Evapotranspiration and water source of a tropical rainforest in peninsular Malaysia

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Abstract
To evaluate water use and the supporting water source of a tropical rainforest, a 4-year assessment of evapotranspiration (ET) was conducted in Pasoh Forest Reserve, a lowland dipterocarp forest in Peninsular Malaysia. The eddy covariance method and isotope signals of rain, plant, soil, and stream waters were used to determine forest water sources under different moisture conditions. Four sampling events were conducted to collect soil and plant twig samples in wet, moderate, dry, and very dry conditions for the identification of isotopic signals. Annual ET from 2012 to 2015 was quite stable with an average of 1,182 ± 26 mm, and a substantial daily ET was observed even during drought periods, although some decline was observed, corresponding with volumetric soil water content. During the wet period, water for ET was supplied from the surface soil layer between 0 and 0.5 m, whereas in the dry period, approximately 50% to 90% was supplied from the deeper soil layer below 0.5 m depth, originating from water precipitated several months previously at this forest. Isotope signatures demonstrated that the water sources of the plants, soil, and stream were all different. Water in plants was often different from soil water, probably because plant water came from a different source than water that was strongly bound to the soil particles. Plants showed no preference for soil depth with their size, whereas the existence of storage water in the xylem was suggested. The evapotranspiration at this forest is balanced and maintained using most of the available water sources except for a proportion of rapid response run-off.

KEYWORDS
evapotranspiration, isotope signal, soil water content, tropical forest, vapour pressure deficit, water budget

1 INTRODUCTION

The response of tropical rainforests to environmental disturbance is of critical concern given the importance of their sustainability and potential to mitigate climate change. In these forests, changes in the amount and/or pattern of rainfall are perhaps the most important environmental disturbance. An understanding of fluctuations in evapotranspiration (ET) under different moisture conditions is necessary to determine how tropical rainforests will respond to climate change.

Research to date has demonstrated that tropical rainforests maintain ET even during the dry period. In Pasoh Forest Reserve (FR), which is located in a dry zone of Peninsular Malaysia and receives the lowest yearly rainfall amount among adjacent south-eastern tropical rainforests, relatively stable ET, which includes transpiration, interception evaporation, and soil evaporation, was observed even during the driest period, based on 7 years of continuous eddy covariance (EC) measurement (Kosugi, Takanashi, Tani, et al., 2012). Consequently, stable annual ET rates (1,287 ± 52 mm) were obtained despite the relatively small annual rainfall amount (1,805 ± 280 mm, from 1995 to 2015) (Kosugi, Takanashi, Tani, et al., 2012) compared to other South-East Asian tropical rainforests (e.g., Kume et al., 2011; Vernimmen, Bruijnizeel, Romdani, & Proctor, 2007; Noguchi, Abdul Rahim, & Tani, 2003; Kumagai et al., 2005). No obvious decline in monthly ET
variability was detected even during the driest month, although the amount of rainfall was much lower than ET (Kosugi, Takanashi, Tani, et al., 2012).

Several other EC flux studies conducted in Amazonian and Southeast Asian tropical rainforests have also consistently demonstrated this characteristic (e.g., Costa et al., 2010; Da Rocha et al., 2004; Kume et al., 2011; Malhi et al., 2002). In the Amazonian rainforests, ET did not drastically decrease and sometimes increased during the dry season (e.g., Costa et al., 2010; Da Rocha et al., 2004). The Amazonian rainforest has distinct dry and wet periods, which is not the case in equatorial Southeast Asian rainforests, although dry and wet periods do exist as part of seasonal fluctuations, with considerable variability between years (Kosugi et al., 2008; Tani et al., 2003). The stability of ET in dry periods and in the dry season seen in tropical rainforests should be supported by stable water sources in the soil throughout the seasons.

Hydrogen and oxygen isotopes (δ18O and δ2H) provide a powerful tool for determining plant water resources under a number of environmental conditions (Brooks, Barnard, Coulombe, & McDonnell, 2010; Dawson & Ehleringer, 1991; Eggermeyer et al., 2009; Evaristo, Jasechko, & Mcdonnell, 2015; West et al., 2012; Yang, Wen, & Sun, 2015). Using isotope indices, we can investigate whether soil water, streamflow, and plant transpiration are all sourced and mediated by the same well-mixed water reservoir originating in the soil (Evaristo et al., 2015). The depth of water uptake can also be estimated by measuring the isotopic composition of xylem water and soil water at different depths (Ehleringer & Dawson, 1992; Yang et al., 2015). Many previous studies utilize only one of the dual stable isotopes of δ18O (Nie et al., 2011; Querejeta, Estrada-Medina, Allen, & Jimenez-Osornio, 2007) or δ2H (Filella & Penuelas, 2003; Jackson, Caveller, Goldstein, Meinzer, & Holbrook, 1995). However, the dual-isotope method (e.g., Cramer, Thorburn, & Fraser, 1999; Eggermeyer et al., 2009; Evaristo et al., 2015; S. G. Li et al., 2006; Orlowski, Frede, Brüggenm, & Breuer, 2013; Rossatto, Silva, Villalobos-Vega, Sternberg, & Franco, 2012; Wang, Song, Han, Zhang, & Liu, 2010; West, Hultine, Burch, & Ehleringer, 2007) is a powerful tool for investigating the water source for ET. The use of a dual-isotope approach could systematically help in the separation of distinct water pools in the ecosystem. These pools usually include water used by trees that do not contribute to streamflow or mobile water that is not related to the water used by trees (i.e., groundwater, streamflow, infiltration, and hill slope run-off; McDonnell, 2014). This approach can improve our understanding of the ecohydrological processes controlling water flows in soil–plant–atmosphere continuums (Berry et al., 2016).

Our study of ET and water sources in the Pasoh FR comprised three objectives: (a) measure and calculate ET using the EC method over a 4-year period (2012–2015); (b) determine spatial and temporal patterns of water uptake and provenance, using water budget methods combining ET, precipitation, and soil moisture data; and (c) determine the provenance of water that is transpired at different times of the year by assessing the stable isotope signatures of water in precipitation, soils, plants, and streams. This information is expected to aid understanding of the likely impact of climate change on water demand and supply in tropical rainforests.

