Effects of spatio-temporal distribution of soil moisture on a lowland dipterocarp forest at Pasoh Forest Reserve in Peninsular Malaysia

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2018

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CHAPTER 1

Introduction

1.1 Background

1.1.1 The Tropical Rainforest

Tropical rainforests cover only 7% of the Earth's land surface but account for over 50% of all known plant and animal species and provide a variety of key resources and ecosystem services to humans, including food, drinking water, timber, and medicines (Lewis et al., 2009; Sitch, 2008; Vittor et al., 2009). In Peninsular Malaysia, forested areas represent 5.80 million ha, or 44% of the total area (FDPM annual report, 2014). Tropical rainforests harbour a great diversity of species and play a significant role in the global carbon cycle due to their large biomass and high productivity (Dixon et al., 1994). Given their potential to mitigate climate change, the response of tropical rainforests to environmental disturbance is of critical importance (Tan et al., 2013).

In tropical rainforests, the amount of rainfall and changes in rainfall patterns are of great concern with respect to future climate change and global warming; shifts in rainfall patterns can subsequently influence soil moisture, evapotranspiration (ET), stand dynamics, and many other forest functions. Therefore, to evaluate important effects of future climate change, an evaluation of the influence of moisture on these forest functions is needed.

In Southeast Asian tropical rainforests, few studies have been conducted on soil moisture and forest functions related to climate conditions. The integration of simultaneous field and tower measurements would provide new insights in forestry research. The findings of such a study could be applied to forest conservation and management, rehabilitation and plantation, and evaluation of the Forest Integrity Index and forest water footprint. According to Malaysian National Forestry Policy, forests should be managed for environmental protection, conservation of biodiversity and genetic resources, and to enhance research and education. The public and private sectors are encouraged to intensify forestry research to achieve targets in environmental stability, sustainable forest management, and maximising yield. Hence, this study is anticipated to provide results that may be applied in future environmental stability research as promoted by Reducing Deforestation and Forest Degradation and Enhancing Environmental Services in Tropical Forests (REDDES), whose objective is to maintain and enhance climate change mitigation and other environmental services of tropical forests. The evaluation of climate change effects on specific environmental parameters will enhance mitigation efforts, and subsequently enhance Malaysia's capacity to reduce climate change impacts, particularly through forest functions.

1.1.2 Moisture as an important factor regulating tropical rainforest climatology

Soil moisture is the water content held in the spaces between soil particles (Ali, 2010); it represents a small fraction (0.15%) of the globally available freshwater (Dingman, 1994) but is an influential store of water in the hydrologic cycle and is fundamentally important to many hydrological, biological, and biogeochemical processes. Soil moisture modulates interactions between the land surface and atmosphere, thereby influencing the climate and weather (Delworth and Manabe, 1993; Jung et al., 2010; Mittelbach et al., 2012). Soil moisture is a key component of the hydrological cycle, controlling the partitioning of precipitation between runoff, ET, and deep infiltration (Daly and Porporato, 2005) and determining the rainfall–runoff response of catchments, particularly where saturation excess runoff processes are important (Wei, 1995). Soil moisture affects ET on land, where it is a central process in the climate system and a nexus of the water, energy, and carbon cycles (Wan et al., 2007; Garten et al., 2009; Holsten et al., 2009; Jung et al., 2010; Falloon et al., 2011). As a link between the biosphere and the edaphic zone, soil water plays a crucial role in terrestrial ecosystems by influencing plant growth. If the soil water level falls below a species-specific threshold, plants experience water stress, and decreased soil moisture under warmer conditions can inhibit photosynthesis (Lindroth et al., 1998). The maintenance of such related ecosystem services enhances the productivity of natural ecosystems (Betts, 1999) and helps to sustain biodiversity (Pielke et al., 2002; Rhymer et al., 2010). Soil moisture retention is also an important determinant of water availability in agroecosystems (Power, 2010). As a key factor of soil–plant–atmosphere continuum and the vector of nutrient cycling in the soil system, soil moisture indirectly affects soil characteristics, plant growth, the distribution of plants and variation in ecosystem microclimates (Yun Lei et al., 2011). The ability to use soil moisture varies with plant species and the spatio-temporal dynamics of soil moisture are also variable, often affecting its storage, transportation, and transformation.

There are various feedbacks between soil moisture and the biological and hydrological cycles (Holsten et al., 2009). For example, vegetation can influence the soil water regime by offsetting drier conditions through decreased transpiration, a phenomenon that is expected to occur more frequently in summer months under a warmer climate (Etchevers et al., 2002; Seneviratne et al., 2002; Yang et al., 2003). In addition, dry soils can cause negative feedback by amplifying the impact and duration of heat waves (Brabson et al., 2005) and prolonging the effects of meteorological droughts (Nicholson, 2000). Understanding the patterns of soil moisture distribution is useful to a wide range of agencies concerned with weather and climate, soil conservation, agricultural production and landscape management (Dobriyal et al., 2012). To understand this complex system requires careful measurements of biomass distribution, water absorption, ET and soil water balance. Each component plays important roles contributing to the spatio-temporal distribution of soil moisture and trees.

