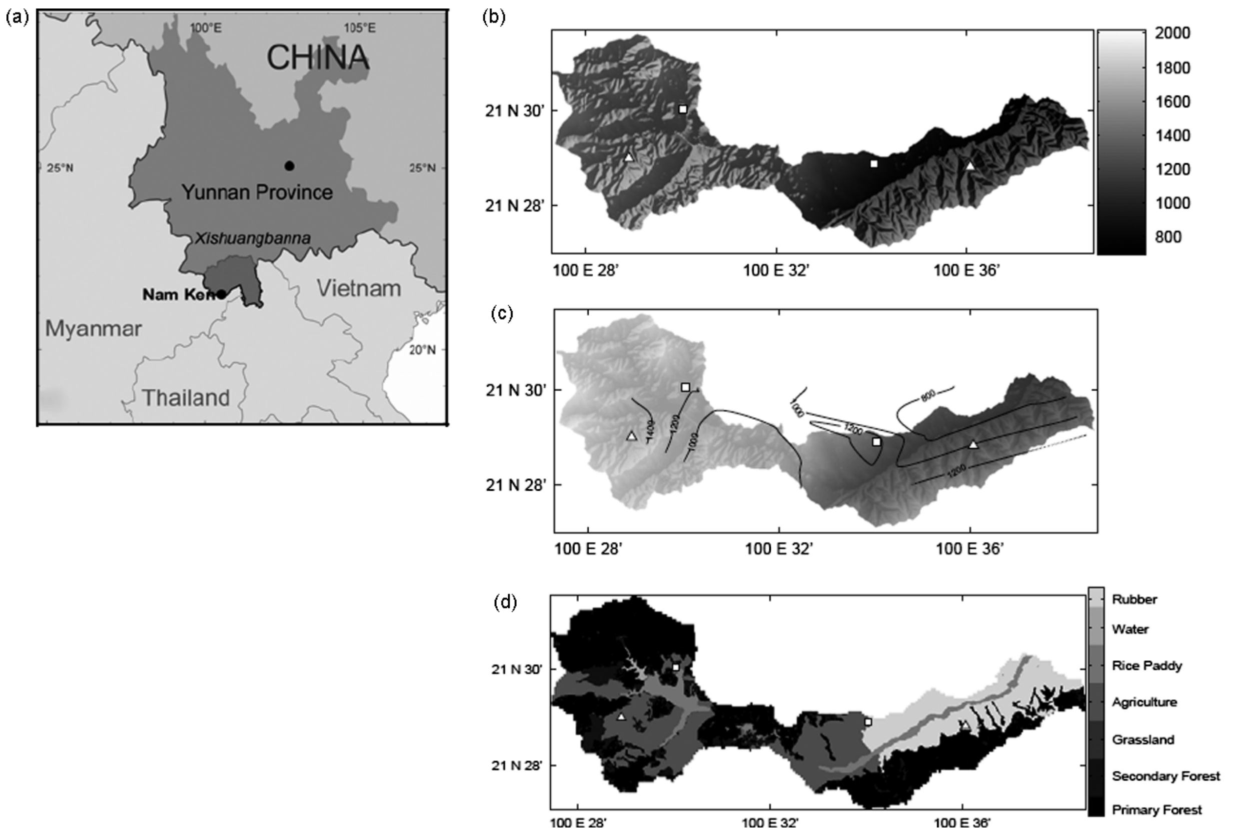

Figure 1. (a) Location of the experimental catchment Nam Ken. (b) Micrometeorological (triangles) and soil moisture stations (squares) in Nam Ken. (c) Isohyets in Nam Ken and (d) land-cover.