## 2 MATERIALS AND METHODS

### 2.1 Site description

The study was conducted in a lowland dipterocarp forest within the 6 ha of Pasoh FR (Figure 1) located at 2°58′N, 102°18′E at approximately 75 to 150 m above sea level. The soil in this area belongs to the local Durian series, which is classified as an ultisol with a yellowish silt-clay layer (40–80 cm thick), overlaying a blocky indurated lateritic horizon (30–40 cm thick) on top of mottled white clay that overlays weathered shale down to a depth of 130–150 cm (Leigh, 1982). The A horizon was thin (0–2 cm) and consisted of brown silty loam, whereas deeper soils were bright yellowish or reddish brown and heavier (light to heavy clay; Yoda, 1978). Lateritic gravel is abundant below 30 cm of depth and increases with depth (Tani et al., 2003; Yoda, 1978). The soil particle size distribution is characterized by low sand and high silt contents (Yamashita et al., 2003). The Durian soil series at 50 cm has 1.50 g cm⁻³ bulk density as well as 39.6% moisture content at 0.33 bar and 8.3% between 0.33 and 15 bars. At the deeper soil layer (100 cm), bulk density was 1.41 g cm⁻³, and moisture content was 46.2% (0.33 bar) and 22.5% (0.33–15 bar), Universiti Pertanian Malaysia, 1979). The underlying rocks at Pasoh FR include shales and sandstones from the Upper Triassic age (Gobbett, 1972; Peh, 1978). The textural details of this soil based on Peh (1978) are listed in Table 1. The maximum depth of tap roots was about 4 m (Niiyama et al., 2010); most of the fine roots were found at the A horizon (Amir Husni, 1989). Most fine roots that have a diameter of 1–2 mm were found at 0–4 cm soil depth, whereas fine roots with a diameter of 3–5 mm were in abundance at 12–16-cm soil depth (based on Figure 7 in Yamashita et al., 2003). Fine roots play an important role in absorbing water and nutrients and in dry matter production. The total fine root biomass down to 2-m depth was estimated at an average of 13.3 Mg ha⁻¹ using a pipe model approach and 16.4 Mg ha⁻¹ using a pit sampling method (Niiyama et al., 2010). The canopy height ranges between 30 and 40 m with emergent trees of ~45 m. Rainfall distribution in Pasoh FR is of short duration and high intensity, with a mean annual rainfall of 1,805 mm (1995–2015) and mean annual air temperature of 25.4 °C (1997–2011) (Noguchi et al., 2003, 2016). Streams in this area are typically shallow with relatively low baseflow (Leigh, 1978). Direct run-off in response to rainfall is dominant, and the streams sometimes dry up during drier periods. Continuous EC flux observations have been conducted at the microclimate observation tower since September 2002 (Kosugi, Takanashi, Tani, et al., 2012; Kosugi et al., 2008; Takanashi et al., 2010) and showed very stable average monthly diurnal ET courses.

Manokaran (1979) reported an annual interception value of 519 mm (21.8%) for Pasoh FR. Subsequently, Tani et al. (2003) recorded an annual interception for Pasoh FR from 1999 to 2000 of 381.3 mm (16.9%). Throughfall ranged between 79% and 94% in this forest (Konishi et al., 2006). In terms of run-off generation, a substantial amount of overland flow was measured using the trap method, indicating a close relationship with the amount of rainfall (Leigh, 1978).
2.2 Micrometeorology and eddy covariance evapotranspiration

Continuous EC flux observations commenced in September 2002. In this study, we analysed the 4 years of data from 1 January 2012 to 31 December 2015, which is compatible with water sampling for isotope analysis. EC fluxes of sensible heat and water vapour were measured at a height of 54 m on the flux tower. Wind velocities and temperatures were measured with a three-axis sonic anemometer (SAT-550; Kaijo, Tokyo, Japan). Water concentrations were monitored with an open-path CO2/H2O analyser (LI-7500, Li-Cor, Lincoln, NE). Data were sampled at 10 Hz and sent to a data logger (CR-5000 or CR-1000, Campbell Scientific, Logan, UT). Momentum, sensible heat (H, W m⁻²), and latent heat (λE, W m⁻²) fluxes were calculated as 30-min averages. Double rotation (McMillen, 1988) was applied, assuming a zero mean vertical wind. The Webb–Pearman–Leuning (Webb, Pearman, & Leuning, 1980) correction for the effect of air density fluctuations was also applied, and linear trends in temperature and water vapour were retained. Our EC measurements of ET included transpiration, interception evaporation, and soil evaporation. We discarded all latent heat flux data recorded during and after rainfall; however, this gap was filled using available energy and sensible heat flux data measured using a three-dimensional ultrasonic anemometer, which can collect data during rainfall. A detailed description of these methods and instruments is provided by Kosugi and colleagues (Kosugi, Takanashi, Tani, et al., 2012; Kosugi et al., 2008). The energy budget correction was executed to overcome the energy imbalance problem described by Takanashi et al. (2010) in estimating ET. Both sensible and latent heat fluxes are corrected using the Bowen ratio to produce zero energy imbalance (Kosugi, Takanashi, Tani, et al., 2012). Gaps were further filled using a second-order polynomial relationship between 30-min λEs after the energy budget correction method, and the available
energy ($R_{n-G-S}$) was determined. Available energy is composed of net radiation ($R_n$), net soil heat flux ($G$), and net change in the storage term ($S$). Net radiation ($R_n$) refers to the balance of all the incoming and outgoing radiation on the Earth's surface. Net soil heat flux ($G$) refers to the conduction of energy per unit area in response to a temperature gradient. The net change in the storage term ($S$) refers to the stored energy under the reference height within a forest canopy (Ohtani et al., 1997).