In tropical rainforests, climate change severely impacts various social factors, including water resource use and human health. Due to the increased frequency of drought events, it is important to determine the specific ecosystem functions affected by soil water status using detailed field observations of the exchange processes of energy and water between terrestrial ecosystems and the atmosphere. Priority should be given to the impact of soil water on plant distribution because the quantity of water present in the soil influences many plant processes, including gas exchange, diffusion of nutrients to plant roots and movement of solutes through root zones. During dry periods, soil moisture plays an important role in controlling ET because soil moisture from deeper soil layers supplies this process. The interaction of spatial and temporal variations in determining water availability is likely an important driver of plant population dynamics that shapes species distributions across habitats (Comita and Engelbrecht, 2009); however, the effects of variation in water availability have rarely been examined.

1.2 Objectives and thesis outline

The objective of this study was to identify moisture sources and estimate water usage in a Southeast Asian tropical rainforest in Peninsular Malaysia, and to evaluate its impact on the forest ecosystem. Three subsequent data chapters address three different objectives:

1) To determine the characteristics of rainfall and stable isotope signatures.

2) To estimate the effect of soil moisture on ET and water sources.

3) To determine the effect of soil moisture on forest stand dynamics.

Chapter 1 is a general introduction to the study framework. This study applies spatial and temporal approaches to understand moisture patterns and their impacts on a tropical forest, the Pasoh Forest Reserve (FR), in Peninsular Malaysia. The temporal variability of oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) isotope signatures in precipitation at the study site is reported in Chapter 2. The daily and seasonal variability of stable isotope signatures in precipitation were analysed, particularly in relation to the effects of monsoon seasons, rainfall characteristics and large-scale trends as compared with those at nearby the Global Network of Isotopes in Precipitation (GNIP) monitoring stations. Chapter 3 evaluates the water use and supporting water sources of a tropical rainforest in a 4-year assessment of ET at the study site. The eddy covariance method and isotope signals of rain, plant, soil and stream water 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 to identify isotopic signals. In Chapter 4, the spatial distribution of volumetric soil water content (VSWC) measured over 1 year were compared in the context of the stand dynamics of the study site. The objective of this chapter was to assess the impact of spatial variation in soil moisture on stand dynamics. Chapter 5 provides a thesis summary and conclusion. The thesis framework is illustrated in Figure 1.1.

1.3 Description of the study site

This study was conducted in a lowland dipterocarp forest within a 6-ha plot in Pasoh FR (Figure 1.2). Pasoh FR is located at 2°58'N, 102°18'E, at approximately 75–150 m.a.s.l. This forest patch, covering an area of 139 km^2, is considered an island forest because it has been isolated from the main Peninsular Malaysian forest range, also known as the Central Forest Spine (CFS). In 1977, the reserve was designated as an FR for a variety of purposes, including production forestry (sustainable timber harvesting) and to protect flora and fauna (conservation and research). An area of 18.4 km^2 was allotted for research purposes; the study plot is located within this area. The reserve is under the custodianship of the State Forestry Department of Negeri Sembilan, and is surrounded by agricultural land, oil palm plantations, and other developed land (Christine et al., 2012).

Low-lying sections of Pasoh FR, particularly in the western portion, become submerged by water during the rainy period (Amir Husni, 1989). The topography of the area varies slightly, ranging from 75 to 150 m.a.s.l; the elevation rises to 600 m at the eastern boundary, where the forest adjoins low granitic hills. Slopes do not exceed 6°, except in the eastern portion, which occasionally reaches 15°. The topography of the forest is lower than that of other tropical lowland forests, such as Lambir in Sarawak (Yamakura et al., 1995). Pasoh FR experiences a northeastern (NE) monsoon from November to March and a southwestern monsoon from May to September; April and October are intermonsoon seasons. There are two major peaks in the monsoon rainfall, in April–May and October–December, forming a bimodal pattern. Rainfall varies considerably between years. The seasons occasionally change in July and August. Mean annual rainfall at the study site is 1,800 (± 285) mm (1996–2015, Marryanna et al., 2017), peaking from March to May and from October to December (Kosugi et al., 2008). These rainy periods are characterised by their short duration and high intensity (Noguchi et al., 2003). The mean annual air temperature is 25.4°C (1997–2011) (Noguchi et al., 2016). Typically, this area receives at least 42.6% of its annual rainfall during the northeastern monsoon (November–March), 39.1% during the southwestern monsoon (May–September), and the remaining 18.4% during the transitional months (April and October) (Noguchi et al., 2003). The study area is located within a dry zone of Peninsular Malaysia, and receives the lowest annual rainfall among adjacent southeastern tropical rainforests (Noguchi et al., 2003, 2016; Marryanna et al., 2017). Pasoh experiences extreme and prolonged dryness during *El Niño Southern Oscillation* events (Tani et al., 2003; Marryanna al., 2017). Thus, the site is suitable for assessing the influence of VSWC on stand dynamics.