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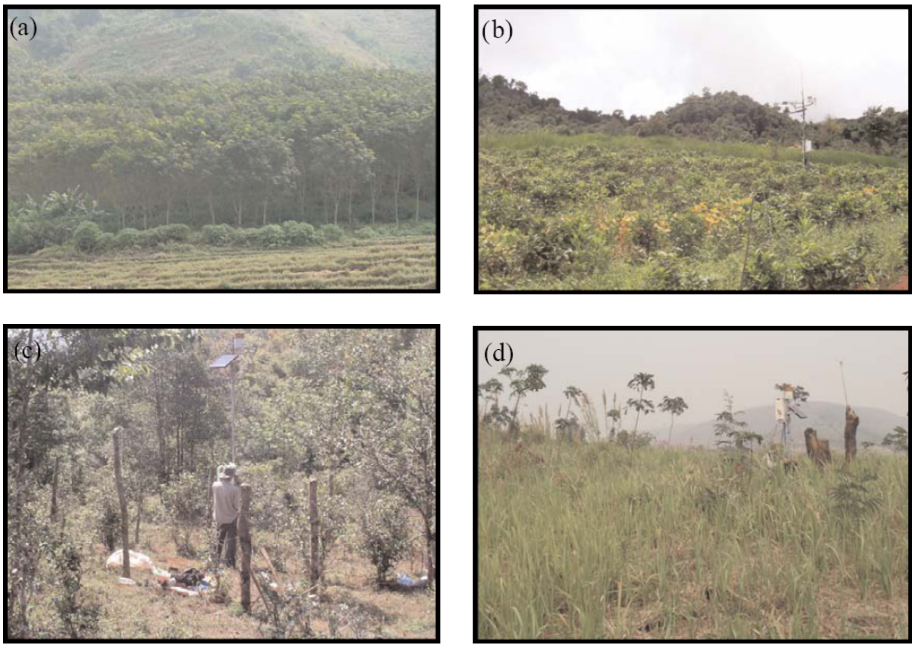

Figure 2. Studied land-covers: (a) rubber, (b) tea, (c) secondary forest, (d) grassland.

1000 m AMSL. Grassland areas, which are fallow components in the ethnic Bulong swidden agriculture system, are also found on most hillslopes (Figure 2(d)).

To simplify future modelling efforts and gain an overall understanding of basin vegetation dynamics, the vegetation in the basin has been grouped into five different categories based on root characteristics and water demand. These five groups are: rice paddies, agricultural sites (e.g. tea), grassland, forest (primary and secondary), and rubber (Figure 2 and Table I). We have ignored rice paddy because its growing area has remained constant for decades (Xu *et al*., 2005), and our focus is on land-covers that rubber is now replacing.

Soils and rooting depth. Most of the soils present in Nam Ken are deep red ultisols, developed over granite or gneiss parent material (Cao *et al*., 2006). Based on the detailed description of seven soil pits we dug

Table I. Land-cover distribution at Nam Ken (69 km^2) in 2005.

	Land-cover type	Surface (ha)	% surface	Station type
Forest	Primary forest	2823·03	43·1	
	Secondary forest	689·94	10·5	SM/RF
Tea	Agriculture	1529·91	23·4	MET
Rubber	Mature rubber	314·55	4·8	
	Young rubber	131·67	2·0	MET
	Upland agriculture/Young rubber	632·43	9·7	
Grassland	Grassland & Barren	3·69	0·1	SM/RF
	Rice paddies	395·28	6·0	
	Water	26·37	0·4	

throughout the basin we conclude that soils are relatively homogeneous. Bulk density was determined from 90 cm^3 samples taken every 0·25 m depth up to 2 m. The data show a decrease in bulk density with depth and altitude, and the presence of an argillic horizon of variable thickness, with a maximum clay accumulation at 75 cm depth. At each site, saturated hydraulic conductivity was measured from three replicates at the surface, 1 m, and 2 m, using a borehole permeameter. The field measured saturated hydraulic conductivity shows important decreases with depth: from $53 \pm 19{\cdot}1$ mm h^{-1} (at the surface) to $3{\cdot}2 \pm 4{\cdot}3$ mm h^{-1} (at 2 m depth). None of the seven study sites presented indications of a shallow groundwater table. One undisturbed soil sample was collected at each site at the surface, 1 and 2 m depths (same locations as the soil moisture measurements, see below) and were used to estimate the soil water retention characteristics. For each sample, volumetric water content corresponding to different suction pressures (0·3, 0·5, 1, 3, 7, 10 and 15 bars) was measured using pressure chambers. The van Genuchten (1980) soil water retention relationship was then used to parameterize these observations (Table II). Using the fitted soil water retention relationships, we converted continuous volumetric water content observations to matrix potential. Unsaturated hydraulic conductivity for each soil type was estimated using the van Genuchten-Mualem model (van Genuchten, 1980). Hydraulic conductivity and matrix potential are needed to estimate vertical soil water flow in the root zone (see Section on Results).