Available energy ($R_{n-G-S}$) was obtained from measurements of both incoming and reflected short-wave radiation (MR22, EKO, Japan, or CMA6, Kipp & Zonen, The Netherlands) and long-wave radiation (Precision Infrared Radiometer, Eppley, RI, or CGR3, Kipp & Zonen, The Netherlands) at a height of 52 m and soil heat flux (HFP01, Hukseflux Thermal Sensors B.V., The Netherlands) measurements at a depth of 0.02 m monitored at three points around the flux tower. The energy released by changes in the air, vapour, and trunk storage was estimated using temperature and vapour pressure differences at a depth of 0.02 m monitored at three points around the tower. These data were compared and corrected with the rainfall measurements at the top of the tower based on Ohtani et al. (1997). Air temperature and humidity at a height of 52 m were observed using an HMP45A instrument (Vaisala, Vantaa, Finland). An Assmann psychrometer (SY-3D, Yoshino Keiki, Japan) was used to calibrate the Vaisala sensors periodically. The vapour pressure deficit (VPD) of the air was calculated from these data. Tipping-bucket rain gauges (Ota Keiki 34-T, Japan) were used to measure rainfall at the top of the 52-m flux tower and at an observatory located 430 m away from the tower. These data were compared and corrected with the rainfall measured with a storage gauge at the observatory. The volumetric soil water content (VSWC) was measured using time domain reflectometry sensors (CS615 or CS616, Campbell Scientific) at depths of 0.1, 0.2, and 0.3 m at three points around the tower logged at the 30-min intervals (Noguchi et al., 2016). This layer contains the majority of the fine roots. The mean rooting depth in a mixed dipterocarp forest has been identified as 2.35 m (Baillie & Mamit, 1983). We used the daily average value of these nine sensors as a reference VSWC for the surface layer between 0 and 0.5 m. The time domain reflectometry sensors were calibrated using the standard procedure for calibrating capacitance sensors outlined by Starr and Paltineanu (2002), which consists of nine steps (Noguchi et al., 2016). Solar noon in this site peaks around 01:00 p.m. local time (Kosugi, Takanashi, Tani, et al., 2012). The antecedent precipitation index (API60) was tested and found to have a significant relationship with the VSWC (Noguchi et al., 2016) and was therefore used as a wetness index in this study area. The API60 is defined as $\sum_{i=1}^{60} P_i / i$, where $P_i$ is the daily precipitation (mm) and $i$ is the number of preceding days (Kosugi et al., 2007).

### 2.3 Isotope signatures of water in precipitation, stream, plants, and soil

A storage-type rain gauge with a double-layered small-mouth inner glass bottle was installed at the observatory station to collect rainwater samples and was buried in the ground to prevent heating and evaporation. The storage gauge has a collar and is surrounded with a sponge to prevent splash-in from surrounding soil during rainfall. Rainwater samples for isotope analysis were collected daily at 8:00–9:00 a.m. from September 2012 to December 2015, using several 10-ml polyethylene terephthalate or glass bottles with no air space to prevent evaporation. Stream water samples were collected on 19 occasions between January 2013 and December 2015 from the main stream between the 6-ha plot and the 50-ha plot (about 500 m away from the flux tower). The collected samples included base flow and storm flow. Out of 19 samples, four samples were collected within 24 hr after rainfall (4 April, 17 June, 29 October, and 9 December 2015), whereas five samples were collected 48 to 72 hr after rainfall occurrence (5 August, 23 September, 15 October, 19 November, and 15 December 2015); however, these samples were not taken during the rainfall. We collected eight samples when there had been no rainfall for more

#### Table 1  Soil texture composition at Pasoh Forest Reserve

| Site                        | Sampling depth (cm) | Sand (%) | Silt (%) | Clay (%) | Silt and clay (%) | Silt-to-clay ratio |
|-----------------------------|---------------------|----------|----------|----------|-------------------|-------------------|
| Total pore space (%)        |                     |          |          |          |                   |                   |
| Saturation point (%)        |                     |          |          |          |                   |                   |
| Field capacity (%)          |                     |          |          |          |                   |                   |
| Permanent wilting point (%) |                     |          |          |          |                   |                   |
| Pasoh field study           |                     |          |          |          |                   |                   |
| (average of 54 samples)     | 5                   | 30       | 45       | 25       | 70                | 1.80              |
| Pasoh (Pit 1)               |                     |          |          |          |                   |                   |
| 5                           | 25                  | 45       | 30       | 75       | 1.50              |
| 20                          | 10                  | 42.5     | 47.5     | 90       | 0.90              |
| 60                          | 70                  | 7.5      | 22.5     | 30       | 0.33              |
| 100                         | 5                   | 37.5     | 57.5     | 95       | 0.65              |
| 140                         | 12.5                | 40       | 47.5     | 87.5     | 0.84              |
| Pasoh (Pit 2)               |                     |          |          |          |                   |                   |
| 5                           | 31.5                | 47.5     | 15       | 62.5     | 3.17              |
| 20                          | 27.5                | 47.5     | 25       | 72.5     | 1.90              |
| 50                          | 25                  | 45       | 30       | 75       | 1.50              |
| 100                         | 47.5                | 27.5     | 25       | 52.5     | 1.10              |
| 140                         | 5                   | 37.5     | 57.5     | 95       | 0.65              |

Source: Peh (1978).
than a week. Samples were filtered and transferred into two 10-ml polyethylene terephthalate bottles for stable isotope analysis.

Soil and plant samples were obtained from the area surrounding the flux tower at Pasoh FR (Figure 1). Four sampling events were conducted for eight species of plants of different sizes and soils at different depths. Sampling days consisted of a dry period (19 June 2013), very dry period (12–13 March 2014), very wet period (28–29 November 2014), and wet period (08 January 2015; Table 2). Twig samples \( (n = 3) \) from each of eight selected species available surrounding the flux tower were collected during each sampling event and were cut into small segments and placed into 30-ml vials, sealed, and placed in a cool box before being frozen in the laboratory. The species selected from emergent trees to the forest floor trees were *Dipterocarpus sublamellatus*, *Xanthophyllum stipitatum*, *Ptychopyxis caput-medusae*, *Syzygium rugosum* (Kelat), *Diplospora malaccensis*, *Homalium dictyoneurum*, *Baccaurea parviflora*, and *Macaranga lowii* (Table 3). Soil samples were collected the same day or the next day with care to prevent soil mixing between preceding layers and in the current soil layer. Auger holes were dredged several times before sampling in the laboratory before water extraction. Soil sampling was undertaken with xylem samples near the flux tower (Figure 1) at soil depths of 0.05, 0.3, 0.75, 1.5, and 3.0 m. We did not find any presence of groundwater within 3 m of the surface during the sampling event. There was no rain over the course of these two sampling days. Soil samples \( (n = 3) \) were obtained using a hand auger at each depth, placed in 30-ml vials, sealed, and placed in a cool box to prevent evaporation. All plant and soil samples were frozen in a refrigerator \( (−15 \text{ to } −20 \, \text{°C}) \) in the laboratory before water extraction. Soil sampling was undertaken with care to prevent soil mixing between preceding layers and the current soil layer. Auger holes were dredged several times before storage to ensure no material from the preceding layer was included in the current sample. Tiny roots, stones, and leaf litter were separated from samples to prevent contamination. Water extraction was conducted using a cryogenic vacuum distillation system (West, Patrickson, & Ehleringer, 2006). Cryogenic vacuum extraction is the most widely utilized method for plant and soil water extraction (Ingraham & Shadel, 1992; Koeniger, Marshall, Link, & Mulch, 2011; Orlowski et al., 2013; Vendramini & da S. L. Sternberg, 2007; West et al., 2006). We treated water extracted from plants with granulated activated charcoal to adsorb organic compounds that may influence the isotope contents of the samples (West et al., 2006). The samples treated with granulated activated charcoal were kept for 1 week before being transferred into measurement vials.