Pasoh FR is a lowland dipterocarp forest with a canopy height of 30–40 m (with emergent trees ca. 45 m tall). The core area (600 ha) of the reserve is primary lowland mixed dipterocarp forest, consisting of various *Shorea* and *Dipterocarpus* species (Symington 1943; Wyatt-Smith 1961, 1964; Soepadmo, 1978; Okuda et al., 2004). A previous study estimated that Pasoh FR houses over 800 species, 21 of which were new to science (Christine et al., 2012).

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, indurate lateritic horizon (30–40 cm thick) on top of mottled white clay that overlays weathered shale to a depth of 130–150 cm (Leigh, 1982). The A horizon is thin (0–2 cm) and consists of brown silty loam, whereas deeper soils are bright yellowish or reddish brown and heavier (light to heavy clay) (Yoda, 1978). Lateritic gravel is abundant below a depth of 30 cm and increasingly abundant with depth (Yoda 1978; Tani et al., 2003). The soil types at the 6-ha study site include petrophlinthic haplorthox and typic paleudults, both with a clay topsoil and are of petrophlinthic haplorthox and typic paleudults, both having clay topsoil with a fine granular structure and silty loam texture in deeper layers (Yamashita et al., 2003). The soil particle size distribution is characterised by low sand and high silt contents (Yamashita et al., 2003). The hydraulic conductivity (Ks) of the study site ranged from 3.3×10^{-2} to 8.9×10^{-4} cm s^{-1} (Noguchi et al., 2016). The Durian soil series at 50 cm had a bulk density of 1.50 g cm^{-3} and moisture content of 39.6% at 0.33 bar and 8.3% between 0.33 and 15 bar. The deeper soil layer (100 cm) had a bulk density of 1.41 g cm^{-3} and moisture contents of 46.2% (0.33 bar) and 22.5% (0.33–15 bar) (UPM, 1979). The underlying rocks at Pasoh FR include Upper Triassic shales and sandstones (Gobbett, 1972; Peh, 1978). The textural details of the soil, based on Peh (1978), are listed in Table 1.1.

The proportion of thin, fine roots to total fine roots was higher than values previously reported (Yamashita et al., 2003). The maximum depth of tap roots was approximately 4 m (Niiyama et al., 2010); most fine roots were found in the A horizon (Amir Husni, 1989). Most fine roots (diameter of 1–2 mm) were found at a soil depth of 0–4 cm, whereas fine roots (diameter of 3–5 mm) were in abundance at a soil depth of 12–16 cm (based on Figure 7 of 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 to a 2-m depth was estimated at an average of 13.3 Mg ha^{-1} using the pipe model approach and 16.4 Mg ha^{-1} using the pit sampling method (Niiyama et al., 2010).

The minimum average VSWC in Pasoh FR was recorded during the first El Niño from June 2009–March 2010, and the maximum value was recorded during a normal rainfall event (May 2008–May 2009) (Noguchi et al., 2016). Streams in this region are ephemeral, appearing briefly in response to rainfall with little base flow and typically shallow depth (Leigh, 1978). Manokaran (1979) reported an annual interception value of 519 mm (21.8%) for Pasoh FR. Subsequently, Tani et al. (2003) recorded a value of 381.3 mm (16.9%) from 1999 to 2000. Throughfall ranged between 79 and 94% in this forest (Konishi et al., 2006). A substantial amount of overland flow has been measured in Pasoh FR using the trap method, indicating a close relationship with the amount of rainfall (Leigh, 1978). Due to its proximity to the equator, the forest has a relatively constant ET (Tani et al., 2003; Takanashi et al., 2010; Kosugi et al., 2012a). The variability of daily ET at Pasoh is dependent on available energy and vapor pressure deficit (VPD), but is also moderately influenced by soil water content (Kosugi et al., 2012a). Temporal drought has been found to induce decreases in soil respiration (Kosugi et al., 2007; Itoh et al., 2012) and gross primary production (GPP, Kosugi et al., 2012), and patchy stomatal closure (Takanashi et al., 2006; Kosugi et al., 2009; Kamakura et al., 2012, 2015). Clear periodic variation in GPP and light-use efficiency (LUE) have not been detected in this forest, and water conditions appear to exert a stronger influence on these parameters than leaf phenology (Nakaji et al., 2014). In addition, detectable declining trends in GPP and LUE were observed to correspond to increases in VPD and reductions in VSWC. Soil water conditions control the spatial distribution of CO_2, CH_4, and N_2O fluxes in this forest, with CO_2 uptake decreasing during wet periods (Kosugi et al., 2007; Itoh et al., 2012). The monthly average daytime change in CO_2 exchange has been found to be constant despite fluctuations in soil moisture (Kosugi et al., 2007).