Root inventories taken from the soil pit under tea indicated abundant roots in the upper half-meter, with some roots extending down to about 0·9 m. In the grassland site, most of the roots are concentrated within the top 0·15 m, despite being reported to be up to 1·5 m in other tropical sites (Canadell *et al*., 1996; Kim *et al*.,

Table II. Soil water retention parameters and observed saturated hydraulic conductivity.

Rubber	Surface	1 m	2 m
θ_{res}	0·10	0·16	0·17
θ_{sat}	0·62	0·59	0·59
n	1·40	1·13	1·17
α	0·005	16·0	6·95
m	0·28	0·11	0·15
K_{sat} (mm h^{-1})	54	51	11
2^{ary} forest	Surface	1 m	2 m
θ_{res}	0·14	0·21	0·35
θ_{sat}	0·77	0·67	0·75
n	1·47	1·15	2·94
α	0·002	1·87	0·0004
m	0·32	0·13	0·66
K_{sat} (mm h^{-1})	35	7	2

Where θ_{res} is the residual water content; θ_{sat} the saturated water content; n, α and m van Genuchten-Mualem fitting model parameters'; and K_{sat} the saturated hydraulic conductivity.

2005). The secondary forest site had roots up to 1·2 m depth, and few below this depth. This is a shallow root depth when compared to the 7 m depth reported by Canadell *et al.* (1996) for tropical evergreen species. Part of this discrepancy results from our secondary forest being a relatively young replacement land-cover (estimated <10 years old). Rubber tree roots are mainly concentrated within the first 1·1 m, but roots were observed throughout the 2·25 m soil profile. Literature on rubber reports a high concentration of roots in the shallow layers (Devakumar *et al.*, 1999; Cunha *et al.*, 2000; Howell *et al.*, 2005).

Data acquisition network

A hydro-meteorological data acquisition network was established in the basin in May 2004 and removed in January 2007. It consisted of two micrometeorological (MET) stations located one on a rubber plantation and the other one on a tea plantation; and two soil moisture/precipitation (SM/RF) stations on a grassland field and on a secondary forest (Figure 2). Rainfall was also measured at five other locations in the basin; Figure 1(c) shows the rainfall distribution in Nam Ken. Both MET stations recorded hourly the 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. Soil heat flux was measured at the soil surface together with soil moisture. Additional soil moisture measurements were taken at 1 and 2 m depth. From the ratio of incoming and reflected shortwave radiation, surface (canopy) albedo is derived. Daily albedo values are calculated by averaging the hourly radiation from 10:00 to 14:00 local time and range from 0·12 to 0·25 for the rubber and tea plantation respectively. The two SM/RF stations recorded hourly soil moisture at three different depths (surface, 1 m, and 2 m) and precipitation above canopy. Additional albedo measured on young secondary forest has been used to supplement the lack of energy flux measurements in the secondary forest study site.

Soil moisture was measured using thirty centimetres long, vertically installed, time-domain reflectometry (TDR) probes. Measured time series of volumetric soil moisture were calibrated based on five to seven gravimetric soil moisture samples collected at each site, for each depth and during both the dry and wet season.

Root zone water balance

During periods of zero precipitation with a deep ground water table and assuming no significant drainage to deeper layers or lateral inflows, soil evaporation and transpiration (root water uptake) are the only mechanisms for depleting the moisture content in the root zone. Under these circumstances, estimates of (combined) soil evaporation and root water uptake can be derived from soil moisture measurements at different depths:

$$S(t) - S(t + \Delta t) = E\Delta t = \int_0^Z [\theta(z, t) - \theta(z, t + \Delta t)]dz \quad (1)$$