All water samples, including precipitation, stream, plants, and soil, were filtered using a phobic polytetrafluoroethylene filter (with 13-mm diameter and 0.45-μm pore size) and transferred into 2-ml vials (C5000-54G) in the laboratory for isotope analysis. A cavity ring-down spectrometer (L2120-i, Picarro, CA) was used to analyse the isotope composition of the samples; this device had a specific analytical precision of 0.06‰ for \( \delta^{18} \text{O} \) and 0.11‰ or less for \( \delta^2 \text{H} \) (Katsuyama, 2014). The delta (\( \delta \)) notation indicates the isotopic ratio value of a water sample with respect to the Vienna Standard Mean Ocean Water. For plant water, we compared the isotope contents for both untreated samples and samples treated with granulated activated charcoal and observed that the results for both cases were very similar (especially in the case of \( \delta^{18} \text{O} \)), although the treated samples sometimes showed less negative \( \delta^2 \text{H} \) values by several per mille when \( \delta^2 \text{H} \) values were low. The results for treated samples are discussed in this study.

### TABLE 2 A list of each sampling day, including the antecedent precipitation index (API60)

| Sampling day          | Plant sampling day | Soil sampling day | Dryness       | API60       |
|-----------------------|--------------------|-------------------|---------------|-------------|
| 19 June 2013          | 19 June 2013       | 19 June 2013      | Dry           | 8           |
| 12–13 March 2014      | 12 March 2014      | 13 March 2014     | Very dry      | 0.4 (12 March) 0.4 (13 March) |
| 28–29 November 2014   | 28 November 2014   | 29 November 2014  | Wet           | 41.8 (28 November) 30.0 (29 November) |
| 8 January 2015        | 8 January 2015     | 8 January 2015    | Wet           | 31.8        |

### TABLE 3 The list of species and heights selected in this study

| ID  | Species                  | Height (m) | DBH (cm) |
|-----|--------------------------|------------|----------|
| G1  |                          |            |          |
| D.s.| *Dipterocarpus sublamellatus* (Keruing) | 45         | 42.5     |
| S.r.| *Syzygium rugosum* (Kelat)       | 25         | 23.0     |
| B.p.| *Baccaurea parviflora*         | 5          | 2.9      |
| M.J.| *Macaranga lowii*           | 3          | 2.1      |
| G2  |                          |            |          |
| X.s.| *Xanthophyllum stipitatum*     | 33         | 52.5     |
| D.m.| *Diplospora malaccensis*       | 17         | 12.5     |
| H.d.| *Homalium dictyoneurum*       | 12         | 7.0      |
| G3  |                          |            |          |
| P.c.| *Ptychopyxis caput-medusae*     | 32         | 38.2     |

Species were selected based on accessibility from the flux tower.
3 | RESULTS

3.1 | Micrometeorology and eddy covariance evapotranspiration

Pasoh FR shows a monsoonal rainfall characteristic, with two major peaks between April and May and between October and December forming a bimodal pattern (Figure 2a). Considerable variation in rainfall was observed between years. The highest monthly rainfall was observed during October, November, and December in each year, ranging between 137 and 367 mm month$^{-1}$ (Figure 2a, Marryanna et al., 2017). The annual rainfall from 2012 to 2015 fluctuated between 1,624 and 1,850 mm on average ± standard deviation of 1,720 ± 101 mm. The number of rainy days for 4 years was an average of 158 ± 13.3 days per year, and the average ± standard deviation of the yearly maximum length of rainless periods was 21.5 ± 8.8 days. These years were characterized as rather dry periods compared with the 21-year statistics on annual rainfall (1,805 ± 280 mm), the number of rainy days (162.38 ± 16.3 days), and the average ± standard deviation of yearly maximum length of rainless periods (16.6 ± 5.8 days) from 1995 to 2015. The VSWC declined in February and March of both 2014 and 2015, including a value of 0.288 m$^3$ m$^{-3}$ observed on the driest day among the observation periods, on 15 March 2014, coinciding with a very small monthly rainfall amount (7.7 mm month$^{-1}$, February 2014) and API60 (0.2 mm; Figure 2b). The average and median API60 values were 22.2 and 18.3 mm, respectively. The average and median VSWC values were 0.351 (±0.028) and 0.352 m$^3$ m$^{-3}$. Annual ET values were 1,200 (2012), 1,208 (2013), 1,156 (2014), and 1,163 mm year$^{-1}$ (2015; Figure 2c). The annual average ET value was 1,182 ± 26 mm for the 4-year period. The percentage ratio of ET to precipitation ranged between 62% in 2014 and 74% in 2015. Daily ET rates plotted alongside 30-day running averages (Figure 2d) showed a generally stable trend, although several declining values were detected in daily ET in the rainy season at the end of the year (November and December), and in some dry periods (February and March in 2014 and 2015). Water evaporation from the forest was observed every day even in the driest period, and ET was generally stable, with average and standard deviation values of 3.24 ± 0.86 mm day$^{-1}$ (Figure 2d). Daily ET increased in proportion to available energy when VSWC was high, and it decreased with a low VSWC (Figure 3a). The ET reaches a ceiling at high VPD, whereas at low VSWC during drier periods, a small decrease in ET was observed with high VPD, indicating stomatal closure (Figure 3b).

