A reconnaissance study of water and carbon fluxes in a tropical watershed of Peninsular Malaysia: stable isotope constraints

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Abstract Evapotranspiration is a nexus for planetary energy and carbon cycles, as yet poorly constrained. Here we use stable isotopes of oxygen and hydrogen to partition flux of water due to plant transpiration from the direct evaporative flux from soils, water bodies and plant surfaces in a tropical watershed of Peninsular Malaysia. Mean annual rainfall, obtained from 30 years of hydrological data, is 2145 ± 237 mm. Tentatively, 48% of this precipitation returns to the atmosphere via transpiration (*T*), with 33% partitioned into discharge (*Q*), 8% into interception (I_n), and 11% into evaporation (E_d). The large *T* emphasizes the role of water cycle as a "conveyor belt" essential for nutrient transport in terrestrial ecosystems. The flux of carbon from the atmosphere to the tropical ecosystem of the watershed, related to this transpiration water flux via water utilization factor (WUE), is 1373 ± 137 g C m^{-2} $year^{-1}$.

Key words water cycle; carbon cycle; river; stable isotopes; hydrology

INTRODUCTION

The difference between annual water input by precipitation (*P*) and river discharge (*Q*) yields the total evapotranspiration (*ET*) flux for the Langat sub-catchment. *ET*, the collective flux of water vapour from plants, soils, and water bodies, is the largest component of the terrestrial water cycle and thus a nexus for planetary energy and carbon cycles. The Langat *ET* appears to be relatively stable with respect to variations in the long-term annual rainfall in the Southeast Asian rainforests (Kumagai *et al*., 2009; Kume *et al*., 2011). Since an increase in solar radiation enhances *ET* and photosynthesis capacity (Tani *et al*., 2003; Goulden *et al*., 2004; Saleska *et al*., 2007) then the ability of tropical forests to maintain stable *ET* during dry seasons is attributed to deep root systems (Oliveira *et al*., 2005; Bruno *et al*., 2006). If this is so, what would be the water budget that maintains *ET*?

OBJECTIVES

The aim of this study is to better quantify the relationship between regional hydrology and biology in the tropical environment of Peninsular Malaysia. The study concentrates on Langat sub-catchment, considered a quasi-closed entity with respect to the overall water cycle. The basic hydrological data, such as precipitation and discharge are available from long-term monitoring by the Drainage and Irrigation Department (DID) Malaysia. This information is coupled with empirical isotopic data of water samples for quantification of natural water fluxes. The terrestrial water cycle also plays a decisive role in nutrient delivery to vegetation and thus carbon intake by the biological system within the watersheds. The water and carbon cycles are coupled via plant transpiration (photosynthesis) at a specific ratio called water-use efficiency (WUE) (Choudhury *et al*., 1998; Choudhury, 2000; Bery & Roderick, 2004; Chen & Coughenour, 2004; Kuchment *et al.,* 2006). This enables conversion of the water transpiration flux into a related first-order estimate of the photosynthetic carbon flux. Considering the paucity of data for tropical regions of Southeast Asia, such a first-order estimate can serve as the first attempt for quantification of regional water and carbon cycles.

MATERIAL AND METHODS

The climate of Peninsular Malaysia is tropical and the humidity is high all year round, with the temperatures ranging from 21°C to 32°C. The rainfall regime over the region is governed mainly by the monsoon seasons, primarily modulated by the atmospheric pressure patterns in Southeast

Asia that result from pressure differences between the Asian continent and Australian land mass, termed the Inter-Tropical Convergence Zone (ITCZ). During the Northern Hemisphere winter, a combination of high pressure in China and low pressure over Australia, forces the ITCZ further south, bringing the northeast monsoon (NEM) (November to January) over Peninsular Malaysia.