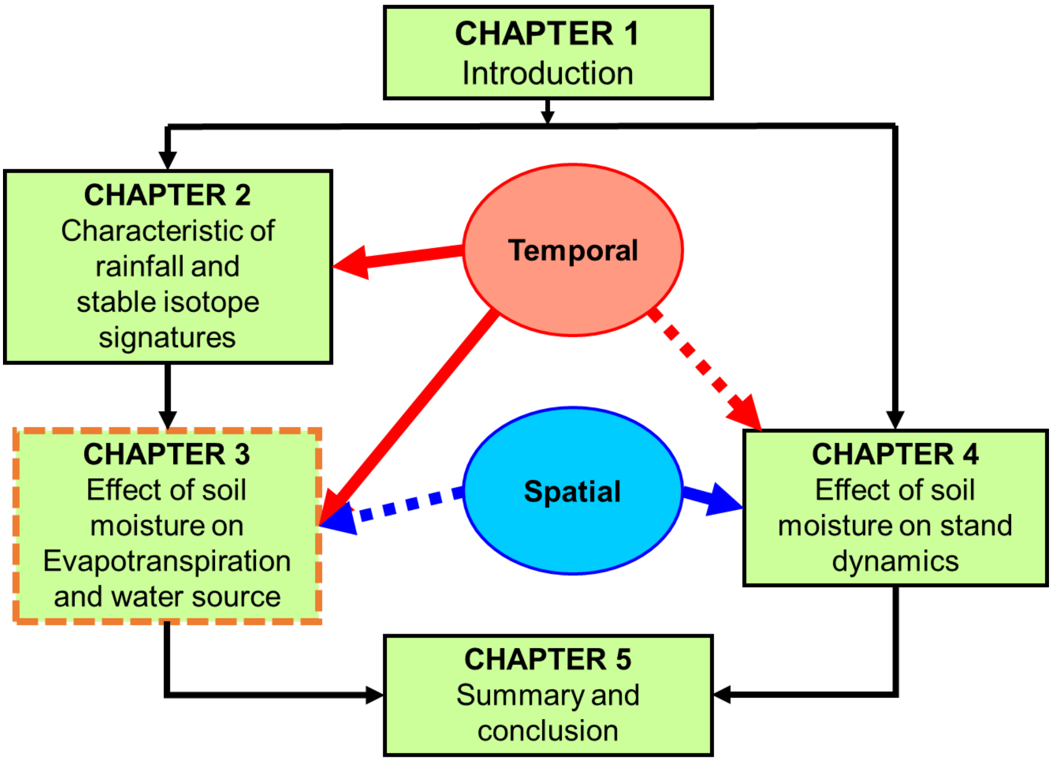

Figure 1.1 Structure of the thesis.