3.2 | Soil water budget

Comparing ET with water budget in the soil provides some insight into the source of water for ET (Figures 4 and 5). Figure 4 compared the
cumulative ET and precipitation for several antecedent timescales to evaluate the minimal storage period of water for ET during dry condition. If water for ET is supplied from 1-month antecedent precipitation, the forest will show a clear lack of water supply. This is shown during the sampling events on 19 June 2013 and 12–13 March 2014 (Figure 4a). In this case, the 1-month antecedent water supply was not sufficient for plant consumption. Even if a further preceding month had been included (2-month antecedent water supply), there was insufficient water to accommodate plant water use for the period between 12–13 March 2014 (Figure 4b), and even the 4-month antecedent water supply was insufficient for plant water use. During the severe dry period (12–13 March 2014), at least 4 months of reserved water was required in Pasoh FR to accommodate ET demand. A substantial amount of overland flow at the slope of this site was previously observed (Leigh, 1978; Peh, 1978). However, some portion of such overland flow is assumed to infiltrate before reaching the stream. If this flow were taken into account, considerable water supply to the soil would be expected. Nevertheless, the water supply would still be less than indicated by the antecedent precipitation values shown in this figure.

Figure 5 examined the comparison between ET demand and water budget in the surface soil layer to evaluate the source depth of water for ET. The ET demand was calculated as the cumulative budget of rainfall and ET. If this flow were taken into account, considerable water supply to the soil would be expected. Nevertheless, the water supply would still be less than indicated by the antecedent precipitation values shown in this figure.

Figure 3 compared between daily evapotranspiration (mm day$^{-1}$) and (a) daily available energy (MJ m$^{-2}$ day$^{-1}$) and (b) daily average vapour pressure deficit (VPD, hPa). Black and white dots represent daily average volumetric soil water content (VSWC) values that were more than and less than 0.32, respectively. The daily available energy is the sum of net radiation, net change in heat flux to soil, and heat flux to stem air and vapour in the canopy space.
whereas if the decline slope of the water budget of the surface soil layer is shallower than that of evaporative demand, water is supplied from deeper layers. Note that the soil water storage differentials in soils at depths of 0–0.5 m are the result of not only ET but also drainage to the deeper layer. Because we did not account for the drainage portion, we should expect some overestimation if we consider that the differential was used only for transpiration and soil evaporation. We should also note that the comparison in this figure becomes too complicated during and just after rainfall, which includes interception evaporation, water input from the soil surface, and drainage to the deeper layer. Figure 5a demonstrated that, spatially, plants in Pasoh FR usually obtained their water supply from the surface soil layer (0–0.5 m) and from the deeper layer when the soil water content at 0–0.5 m decreased. For example, at the beginning of 2014 and 2015, when the slope of the water budget declined drastically compared to that of the surface soil water budget, it can be inferred that plants used a substantial portion of water from deeper soil layers. The individual trend on each sampling day was investigated (Figure 5b). The declining slopes of evaporative demand in June 2013 and March 2014 were greater than the declining slopes of soil water storage at 0–0.5 m. Approximately 50% of ET demand in June 2013 and only 10% in March 2014 were supplied from surface soil layers. This indicates that water was supplied from deeper soil layers. In November 2014 and January 2015, the declining slopes of the water budget of surface soil water and ET demand could not be compared simply because of rainfall intermissions, although similar decline slopes for the ET demand and surface layer soil water budget were observed, with a slightly larger ET demand.

3.3 Stable isotope signatures of plants, soil, and stream water

Figure 6 provides an overview of how water is compartmentalized for different uses in the forest ecosystem. The daily δ18O in precipitation in Pasoh FR varied considerably (Figure 6a, Marryanna et al., 2017). The δ18O value in precipitation during the monsoon onset in May (south-west) and November (north-east) tended to decrease and was lower during the middle of the rainy season compared to the beginning of the rainy and drier seasons. The isotope value was depleted when rainfall was greater (Marryanna et al., 2017). The δ18O values of the occasional stream water samples showed a similar time series trend to the rainwater isotope value (−4.97 ± 1.9, n = 19). Substantial fluctuations in δ18O in stream water were detected, corresponding well to those in precipitation. The δ18O values in soil water at deeper soil layers (3.0 m) were generally stable for the whole observation period regardless of season and thus sometimes showed more negative values (−7.80 ± 0.29) compared to the 30-day running average of these values in precipitation. Larger temporal fluctuations were observed in surface soil layers (0.05 m: −6.67 ± 1.96; 0.3 m: −7.92 ± 1.44).

Considering the relationship between δ18O and δ2H (Figure 6b), stream waters had isotope values corresponding more closely to rainwater, whereas isotope signatures in surface soils (0.05 and 0.3 m) and plant water tended to deviate to the right side of the local meteoric water line (LMWL) of rainwater isotopes. This phenomenon indicates the influence of evaporation. This deviation was not observed in the deeper layer. Temporal fluctuations in soil water (Figure 6c) were greater at the surface (0.05 m) and became smaller in the deeper soil layer. The fluctuation was smallest in the deepest layer (3.0 m). Isotope values of plant water (Figure 6d) largely deviated to the right side of the LMWL and also plotted out of the range of soil water isotopes. Three rough groupings could be identified in the plots for plant water (Table 3): Group 1 with medium isotope values that fell within or near the range of soil water isotopes (D. sublammellatus, 45 m; S. rugosum, 25 m; B. parviflora, 5 m; and M. lowii, 3 m), Group 2 with more negative plant water isotope values that were clearly out of the range of soil water isotopes (H. dictyoneurum, 12 m; D. malaccensis, 17 m; and X. stipitatum, 33 m), and Group 3 showing less negative δ18O and δ2H values with smaller temporal fluctuations (P. caput-medusae,
32 m). The temporal fluctuations of plant water isotope values in the first (circles) and second (triangles) groups, as can be seen from the standard deviations of plant water isotope values ($\delta^{18}O$) for each species in Figure 6d, were similar in size to the temporal fluctuations in isotope values for upper layer soil water (0.05, 0.3, and 3.0 m, Figure 6c) and larger than those for deeper layer soil water (1.5 and 3.0 m). For $P$. caput-medusae, the temporal fluctuation was smaller and similar to those of deeper layer soil water; however, their average values were significantly different, which indicates that $P$. caput-medusae did not use this water.