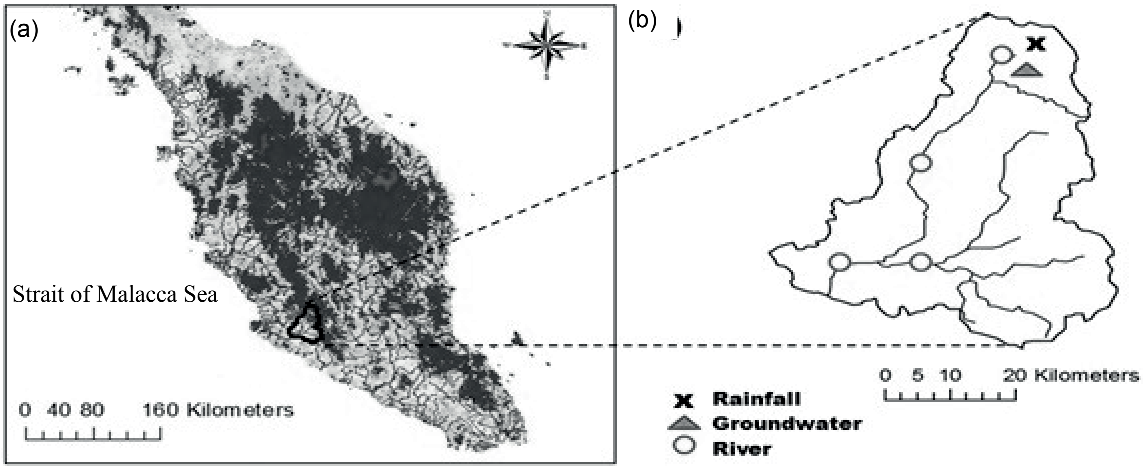

Fig. 1 The study area: (a) Peninsular Malaysia, (b) Langat sub-catchment and sample locations.

The circulation reverses during the Northern Hemisphere summer, with low pressure over Asia and high pressure over Australia, resulting in migration of the ITCZ northwards. At this time, Peninsular Malaysia is influenced by the southwest monsoon (SWM) (April to July) and the whole of Peninsular Malaysia experiences a relatively drier period (Suhaila *et al.,* 2010). Nevertheless, Peninsular Malaysia does not have distinct dry and wet seasons (Takanashi *et al.,* 2010). The Langat sub-catchment, located in the coastal region (Fig. 1), west of the main orographic barrier of the Titiwangsa mountain range, is influenced by both monsoon systems.

In this study, we utilized the steady-state isotope mass balance equation proposed by Gonfiantini*,* (1986) to estimate the proportion of E_v relative to the annual water input *I*.

$$\frac{E_v}{I} = \frac{(\delta_S - \delta_I)(1 - h + \Delta\varepsilon)}{(\delta_S + 1)\left(\Delta\varepsilon + \frac{\varepsilon}{\alpha}\right) + h(\delta_A - \delta_S)} \tag{1}$$

where *h* is the ambient humidity normalized to saturation vapour pressure (mean annual value for temperature and humidity were provided by the Meteorological Department of Malaysia), α is the equilibrium fractionation factor ($\ln\alpha = 1137T^2 - 76.248T^{-1} + 0.05261$) for oxygen isotopes during evaporation, $\Delta\varepsilon = \alpha - 1$, and δ_I, δ_A, δ_s are the mean $\delta^{18}O$ (or δ^2H) values of precipitation, ambient moisture, and outflow, respectively.

E_v/I value essentially represents the amount of evaporative water loss from a watershed required to produce the observed isotope separation between initial water input (δ_I) and output (δ_S) at the ambient climatic conditions (i.e. temperature and relative humidity). The approximation for isotope composition of atmospheric moisture and mean annual precipitation is based on the equation $\delta_A = \delta_I - \varepsilon^*$ (Gat & Matsui, 1991).

RESULTS

$\delta^{18}O$ and δ^2H values of rainfall, collected at Langat from May 2010 to December 2011, define a Local Meteoric Water Line (LMWL) approximated by equation $\delta^2H = 7.7(\pm0.4).\delta^{18}O + 6.3(\pm2.6)$‰ (Fig. 2(a)). During July ITCZ (southwest Monsoon), evaporation in the Straits of Malacca enriches atmospheric moisture in ^{16}O and ^1H. This moisture is then transported by the trade winds from the Indian Ocean and subsequently subjected to isotopic rainout effects at the base of the Main Range. The samples collected during the January ITCZ, with similar spread of $\delta^{18}O$ and δ^2H values (Fig. 2), reflect an analogous rainout process for moisture from the Northeast

Monsoon (NEM) when abutting the Main Range from the east. During the inter-monsoon (either early or late SWM and NEM), the isotopic compositions of $\delta^{18}O$ and $\delta^{2}H$ are somewhat lighter, possibly due to local convective systems.

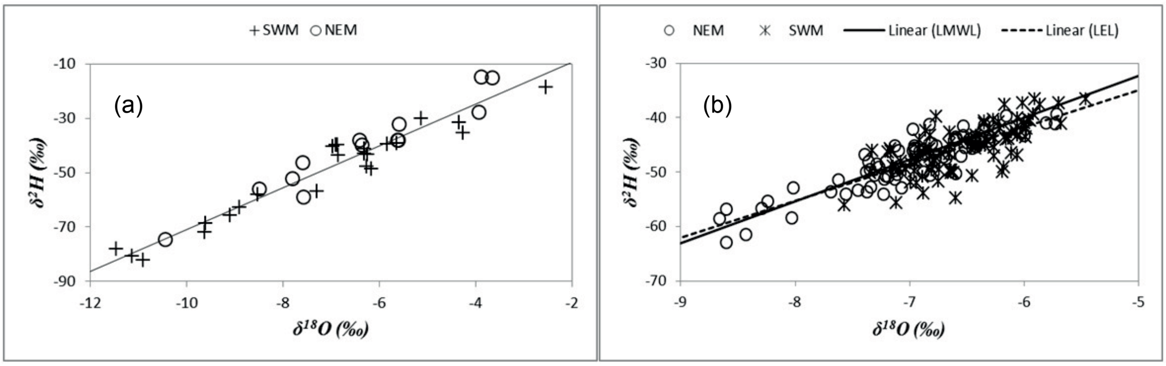

Fig. 2 Stable isotopes variations; (a) rainfall at Pongsun (b) Langat River watershed.