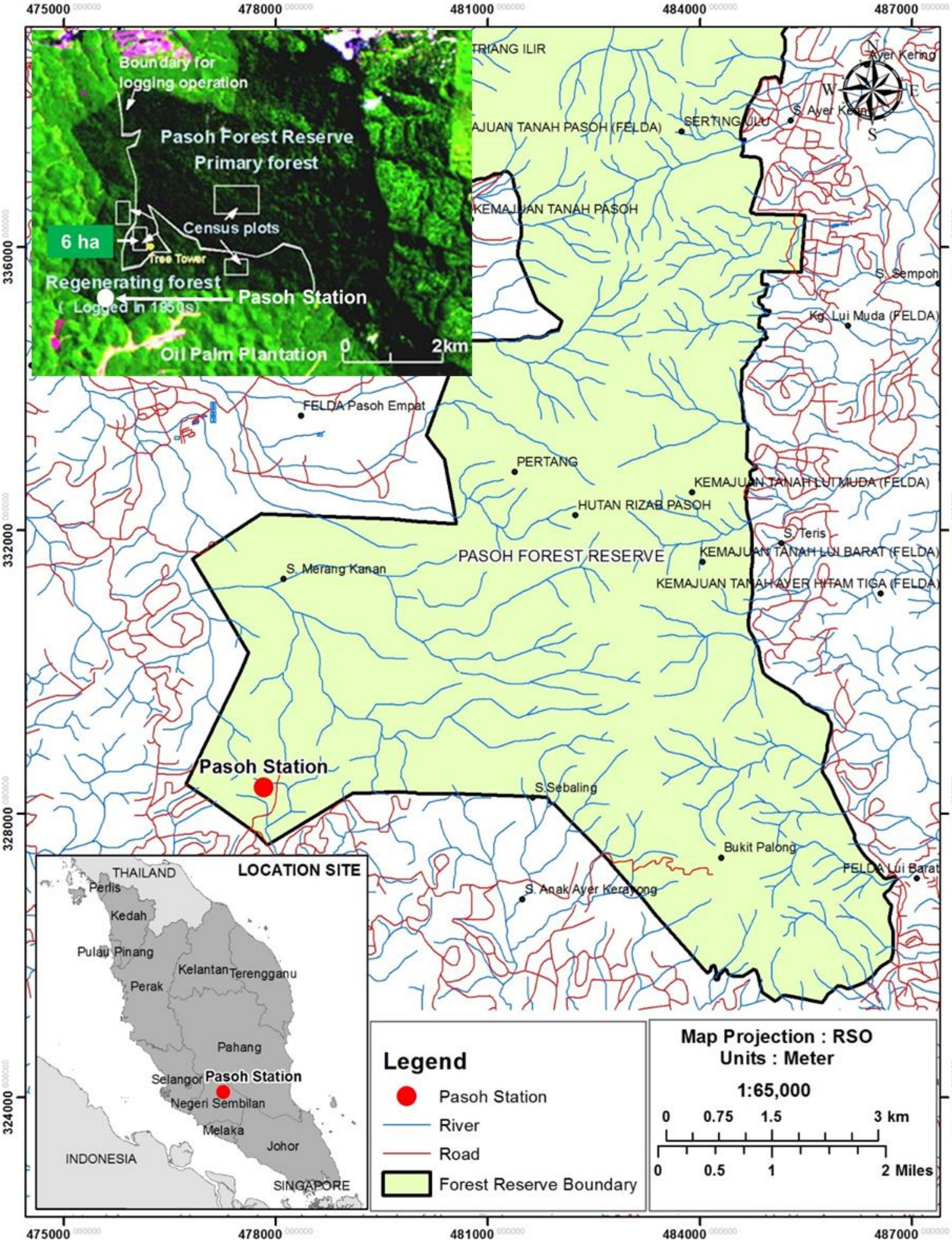

Figure 1.2 Location of the Pasoh Forest Reserve in Negeri Sembilan, Peninsular Malaysia. The forest island covers an area of 139 km^2, an area of 18.4 km^2 were gazzetted for research purposes. Soil, plant and river water are sampled from this location.

Table 1.1 Soil texture composition at Pasoh FR

Site	Sampling Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Silt & Clay (%)	Silt/Clay ratio
Total pore space (%)			55.30 (average)			
Saturation point (%)			46.88 (average)			
Field capacity (%)			34.58 (average)			
Permanent wilting point (%)			21.86 (average)			
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, Occasional paper no. 3, Department of Geography, University of Malaya, Kuala Lumpur, Malaysia

CHAPTER 2

Characteristics of rainfall and the stable isotope signatures

2.1 Introduction

One of the greatest concerns related to maintaining the Malaysian tropical rainforest ecosystem is the change in rainfall pattern and amount because it will eventually change the microclimate, ET, soil moisture, carbon flow and tree density. Compared with Amazonian forest, South-East Asian rainforest does not experience distinct dry and wet seasons during the year, although dry and wet periods do occur with considerable variability between years (Tani et al., 2003; Kumagai et al., 2005). Stable isotope signals in precipitation water serve as indices of site-dependent rainfall and climate characteristics. They can be also used as tools for monitoring possible climate change. Therefore, in the effort to conserve the Malaysian tropical rainforests, it is very important to record stable isotope signals in precipitation water. These records can also serve as basic information for regional research. The use of dual isotope (oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$)) approach in this study could systematically help in the separation of distinct water pools in the forest ecosystem. These pools mainly include (1) water used by trees and not contributed to stream flow and (2) mobile water unrelated to water used by trees (i.e. groundwater, streamflow, infiltration and hillslope runoff) (McDonnell, 2014). This will improve understanding of the ecohydrological processes controlling water flow in the soil–plant-atmosphere continuum (Berry et al., 2016). This chapter reports only the isotope properties of rainfall received by Pasoh Forest Reserve (FR). The result from this study will later be used to estimate tree water use and soil water in the Pasoh forest.

This study examined the characteristics of rainfall and the signal of stable isotopes in precipitation water. A water molecule consists of one oxygen atom and two hydrogen atoms. Hydrogen and oxygen each have several naturally occurring isotopes. The stable isotopes of oxygen are ^{18}O, ^{17}O, and ^{16}O and those of hydrogen are ^{1}H and ^{2}H. The stable isotope ratios in water are expressed relative to an internationally accepted standard material for hydrological application known as Vienna Standard Mean Ocean Water (Gonfiantini, 1978). According to this standard, the isotopic ratio is defined using delta notation as:

$$\delta = (R\ sample - R\ standard)/(R\ standard) \times 1000, \text{ i.e. } \delta^{18}O \text{ and } \delta^{2}H$$

where δ = isotope ratio, R = ratio of heavy to light isotopic, $\delta^{18}O$ = oxygen isotope and δ^2H = deuterium. Delta values are often expressed in permil (‰). Changes in $\delta^{18}O$ and δ^2H occur during the condensation process, where water vapour loses its heavy components and the $\delta^{18}O$ and δ^2H values become more negative as condensation continues.