During the dry period (Figure 7a; 19 June 2013), for 30-day antecedent rainfall, most plant water isotopic contents were different from rainwater, whereas for longer (60-day) antecedent rainfall, rainwater isotopic contents corresponded with plant and soil water, although plant water still deviated slightly from the rainwater meteoric water line, especially in the case of Group 2 species. During the very dry period (12–13 March 2014; Figure 7b), most rainfall values were larger than soil and plant water values for 60-day antecedent rainfall, and 120-day antecedent rainfall should be analysed to identify the source water for plants and soils. The isotope values of plant water became closer to those of soil water in this very dry period, and both soil and plant water (except at 3.0-m soil) deviated from the rainwater meteoric water line. The isotope values of plant water for each of the three groups can be explained by the soil water mixture. During very wet periods in the rainy season (Figure 7c; 28–29 November 2014), the soil and plant water isotopic signature corresponded with the rainwater meteoric water line for 30-day antecedent rainfall but did not fall within the range of antecedent rainfall between 31 and 60 days. Soil water at all depths did not show any deviation from rainwater. However, the plant water of Group 2 and Group 3 species showed a deviation to the right side of the LMWL. The isotope values of plant water were more negative and out of the range of soil water in Group 2 species. During the wet period at the end of the rainy season (Figure 7d; 8 January 2015), both plant and soil water corresponded relatively closely to rainwater isotope signatures in the 30- and 60-day antecedent rainfall. Most water (except $P$. caput-medusae in Group 3) did not show any deviation from the LMWL; however, plant water from Group 2 species had more negative values and was out of the range of soil water. Isotope signals from different tree heights and species at different periods did not show any clear tendency towards a specific water uptake depth (Figure 7). Plant water isotope values were mostly deviated to the right side of the rainwater LMWL (except Groups 1 and 2 on 8 January 2015). They also differed from the values of soil water at any depth and became closer to those of soil only in the very dry period.

4 | DISCUSSION

4.1 | Micrometeorology and eddy covariance evapotranspiration

Pasoh FR has typical monsoon-type rainfall variations (Figure 2a,b). It has significant interannual variations, with a bimodal pattern consisting of two distinct peaks; during March to May and October to December (Marryanna et al., 2017). Using long-term average climate records, this area falls under the Af (tropical rainforest climate) in the Köppen-Geiger climate classification scheme and is located within an equatorial region that hosts a fully humid climate (all months of the year are warm). This is the synoptic climate of Southeast Asia that is
predominately affected by the annual cycle of the Asian Monsoon, with defined wet and dry seasons (Tanaka et al., 2008). During the El Niño events in 2014–2015, the study site experienced two drought periods at the beginning of the year (February and March).

It should be noted that annual ET values during the study period (2012–2015) were lower than in most normal years (1,287 ± 52 mm, 2003–2009, Kosugi, Takanashi, Tani, et al., 2012). The 7-year average annual value of ET found by Kosugi, Takanashi, Tani, et al. (2012) is in a range similar to those of two Amazonian rainforests, Manaus (1,307 mm, Da Costa et al., 2010) and Santarem (1,274 mm, Da Costa et al., 2010). Another Malaysian lowland tropical rainforest, Lambir in Borneo, also showed a similar value (1,323 ± 74 mm, Kume et al., 2011), which was estimated using a Penman–Monteith model parameterized with occasional EC measurements. Indonesian peat swamp forests show larger values (1,636 ± 53 mm, Hirano, Kusin, Limin, & Osaki, 2015), and one half-deciduous tropical forest in Xishuangbanna,

FIGURE 7  The relationship between δ¹⁸O (‰) and δ²H (‰) of rainwater, soil water, and plant water for (a) 19 June 2013 (dry, antecedent precipitation index [API60] = 8), (b) 12–13 March 2014 (very dry, API60 = 0.4), (c) 28–29 November 2014 (wet, API60 = 30–42), and (d) 08 January 2015 (wet, API60 = 32). Individual plant and soil water isotope values are shown in this figure to analyse plant water uptake characteristics in different wetness periods (wet to very dry periods) and different plant species. Syzygium rugosum (S.r.) was not sampled in 19 June 2013. Antecedent rainfall is also plotted to identify water sources.
Southwest China, showed a smaller value (1,029 ± 29 mm, Z. Li et al., 2010). Here we only cited the values based on EC measurement and after correction or consideration of energy budget imbalances. EC methods often suffer energy imbalance problems, whereas water budget methods suffer from an unknown water supply in deeper layers. Thus, careful comparisons of the ET values in the literature are needed in the future to clarify the ET traits of tropical forests.

During the driest period, the ecosystem of Pasoh FR was still showing considerable ET (Figure 2c,d). Similar ET stability was seen in several other EC flux studies conducted in Amazonian and Southeast Asian tropical rainforests (e.g., Costa et al., 2010; Da Rocha et al., 2004; Kume et al., 2011; Malhi et al., 2002). Nepstad et al. (1994) reported that some rainforests are able to extract soil water even in the dry season because of deep rooting depths. In Pasoh FR, the rooting depth was concentrated in the A horizon (Amir Husni, 1989) but extended down to 4 m (Niiyama et al., 2010). On the basis of energy imbalance filtering data, ET was stable with a slight increase in the dry season in central Amazonian rainforest sites, whereas in drier semideciduous sites, it showed a slight decrease during the dry season (Costa et al., 2010). This site-dependent difference was caused by differences in the increasing radiation energy and the stomatal behaviour during the dry season. ET is mainly determined by atmospheric evaporative demand (e.g., Carswell et al., 2002; Da Rocha et al., 2004; Z. Li et al., 2010) and stomatal control (e.g., Cunningham, 2004), the latter of which is influenced by the factors related to water supply, such as available water in the soil (e.g., Burgess, Adam, Turner, & Ong, 1998; Rafael, Todd, Burgess, & Nepstad, 2005), rooting depth (e.g., Z. Li et al., 2010; Nepstad et al., 1994), and upward flow in the soil (e.g., Da Rocha et al., 2004; Z. Li et al., 2010). In Malaysian tropical rainforests located near the equator (Costa et al., 2010; Da Rocha et al., 2004; Kume et al., 2011; Tani et al., 2003). The variability of daily ET at Pasoh was dependent on available energy and VPD but was also moderately influenced by soil water content (Figure 3a,b, Kosugi, Takanashi, Tani, et al., 2012). During El Niño events in 2014–2015, Pasoh FR experienced drought periods and plants regulated stomata to prevent excessive moisture loss under the high VPD conditions (Figure 3; Cunningham, 2004). However, the stability of ET was not greatly influenced by the amount of rainfall, because the forest transpired water even during dry periods such as in February and March in 2014 and 2015 (Figure 2c,d), although there was a moderate decrease in transpiration. ET was still detected during the driest months of the observation period. Under these conditions, the large rooting depth for lowland rainforests on sufficiently deeply weathered substrates suggested by Nepstad et al. (1994) and Z. Li et al. (2010) could be the driving factor. The drought-tolerant tree and deep root system (Hodnett, Tomasella, Marqués, De, & Oyama, 1996; Nepstad et al., 1994) could also be the underlying factor. ET decreased in the rainy season because the available energy and temperature decreased. It has been reported (Kosugi, Takanashi, Tani, et al., 2012) that this forest used on average (±standard deviation) 1,287 ± 52 mm year⁻¹ for ET during 2003 and 2009. These values were slightly higher compared to those found in this study during 2012 and 2015 (1,182 ± 26 mm). This is probably because of the drier conditions during these 4 years.