δ^{18}O and δ^{2}H values of river water collected from the upstream, tributary and downstream of Langat watershed define a Local Evaporation Line (LEL) that has a slightly shallower slope ($\delta^{2}H = 6.8\ (\pm 0.4).\delta^{18}O - 0.9(\pm 2.5)‰$) than the rainfall that was collected in the upstream section of the watershed. This shallower slope of 6.8 reflects evaporation of the surface waters (Fig. 2(b)).

ANNUAL TERRESTRIAL WATER VAPOUR FLUX, *ET*

The flow *Q* of the Langat River is influenced by the intensity of the rainfall in the upstream areas and its distribution within the basin. This is particularly true for periods of consistently high daily rainfall (Bruno *et al.*, 2006). River flow responds rapidly to rainfall events because 56% of water uptake by plants is taking place within a depth of 0–2 m. On annual time frame, the proportion of *P* stored in the soil zone may be considered constant (ΔS = 0) and *P* – *Q* is an approximation of *ET*. Despite uncertainties related to the area of contributing drainage, rainfall exceeds discharge and a proportion of annual rainfall that is not stored in the watershed must be transferred to the atmosphere via *ET*, composed of evaporation, interception and transpiration fluxes ($E_d + I_n + T$). Considering that the average watershed precipitation of 1 mm year^{-1} corresponds to 10^3 g H_2O m^{-2} year^{-1}, the magnitude of the water flux can then be calculated for the scale of a watershed. Because the estimate for rainfall in the Langat sub-catchment is based on a single station, this arithmetic average is employed for the entire watershed (Dingman, 2008). Based on these estimates, almost 70% of *P* was transferred to the atmosphere as water vapour via *ET*. The contributing drainage area, defined by topography for the Langat sub-catchment was estimated at 1443 km^2.

EVAPORATION ESTIMATE

Quantitatively, an isotope mass balance equation can be used to estimate the amount of evaporation required to generate the observed isotope separation between initial rainfall (δ_I) and eventual outflow via river water (δ_s), provided the information on temperature, humidity and related isotope fractionation factors for oxygen and hydrogen isotopes are available.

Input parameters substituted into equation (1) and the calculated E_v/I for Langat watershed are summarized in Table 1.

This isotope separation between δ_I and δ_S values corresponds to E_v/I values of ~11% for Langat watershed. This estimate includes evaporation of surface waters from the actual watercourse as well as from the dam.

The E_v/I value from equation (1) enables partitioning of *ET* into fractioning water vapour flux (direct evaporation from water bodies and soils, E_d) and non-fractioning water vapour flux (canopy evaporation, I_n, plus plant transpiration, *T*). The proportion of gross rainfall that is captured by plant surfaces and subsequently evaporated prior to infiltration into soil waters is termed rainfall interception, I_n, also referred to as canopy evaporation. The I_n value of 176±160 mm is based on area weighted I_n/P (Table 2), similar to Pasoh Forest Reserve (Tani *et al*., 2003) that is adjacent to Langat Basin. The I_n for the cassava, cocoa and oil palm were obtained from van Dijk & Bruijnzeel (2001), Dietz *et al*. (2006) and Bentley (2007), respectively.

Table 1 Input parameters for steady-state isotope mass balance equation with 95% confidence intervals (1) and the calculated E_v/I from oxygen isotopes.

Watersheds	Input parameters							Output
	T	h	δ_I	δ_A	ε	$\Delta\varepsilon$	δ_S	Ev/I
	K	%	‰	‰	‰	‰	‰	%
Langat	298.7	82	–7.8 ± 0.7	–16.9 ± 0.7	9.3	2.5	–6.7 ± 0.1	10.6

Table 2 Estimate of the area-weighted I_n/P for the Langat watershed based on GLC 2000 land-cover classes (Stibig *et al*., 2007).

Langat Land type	Area		Interception, I_n		Rainfall, P
	km^2	%	%	mm	mm
Forest	635	44	18	170	944
Oil palm	491	32	41	281	686
Non-irrigated cultivation	289	20	18	77	429
Urban	43	3			64
Others	14	1			21
Total	1443	100	~8%		2145
Average I_n				176	

Table 3 Components of annual water balance for the Langat watershed in 2010–2011.