where S is water stored in the root zone, E represents the evaporation losses from the root zone (both soil evaporation and root water uptake), θ is volumetric soil moisture, z is the depth of the root zone and Δt is an appropriate time step (in our case, 1 day). Equation (1) can be safely applied during the dry season in our catchment, when precipitation inputs are negligible and deep percolation is restricted (see Section on Results). To apply (1) we have divided the soil profile into three layers (surface to 0·75 m, 0·75–1·50 m and 1·50–2·25 m depth). For each of these layers, we assume that the change in water content is uniform and contributes equally to E. We therefore assume that soil evaporation is a negligible fraction of total evapotranspiration losses during the dry seasons. Based on Equation (1) we define the evaporation reduction factor (Williams and Albertson, 2004):

$$\lambda = \frac{E}{E_{max}} \quad (2)$$

where E_{max} is the maximal rate of evaporation (atmospheric demand), and E is the actual evaporation or root water uptake, derived from Equation (1). This reduction factor can be computed for each soil layer, and allows us to compare variability of root water uptake within the root zone (see Section on Results).

The previous equations assume negligible deep percolation. To verify this assumption, estimates of vertical water flow were made using the Darcy-Buckingham law. Because of the lack of soil suction measurements, matrix potential and unsaturated hydraulic conductivity were estimated using soil moisture measurements and applying the van Genuchten-Mualem model (van Genuchten, 1980). An average hydraulic conductivity for each layer

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was calculated using the harmonic mean of the hydraulic conductivity of the top and bottom layer. Assuming the positive z-axis pointing downwards and using the surface as the reference plane, vertical soil water flux for each soil layer is given by:

$$q = -K_{\mathrm{T-B}}(\theta)\frac{H_{\mathrm{B}}(\theta) - H_{\mathrm{T}}(\theta)}{d_{\mathrm{T-B}}} \quad (3)$$

where q is vertical flow rate, $K_{\mathrm{T-B}}$ is the harmonic mean of the hydraulic conductivity of the top and bottom layers, θ is the volumetric water content, $d_{\mathrm{T-B}}$ is the flow distance between observations and H_{T} and H_{B} are the hydraulic heads at the top and the bottom of the studied layer, respectively.

RESULTS

Root water uptake during the dry season

Water content at the tea, secondary forest and grassland sites increases with depth, but soil moisture tends to decrease with depth at the rubber site (Figure 3). Surface soil moisture fluctuations resulting from rainfall are propagated to deeper layers faster at the tea, secondary forest and grassland sites than under rubber, where the signal is strongly dampened with depth. Changes in water content at 1 and 2 m under rubber show an important time delay with respect to the increasing surface soil moisture content at the onset of the wet season. Such a delay is not present at the other three sites.

For the entire study period (including the wet seasons), the estimated Darcy flux calculated using (3) gives flows that are not greater than 0·2 mm/day under the rubber site. Flow values are one to two orders of magnitude smaller during the dry season. Percolation in the secondary vegetation site is a little larger but never exceeding ±1·5 mm/day early in the dry season. Furthermore, in both vegetation sites, upward flow dominates the top layer, and downward flow the lower one. Therefore, neglecting deep percolation during the dry seasons is a reasonable assumption. For each layer, changes in water content with time have been calculated using (1) with appropriate integration limits. Changes in water content for a certain layer are transformed to evaporation fractions, λ, using (2) and the equilibrium evaporation as the assumed maximum evaporation (Priestley and Taylor, 1972). Contrary to general applications, we assume the large-scale advection correction factor in the Priestley-Taylor method to be 1. It has been reported (McNaughton and Black, 1973) that such a value is more representative for rough land surfaces, as is the case in our study site. This value also agrees with results for rubber plantations in Ivory Coast (Montény *et al*., 1985).