### 4.2 Water budget in the soil

Soil water content is a major control of hydrological processes such as ET, the precipitation run-off response, energy transfer, and a climate predictor (e.g., Betts, Ball, Beljaars, Miller, & Viterbo, 1996). The soil water budget is a useful method for estimating total water loss from the soil caused by transpiration and soil evaporation (Wilson, Hanson, Mulholland, Baldocchi, & Wullschleger, 2001) once soil water content has dropped below field capacity. The other benefit of the soil water budget is that it can provide insight into the relative contribution of various rooting depths to total transpiration sources (e.g., Teskey & Sheriff, 1996). This forest needs at least four months of water storage to accommodate the ET demand during extended dry periods (Figure 4). The typical clay soil in Pasoh FR would delay water infiltration into the soil during rainfall and therefore contribute to overland flow. This means that the required water storage period should be longer than the analysis shown in Figure 4. During dry periods, soil may experience excessive drying, and plants therefore need to use the previous water storage that is more strongly bound to soil particles.

The slope of ET demand (Figure 5b) is an important indicator of the water change in the soil. When water supply from a specific soil layer is less than the ET demand, the forest may obtain supplies from other sources. The analysis in Figure 5 shows that in Pasoh FR, the forest mainly acquired water from the surface layer; however, during dry periods, insufficient water was available and water was acquired from deeper layers through the rooting system. The soil moisture content for soils at a depth of 0.05 m in this forest was reported to have an average field capacity of 34.6%, a permanent wilting point of 21.9%, and a saturation point of 46.9% (Peh, 1978). In dry periods, the observed ratio of water supplied from deeper layers (<0.5 m) ranged from approximately 50% to 90%, depending on the intensity of dryness. On the basis of our occasional observations of soil water content at 0.05-, 0.3-, 0.75-, 1.0-, 2.0-, and 3.0-m soil depths (Noguchi et al., unpublished data), very little fluctuation was detected at 2.0 and 3.0 m. If we assume fluctuations in soil water content in the layer between 0.5 and 1.0 m were the same as those at the surface layer between 0 and 0.5 m, then an additional 50% of water supply can be explained in the case of normal dry periods such as June 2013. In an extremely dry period such as March 2014, the forest will consume the water from the much deeper layer. The maximum depth of roots in Pasoh FR was about 4 m, and it was noted that fine roots were still found at 4-m depth (Niiyama et al., 2010). This finding supports our result.

### 4.3 Plant and soil water isotopes

Rainwater is partitioned into three components: (a) interception loss, (b) infiltration excess overland flow, and (c) water infiltration to soil. Infiltrated water is divided between percolating water held at tension below field capacity (drainable pore space), plant-available water held at tension between field capacity and permanent wilting point (water available for plant ET), and immobile residual water not participating in the hydrological cycle. Our results (Figures 6 and 7) strongly suggest that water sources for stream, plants, and soil at this forest, corresponding to infiltration excess overland flow + water infiltration to soil,
plant-available water held at tension between field capacity and permanent wilting point, and immobile residual water not participating in the hydrological cycle, respectively, are separated.

Large fluctuations in isotope values in stream water corresponding with rainwater (Figure 6a) indicate that the portion of new water run-off is large in this watershed. Streams lose water flow during severe drought periods at this site. Due to the rainfall characteristics in Pasoh FR, which is intense and of short time duration (Noguchi et al., 2003), and the clay soils with low permeability, overland flow is often observed at the slope (Leigh, 1978; Peh, 1978). Our results are consistent with this. Generally (e.g., Clark & Fritz, 1997), the isotope values in stream water will lie close to the long-term weighted mean value for rainwater because stored, well-mixed groundwater maintains the streamflow. We need more intensive data of stream water to check this consistency and to obtain more precise partitioning of run-off pathway in this site.

Soil and plant water showed different characteristics from stream water and, additionally, differed from each other (Figures 6 and 7). Only in the very dry period did plant and soil isotope values become closer, because plants used water from the same reservoir in the soil. Clay soil typically has higher saturated and residual soil water content in the water retention curve, and hence a substantial portion of the water is strongly bound to soil particles and is not available to plants. This most likely explains the different water sources between soils and plants at the study site. Interactions between the matrix and the gravitational potential lead to pores, with the largest diameter filling first and pores with the smallest diameter draining last and containing immobilised water compared to the larger pores (Brooks et al., 2010). Evaporation from soil decreases rapidly with depth, and thus, plant roots are the primary cause of soil drying to below field capacity. Additionally, water with the longest residence times in soil is more likely to be removed by plants and not delivered to the stream during dry seasons (Brooks et al., 2010). This situation was also observed in our study during the driest sampling period (June 2013 and March 2014, Figure 7 a,b), when the isotope compositions of plant waters were similar to soil water and deviated from rainwater. This could indicate that plants are using water with the longest residence time and bound tightly to soil particles to supply their ET demand during dry periods. We did not test how tightly the water was bound to the soil, and this could be a significant topic for future study. However, it can at least be inferred from Figure 2 that the VSWC of soils from the study site was approximately 0.28 m$^3$ m$^{-2}$ in the driest period; thus, this value should be close to the residual soil water content. This means that the soil contained more than 20% water that was very tightly bound to soil particles, and thus inaccessible to plants. This amount of water would be included in the soil even in the wettest period, and we can conclude that this is one of the main reasons for the isotopic difference between water from soil and plants. The two only became similar in the very dry period.

Both the deviation in isotope values for plant water to the right side of the LMWL and the similarity in the range of fluctuation in the isotope values of plant water and soil water at the surface soil layer suggest that a substantial part of plant water was supplied from the surface soil layer. However, it should also be noted that the isotope values of plant water could not be explained entirely by surface soil water isotope values; this suggests plant water uptake also includes water in deeper soil layers. This analysis is consistent with the results of the water budget analysis shown in Figure 5.