The use of oxygen isotopes in paleoclimatology was reported in the first analysis of the Global Network of Isotopes in Precipitation (GNIP) due to the composition of meteoric precipitation, which exhibited variation based on temperature, altitude, continental and rainfall amount effects (Dansgaard 1964; Clark & Fritz 1997; Ingraham 1998). The effect of temperature on isotope composition typically occurs in temperate and high-latitude regions but not in tropical regions. Isotopic values of rainfall decrease when water vapour moves from lower to higher elevation. This is known as the altitude effect. Isotopes get progressively lighter as clouds move towards high altitudes and precipitation occurs. The continental effect (i.e water vapour moving over large areas throughout continent) consists of storm routes carrying water vapour from their origin and the distance to the destination. The variability in the continental effect is driven by variation in source regions of moisture, air mass transport pathways, and precipitation history (Dansgaard 1964; Araguás-Araguás et al., 2000). Isotope values decrease with increasing amounts of rainwater. This decrease is also influenced by seasonal variation in the isotopic composition of precipitation because large and small amounts of rainfall also show seasonality (i.e. monsoon seasons and wet and dry seasons). The relationship between $\delta^{18}O$ and δ^2H in precipitation compared with the Global Meteoric Water Line (GMWL) is also used to analyse the source of rainfall. The best-fit equation for GMWL is expressed as $\delta^2H = 8 \times \delta^{18}O + 10$ for all data points (Dansgaard, 1964). Deuterium excess is useful for interpreting the hydrological cycle in the atmosphere. For example, increased deuterium excess in precipitation can arise from the addition of re-evaporated moisture from continental basins to the water vapour travelling inland (Kondoh & Shimada, 1997). Several studies have examined the isotope composition of precipitation in South-East Asia. Seasonal $\delta^{18}O$ values are negatively correlated with monsoon strength over almost the entire Asian countries experiencing monsoon season, indicating that the stable isotope composition of precipitation is more depleted during intense monsoon seasons and more enriched during weak monsoon seasons (Vuille et al., 2005). Variation in seasonal isotopes in precipitation in subtropical and tropical regions does not reflect the degree of rainout at a cloud scale but rather at the regional scale (Kurita et al., 2009).

Information on variation in isotopes in precipitation in South-East Asia has increased. However, no study has been performed on the rainforests in Peninsular Malaysia as a possible indicator of local climate phenomena. Information in this area is needed to understand the symptoms of climate change in tropical rainforests in this area. Isotope signals in precipitation at Pasoh FR, a tropical rainforest in Peninsular Malaysia were studied to understand their characteristics. These data are fundamental and useful for future studies related to forestry and climate change in the region. The origin of monsoonal precipitation is likely to vary due to the location of the study area. If monsoonal rainfall is considered, the water vapour could be originating from the ocean. However, this assumption must be empirically investigated because the area is subjected to two monsoonal seasons, namely, the north-east (NE; November–March) and the south-west (SW; May–September), while and April and October are intermonsoon periods. These seasons may have different isotopic signatures, marked by different water sources in the area. Other factors, such as local rainfall characteristics, the reuse of land-originating re-evaporated moisture, larger-scale atmospheric conditions and the El Niño Southern Oscillation may also be related to variation in the isotopes of precipitation. The daily, seasonal (four seasons annually, i.e. NE monsoon, first intermonsoon, SW monsoon and second intermonsoon) isotope signature in precipitation were investigated with specific consideration given to the effects of monsoon season, rainfall characteristics and larger-scale trends compared with nearby GNIP monitoring stations in Peninsular Malaysia, Singapore and Bangkok, Thailand.

2.2 Materials and methods

2.2.1 Site description

The study was conducted at Pasoh FR. Details of the vegetation, micrometeorology are in chapter 1.3.