For each vegetation type and each soil layer, Figure 4 shows stacked λ values for the dry season of 2005 and 2006. The total height of the bars represents the scaled total root water uptake. During 2005, the evaporation reduction factors for rubber, secondary forest and tea follow a similar trend with more or less constant root uptake in the deeper layers (λ_2 and λ_3) and a decreasing trend at the surface (λ_1). Forest shows the highest root water uptake at the surface. All the sites have an apparent drop in root water uptake in the middle of January due to a small rain event that affected the measured soil

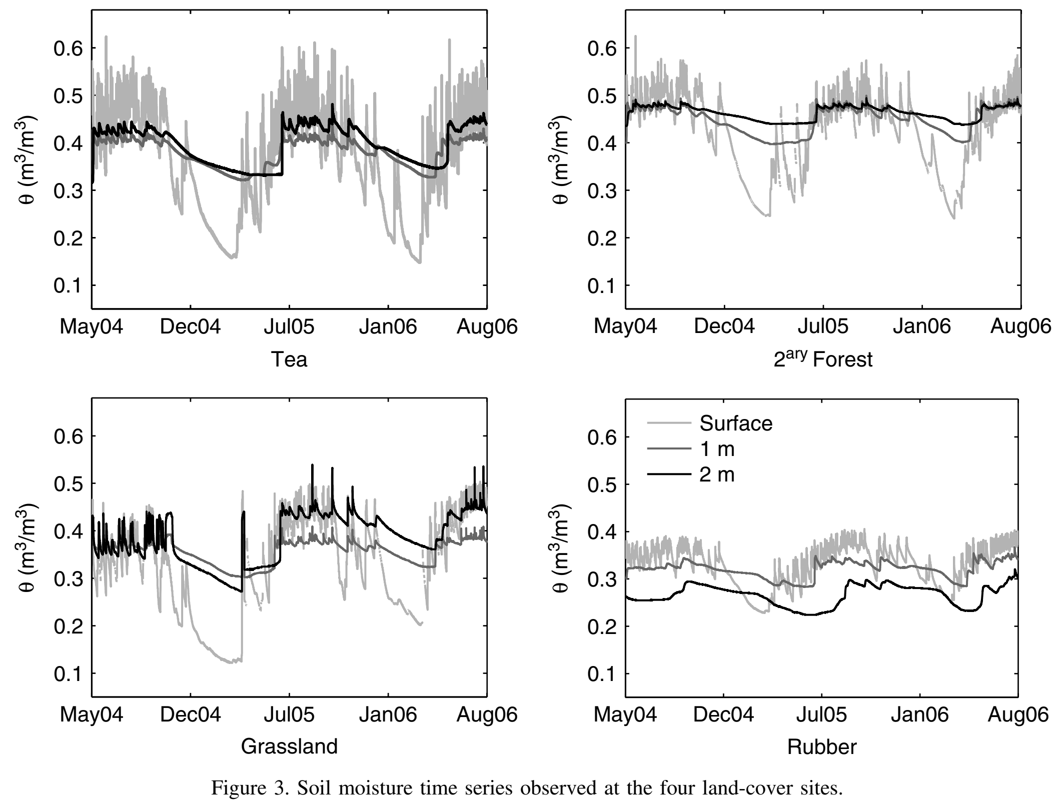

Figure 3. Soil moisture time series observed at the four land-cover sites.

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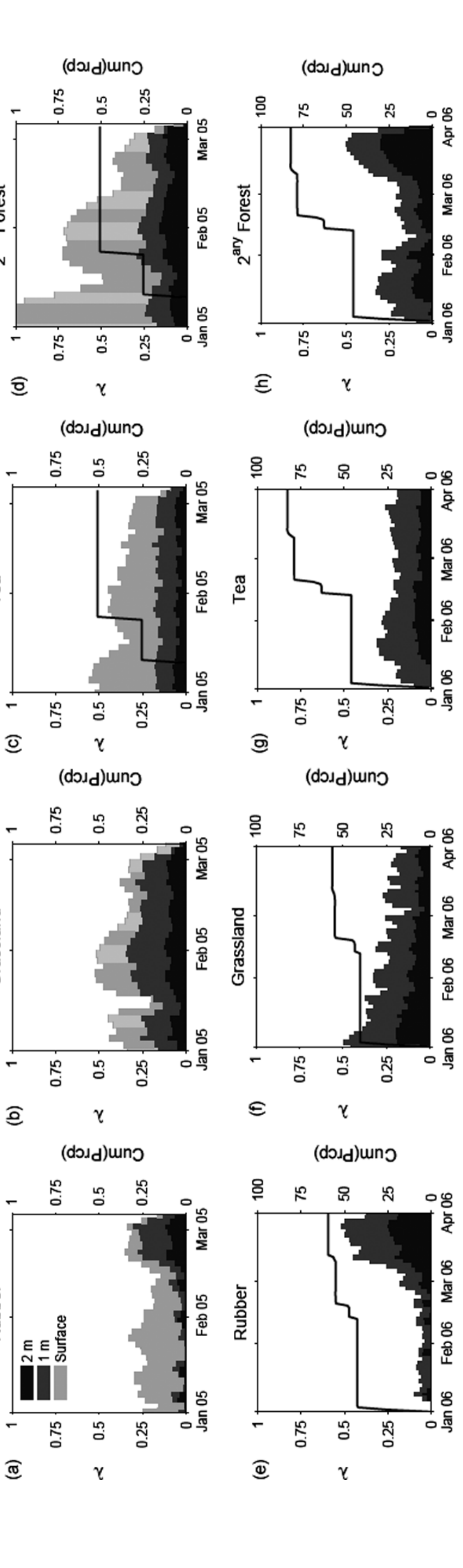