Watersheds	Values in mm or 10^3 g H_2O m^{-2} year^{-1}					
	P	R	I_n	E	T	ET
	2145 ± 237	703 ± 81	176 ± 160	236 ± 24	1030 ± 103	1442 ± 131

P and *Q* are based on the 30 year data (1980–2011) obtained from the Drainage and Irrigation Department of Malaysia (DID).

E_d is then calculated as the product of E_v/I value from equation (1) plus ($P - I_n$). E_d flux represents the net water input to the soil zone of 236 ± 24 mm. Transpiration required to balance the annual water input by P for the entire Langat watershed is 1030 ± 103 mm. The summary for Langat water budget is given in Table 3.

DISCUSSION

Solar radiation, temperature and water are the principal regulators of Net Primary Productivity (*NPP*) and hence the plant growth (Nemani *et al*., 2002). In the tropics it is the intensity of solar radiation that promotes photosynthesis (Kumagai *et al*., 2004). Carbon intake during the photosynthesis is regulated by stomata in order to maximize carbon gain per unit of water loss (Katul *et al*., 2010) via transpiration (*T*) (Ferguson & Veizer, 2007).

Our estimate shows that about 50% of *P* in the Langat watershed was transferred to the atmosphere as water vapour via *T*, in agreement with Jasechko *et al.* (2013) and with other tropical regions (Fig. 2). The high primary productivity of tropical rainforests requires this large *T* flux for nutrient transport. Since the tropics have abundant water (Tani *et al*., 2003) its availability is not the rate-limiting factor for plant growth. Note that *P* in Langat watershed is relatively small compared to Ok Tedi and Upper Fly in New Guinea (+ symbol in Fig. 2), yet the absolute fluxes of *T* are comparable. The plateau in Fig. 2 suggests therefore that the flux *T* in the tropics is limited by solar radiation (Tani *et al*., 2003; Kumagai *et al*., 2004; Huete *et al*., 2006; Mynenei *et al*., 2007), as opposed to subtropics and higher latitude regions where it is limited by water availability.

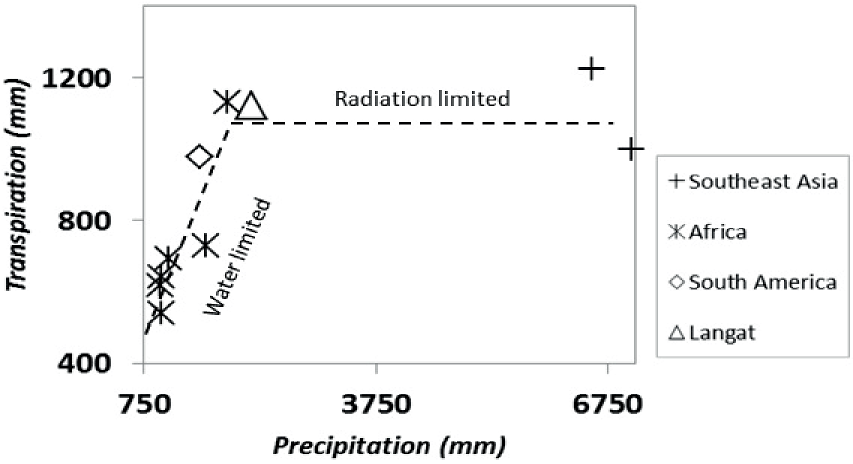

Fig. 3 Cross-plot of Transpiration (*T*) *versus* Precipitation (*P*) in the tropics and sub-tropical regions, exhibiting solar and water limited domains. Modified from Ferguson & Veizer (2007).

The fixation of atmospheric CO_2 as organic C is proportional to the *T* flux by the Water Use Efficiency (WUE) factor, with an average value of 1 molecule of C per 500 or 250 molecules H_2O for C3 and C4 plants, respectively (Taiz & Zeiger, 2006). Given that the estimated *T* for the Langat watershed relates to steady state condition on an annual basis, and the plants are almost exclusively of C3 type, the long-term WUE of 500 has been utilized for calculation of the *NPP*. This yields the annual fixation of carbon of 1373 ± 137 g C m^{-2} $year^{-1}$. The interpolated value for the watershed of the transpiration flux of water (~8.26×10^{13} mol H_2O $year^{-1}$) is far larger than the carbon intake (~1.65×10^{11} mol CO_2 $year^{-1}$), emphasizing the role of water cycle as a "conveyor belt" essential for nutrient transport in terrestrial ecosystems. Potentially, this may change our perspective on the role that biology plays in the water cycle. Following such a perspective, the global water cycle is the medium that redistributes the incoming solar energy across the planet, and the anatomical structure of plants then helps to optimize the loop of energy transfer via evaporation and precipitation in the hydrologic cycle.

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