2.2.2 Rainfall measurement and isotope analysis

Rainfall was measured at 30-min intervals using a 0.5-mm tipping bucket rain gauge. Rainfall data were collected using storage type and tipping bucket rain gauges in an observatory located 430 m away from the flux tower. The storage rain gauge was buried in the ground to prevent heating which would cause evaporation. A double-layered small-mouth inner glass bottle was also used to prevent evaporation. Water samples for the isotope analysis were collected daily from this bottle at 8–9 a.m. (solar noon in this area is 1 p.m.), using 10-mL polyethylene terephthalate or glass bottles with no air space to prevent evaporation. Rain water samples were collected from 5 September 2012 till 29 December 2015. Rainwater samples were filtered using 13-mm 0.45-μm phobic polytetrafluoroethylene filters and transferred to a 2-mL vial. A cavity ring-down spectrometer was used to analyse isotope composition in the rainwater samples. The laboratory had a device with specific analytical precision of 0.06‰ for $\delta^{18}O$ and ≤ 0.11‰ for $\delta^{2}H$ (Katsuyama, 2014). The deuterium excess value for each rainwater sample was determined. The deuterium excess (d) was defined as (Dansgaard, 1964):

$$d\ (‰) = \delta^{2}H - 8 \times \delta^{18}O$$

It was an index of deviation from the GMWL, which has a deuterium excess value of 10‰ (Froehlich et al., 2002). A total of 465 samples were collected throughout the study period. Samples collected with more than a 1-day interval or with < 0.5 mm rainfall were omitted from the analysis. In all, 333 samples were analysed for composition of isotopic. It was assumed that these samples were not affected by evaporation during storage because most rainfall at the site occurred from evening till midnight and the storage rain gauge was carefully designed to prevent evaporation.

The daily amount of rainfall, maximum rainfall intensity and duration were calculated for each 24-hour period (8 a.m. till 8 a.m. the next day to correspond with rainwater sampling). Maximum rainfall intensity was the maximum value that occurred during a 30-min period of each day. Duration was calculated by counting the number of rainfall events in one day using a 30-min interval dataset. Generally, in Malaysia, the NE monsoon brings heavy rain, particularly to the states on the east coast of Peninsular Malaysia and western Sarawak, whereas the SW monsoon brings drier weather to these states although sometimes it brings more rainfall in certain areas. Each year was divided into three seasons, namely, SW and NE and intermonsoon to investigate differences between monsoon seasons.

The data were compared to larger-scale, long-term mean monthly isotope and rainfall data collected from five stations in Peninsular Malaysia (Kuala Lumpur, Cameron Highlands, Kota Bahru, Alor Setar and Langkawi) and two stations (Singapore and Bangkok) from neighbouring countries (Figure 2.1 and Table 2.1). These data were obtained from the Atomic Energy Agency–GNIP database (available at https://nucleus.iaea.org/wiser/gnip.php). To investigate the antecedent rainfall conditions, the 60-day antecedent rainfall index (API60) used which defined as:

$$\sum_{i=1}^{60} P_i / i$$

where P_i = daily precipitation (mm) and i = the number of preceding days (Kosugi et al., 2007). The API60 indicated the seasonal rainfall pattern including antecedent conditions at the study site. The API60 was used in this study because it was tested beforehand and gave the highest correlation with isotopes among several antecedent rainfall indices. API60 used to know whether a specific date was at the beginning or in the middle of the rainy seasons. A 30-day running average of API60 also used to show the monthly scale trend excluding the daily scale trend.

Figure 2.1 The location of Global Network Isotope in Precipitation (GNIP) in Peninsular Malaysia, Singapore and Bangkok. Data from GNIP used for comparison with Pasoh FR.

Table 2.1 Details of the five Global Network of Isotopes in Precipitation (GNIP) monitoring stations in Peninsular Malaysia (Kuala Lumpur, Cameron Highlands, Kota Bahru, Alor Setar and Langkawi) and two nearby stations (Singapore and Bangkok)

Station	Latitude (N)	Longitude (E)	Elevation (m)
Pasoh	2°58′	102° 18′	75
Singapore	1° 21′	103° 54′	32
Bangkok	13° 43′	100° 30′	2
Kuala Lumpur	2° 53′	101° 46′	26
Cameron Highlands	4° 28′	101° 22′	1430
Alor Setar	6° 11′	100° 24′	5
Langkawi	6° 19′	99° 43′	31
Kota Bahru	6° 9′	102° 16′	7

2.3 Results

2.3.1 Rainfall characteristics

Monthly rainfall varied from 6 to 367 mm month^{-1} (in June 2012 and November 2015 respectively) during the four years of study (Figure 2.2a). Pasoh FR experienced two major peaks of monsoonal rainfall in April–May and October–December to form a bimodal pattern. Rainfall varied considerably between years. The seasons occasionally changed in July and August. Heavier rainfall occurred during the NE monsoon than during the SW monsoon season (Figures 2.2 a, b). Most of the rain fell from late afternoon till midnight (Figure 2.2c), and rainfall frequency increased during this time. Amount and rainfall events peaked around evening, but they were little and rare in the morning. Relatively small amount of rainfall (1–4 mm day^{-1}) was collected during the NE and SW seasons (Figure 2.2d). The most frequent maximum rainfall intensity in one day was 1–3 mm 30 min^{-1} (Figure 2.2e), and the most frequent duration of rainfall in a day was 1.5–2 hours (Figure 2.2f). Rainfall at the study site was characterised as relatively small amount and of short duration, though sometimes larger amount of rainfall with longer duration occurred. The NE monsoon season had greater number of rainfall events with some events of being longer than the rest.