Figure 4. Two days average of evaporation reduction functions for the four vegetation types ((a)–(d): 2005 dry season; (e)–(h): 2006 dry season). The lighter gray in the surface layer of (b) and (d) indicates interpolated values due to missing data. There is no significant precipitation during the 2005 dry season on rubber and grassland. In 2006, because of the scattered precipitation events, no evaporation reduction function was calculated for the surface layer.

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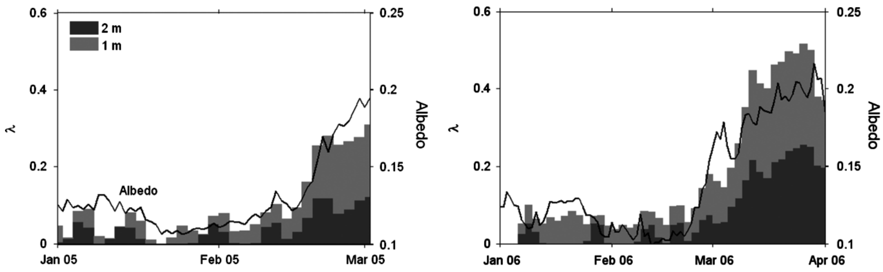

Figure 5. Daily albedo values and evaporation fraction (λ) for 2005 and 2006 dry seasons. Average two days evaporation reduction function for rubber in 2005 and 2006.

moisture. Rubber shows a distinctive trend in the surface and subsurface layers. From January and throughout most of February 2005, evaporation mainly depletes water content from the surface layer. Starting in mid-February, root water uptake from the deeper layers increases rapidly while no changes occur at the surface. The maximum root water uptake from the deeper layers occurs at the end of February, a few weeks before the arrival of the first rains.

The 2006 dry season is characterized by a few significant rainstorms occurring at the beginning of January (∼40 mm) and mid-February (∼30 mm) (Figure 4(e)–(h)). Again, the secondary forest site shows the highest subsurface water uptake. Secondary forest has increased root water uptake in both deeper layers a few days after the two main precipitation events. Rubber shows a similar response as in 2005, with very low root water uptake for the first two months of the dry season and a sudden increase from mid March through the end of March. During this dry season, λ in tea and grassland shows a similar pattern as in 2005. The most notable difference is the pronounced decline of root water uptake in the deepest soil layer under the grassland site.

Changes in surface albedo

Albedo values at the rubber plantation range from 0·12, measured early in the year, to over 0·20 in March (Figure 5). Because vegetation cover at the 3-years old tea plantation was low in 2004, albedo measurements reflect, to some extent, soil moisture variations in addition to vegetation phenology. Albedo was not measured at the secondary vegetation and grassland site. Additional albedo measurements were recorded in a younger secondary vegetation site located within the basin. These limitations in data availability were taken into consideration, and the major findings are not based on them.