It has been assumed that plants take up water according to their height (Kim, Park, & Hwang, 2014) and rooting depth (Meinzer, James, & Goldstein, 2004). Water uptake and transport are associated with a hydraulic flow process that is controlled by resistance and hydraulic gradients (Honert, 1948). The overall resistance is determined by soil water potential, conducting vessels, transpiration rate, plant height, and gravity (Kim et al., 2014); however, the results from this study do not necessarily reflect this trend. The isotopic signals from trees of different height and species did not show any clear tendency of water uptake depth during the study period. From these results, we could not distinguish whether shorter or smaller trees use water from the shallow soil layer, whereas taller trees take water from the deeper soil layer. Water uptake by co-occurring woody species showed that some species only take water from deep or shallow soil, whereas others use both layers (Eggemeyer et al., 2009; West et al., 2007). In tropical and subtropical forests, plants typically have shallow roots, meeting their water needs from the surface soil layer due to the plentiful rainfall (Schenk & Jackson, 2005) at lower energetic cost. In contrast, in this study, no difference was evident in the isotope signatures of different plants. The large residual soil water content of the clay soil could be one reason why the isotopic signatures of plant water did not show any clear tendency with water depth. Soil water extraction techniques and soil properties would also be associated with variability in isotopic values (Orlowski et al., 2016). The comparison of different extraction techniques for different soil types (sandy and clay soils) identified that differences between the methods were small in sandy soil but large in clay soils (Figueroa-Johnson, Tindall, & Friedel, 2007; Orlowski et al., 2016). Despite this, there are still many factors that may influence isotopic unfraccionated water, and as a result, this issue remains poorly understood and there is a need for further studies (Munksgaard, Cheesman, Wurster, Cernusak, & Bird, 2014; Orlowski et al., 2016). The centrifugation method to extract soil water, which can collect only capillary water with a certain limit of capillary pressure, could be used for this purpose.

Our study also found some classifications for plants in terms of water isotope characteristics. Group 1 showed isotope values close to that of soil water. This group consisted of an emergent tree (D. sublamellatus), two forest floor trees (M. lowii and B. parviflora), and a middle-sized tree (S. rugosum). Group 2 showed more negative isotope values that were out of the range of soil water, but still within the range of the antecedent rainwaters. All three trees in Group 2 were middle-sized trees (X. stipitatum, H. dictyoneurum, and D. malaccensis). The Group 3 tree (P. caput-medusae) was also middle sized and showed very stable and less negative isotope values during the whole observation period; however, these values differed from those of the deepest layer soil water. Some Group 2 (X. stipitatum) and Group 3 (P. caput-medusae) trees have small stomatal conductance and maximum photosynthesis (Kosugi, Takanashi, Yokoyama, et al., 2012). These may be protective mechanisms allowing trees to retain more water in their xylem to prevent water loss, and the portion of storage water may be large. As the portion of newly absorbed water in xylem becomes smaller, the characteristics of isotope values would shift from that of Group 1 to Group 2 and finally to Group 3. Group 3 may store more
water inside the xylem, rendering these plants more drought resistant. All trees in Groups 2 and 3 are medium-sized trees, which may indicate the origin of these characteristics. We found smaller stomatal conductance and photosynthesis in middle-sized trees at this site compared with emergent trees (Kosugi, Takanashi, Yokoyama, et al., 2012). These middle-sized trees might suffer from water stress and operate in a highly protective manner (Kosugi, Takanashi, Matsuo, & Abdul Rahim, 2009). The utilization of released water from stored compartments near the canopy may play an important role in mitigating water stress in canopy leaves, thereby maintaining stomatal opening for photosynthesis. Some previous studies have also shown that increased withdrawal of internally stored water occurs during water deficits (e.g., Scholz et al., 2007), whereas others have shown that stem-stored water may be used for buffering the daily water deficit even when soil water is abundant (Goldstein et al., 1998; Holbrook, 1995).

### 4.4 Impact of vegetation on hydrology

Pasoh FR used most of the available water to maintain ET particularly during dry periods in which there was no decrease of ET (Figure 2d). During dry periods, that is, when surface soil water was not available, the forest's root system was able to access water from greater soil depths to maintain ET (Nepstad et al., 1994) corresponding to the existence of a deep unsaturated soil layer in this forest. Our sampling revealed no groundwater within 3 m of the surface, including during the rainy season. Streams in this area are typically shallow with relatively low baseflow (Leigh, 1978). Direct run-off in response to rainfall is dominant, and the streams sometimes dry up during drier periods. This forest is mainly characterized by clay soil (Yoda, 1978), with low sand and high silt soil particle distributions (Yamashita et al., 2003). The physical traits of the clay soil likely influenced the water storage capacity of the watershed available for ET. Streamflow characteristics are typically determined by soil physical traits, topography and geography. In our study area, the uptake of almost all available water by vegetation also influenced streamflow characteristics. In many tropical rainforests with rainfall amounts of ~2,000 mm and having occasional dry period, the amount of run-off is not large, as illustrated by several reviews of hydrology in the humid tropical region (e.g., Wohl et al., 2012). Rather, run-off is typically low and occasionally ephemeral during dry periods due to the large ET demands of rainforest ecosystems.

### 5 Conclusion

Overall, although ET during the observation years was lower than in previous studies, a stable pattern was observed. At least four months of water storage is needed to accommodate ET needs during a very dry season. Spatially, plants in Pasoh FR typically obtained their water supply from the surface soil layer (0–0.5 m) and sourced further water from deeper layers during the dry period. Deep rooting and stomatal control are two well-known mechanisms that allow plants to cope with periods of high atmospheric demand and low water availability. Isotope analysis results show that plants, soil, and stream have different sources of water in this forest. Similarity in rainwater and stream water indicates the dominance of new water run-off. There are occasional isotopic differences between plants and soil water, probably because water source for plants is different from water strongly bounded to the soil. The source of water for this forest does not have a distinct pattern corresponding to soil depth and tree height. The results also suggest the existence and use of water storage in tree xylem. ET at Pasoh FR is balanced and maintained using most of the available water sources except for a proportion of rapid response run-off. This study demonstrates that tropical rainforests show a degree of water stress; under climate change, precipitation amounts and/or pattern are expected to change, which potentially cause not only ET but also shifts in vegetation patterns in the tropical zone.

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