DISCUSSION

The phenology of rubber is determined mainly by either the annual course of photoperiod (the physiological reaction of vegetation to the length of day or night), or insolation (Renner, 2007; Yeang, 2007). The time series in Figure 6 show rubber's albedo, increase of day-length, noon insolation, and precipitation during the study period. Albedo measured above rubber, tea and secondary vegetation was correlated with increase of day-length, insolation, precipitation and temperature. Rubber's albedo is most highly correlated with the increase in day-length, with a correlation coefficient of 0·56. No significant correlation was found between rubber phenology and the

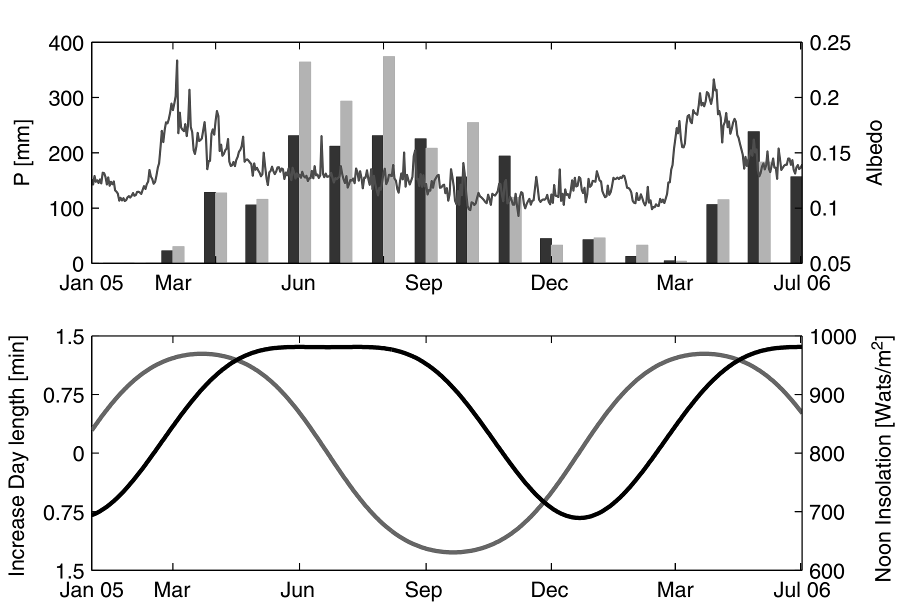

Figure 6. The top panel shows precipitation (left axis) measured in rubber plantation (black) and secondary forest (grey); the lower panel presents day-length increments (solid black line) and surface albedo (solid grey line) at the rubber plantation.

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other climatic variables. Insolation, theoretically calculated incoming noon radiation (Figure 6), or similarly, measured incoming solar radiation, showed no correlation with rubber albedo. These results highlight the importance of increase in day-length on the dynamics of rubber in this environment. Other environmental variables suggested elsewhere (such as precipitation and temperature) play, at best, a minor role in the rubber phenology (Rao *et al*., 1990, 1998; Chandrashekar *et al*., 2002; Raj *et al*., 2005). Tea shows trends similar to rubber, with higher correlation of tea's albedo with the increase in day-length. However, albedo of secondary forest seems to correlate more strongly with temperature.

In Nam Ken, *Hevea* is dormant from November to March and retains its foliage until the end of February, when leaves are shed within 2–4 weeks. Bud break and growth of new leaves start in late March, several (2–4) weeks before the arrival of the first monsoon rains. Shedding of old leaves results in an increase in albedo from 0·12 (typical value of evergreen forest) to 0·20 (a typical value for dry soil) in March; and flushing of new leaves decreases albedo back to 0·12 in April (Figure 6). Rapid shoot growth during the late dry season (April) is accompanied by increased water uptake from deeper soil layers (Figure 4(a), (e); *cf.* Borchert *et al*., 2002). This subsurface water uptake is necessary to increase stem water potential above a certain threshold to allow bud break (Borchert *et al*., 2002). In support, a study in northern India showed girth perimeter increasing several weeks before the first rainfall, possibly indicating rehydration of the tree from deep layer water uptake, associated with bud breaking (Chandrashekar *et al*., 1998). Furthermore, flushing induced by increasing day-length during the late dry season has been observed in many tropical tree species in monsoon forests around the globe (Rivera *et al*., 2002; Elliott *et al*., 2006). It depends on the availability of adequate subsoil reserves, as observed earlier in Amazonian forests (Nepstad *et al*., 1994).

The causes of bud break and flushing of certain tropical species during the dry season (a phenomenon referred to as the *leaf flushing paradox;* Rivera *et al*., 2002; Elliott *et al*., 2006) is under debate (Renner, 2007). As pointed out by Rivera *et al*. (2002) and Elliott *et al*. (2006) rubber flushing is independent of climate conditions and is primarily associated with photoperiodic induction (increase in day-length) and the availability of deeper subsurface water. Flushing occurs around the equinox, which corresponds to the maximum increase in day-length. Observations of changes in the albedo of rubber together with increase of day-length (Figure 6) and with root water uptake (Figure 5) confirms that rubber is indeed a brevideciduous spring flushing species. It seems that water availability plays a secondary role in triggering rubber dynamics during the dry period, either for shedding or flushing new leaves. As shown in Figure 4, rubber exhibits a distinct behaviour compared to the other land use types. Secondary forest, tea, and grassland seem to depend primarily on water availability in the form of rain. In 2005 (the drier of the two dry seasons) no increase in deep root water uptake was observed in the secondary forest site. However, the few rain events in 2006 did trigger activation of vegetation and growth (Figure 4(h)). Tea and grassland do not show any activation of deeper roots after the rainstorms, possibly because their water needs are fulfilled with near-surface water sources.

Rubber currently (in 2005) represents over 16% of the land-cover in the Nam Ken basin (Table I). Replacing 16% of the native vegetation by rubber could have important implications on the local and regional hydrological cycle. Based on long-term observations, Liu (1990) (reported in Wu *et al*., 2001) shows a negative relationship between the presence of fog and the increase of rubber plantations in the Xishuangbanna region. The author claims that the reduction of fog in the region is a direct consequence of replacing forest with rubber, given that rubber trees shed their leaves during the dry season (Wu *et al*., 2001), with a consequent reduction of leaf interception and drip. Liu *et al*. (2004) refer to this alteration of hydrologic partitioning by rubber as the main reason for the observed reduction in soil water content. This could also explain our observations of lower water content with depth for rubber, as compared to secondary forest (Figure 3). Soil moisture under grassland and tea does not decrease with depth because of the absence of deep roots to deplete the water content at deeper layers, as field observations and the literature suggest. We now know that rubber's water demand is concentrated around the equinox, when soil water availability is lowest and atmospheric demand is greatest. In similar settings (where precipitation and atmospheric demand are 'out of phase') changes in native vegetation have resulted in dramatic changes in streamflow and/or groundwater levels (Wilcox *et al*., 2006).

CONCLUSION

Observations of vegetation dynamics and soil moisture time series analysis suggest a dramatically different behaviour in terms of timing and rates of water consumption between the studied vegetation types. Albedo trends and field observations indicate that rubber sheds its leaves for a couple of weeks during the driest and hottest period in the region. Leaves fall to minimize water loss through evaporation and to allow the build-up of stem potential to initiate next season's bud break. The additional stem potential needed for flushing is acquired through deep subsurface water uptake. Leaf flushing is triggered by the increase in day-length. At the secondary forest site, root water uptake is linked to water availability in the form of rain. Native forest trees rehydrate after occasional rain events during the dry season, or shortly after the start of the rainy season. Water extraction from deep soil layers was not observed under shallow-rooted tea and grassland covers.

These results indicate that a specific conceptual model is needed to predict hydrologic changes due to land-use changes. In general, evaporation reduction functions

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depend solely on soil water content; however, our results emphasize the importance of an ecohydrological perspective for modelling purposes. We have shown that in the case of rubber trees, the increase in day-length is the deterministic variable that controls vegetation dynamics and water uptake in the dry season. The need to build an evaporation reduction function based on vegetation dynamics and hydrologic information corroborates the importance of bridging ecology and hydrology to elucidate and solve common problems. Future work will involve the development of a conceptual evaporation reduction model consistent with the ecohydrological observations, and the application of the model at the catchment scale.

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