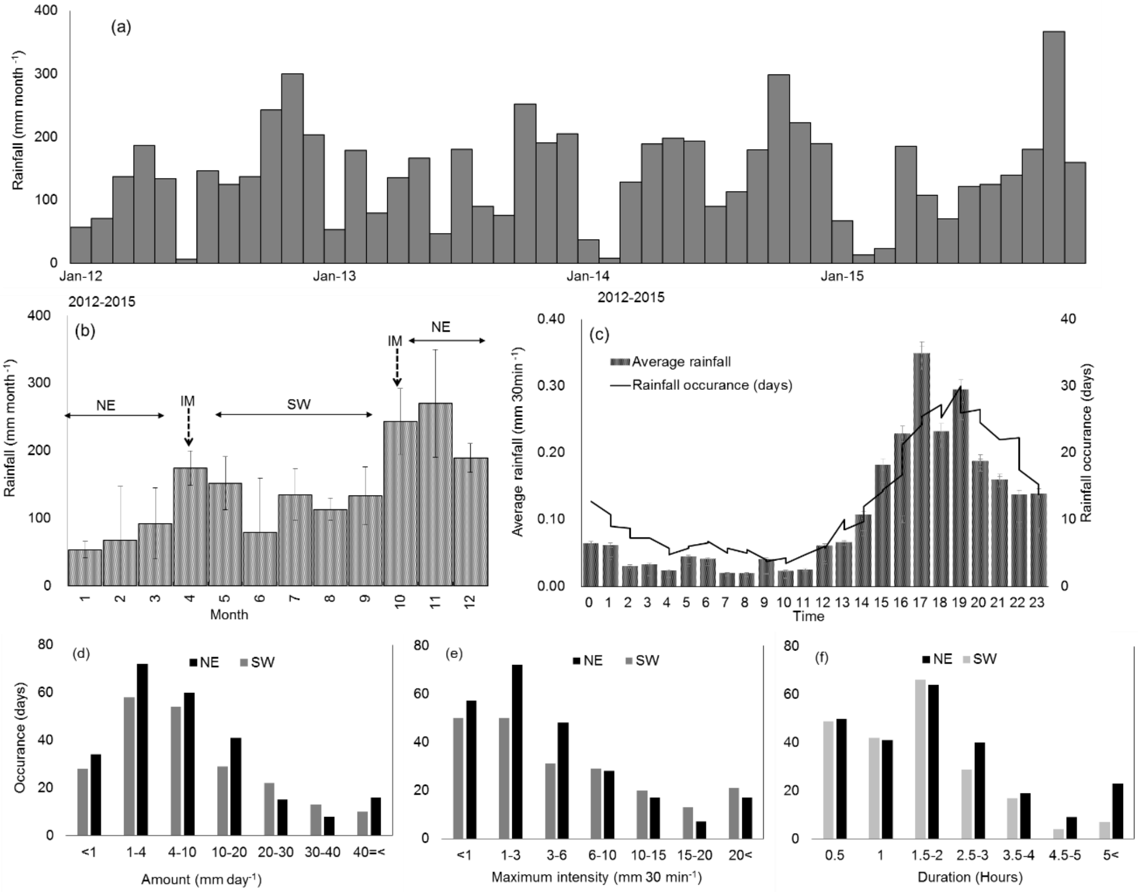

Figure 2.2 Rainfall characteristics in Pasoh FR in 2012–2015; (a) monthly amount of rainfall, (b) 4-year average and standard deviation of monthly rainfall; (c) 4-year average of rainfall amount and rainfall at 30-min intervals in one day, (d) distribution of daily rainfall amount (mm day^{-1}), (e) maximum rainfall intensity in 30 min (mm 30 min^{-1}) for each day and (f) rainfall duration (hours) for each day during the north-east (NE) and south-west (SW) monsoon seasons; each monsoon season was 4 months long; IM = intermonsoon

2.3.2 Distribution of isotope values in precipitation

Means and standard deviations of daily $\delta^{18}O$, $\delta^{2}H$ and deuterium excess values were -5.90 ± 3.0 (median = -5.40), -35.4 ± 24.1 (-31.5) and 11.7 ± 3.0 (11.9) respectively. Daily means and standard deviations of $\delta^{18}O$ and $\delta^{2}H$ values for SW monsoon were -5.60 ± 2.75 and -32.7 ± 22.0‰ respectively and were slightly greater during the SW monsoon than during the NE monsoon season ($\delta^{18}O$ = -6.32 ± 3.36‰ and $\delta^{2}H$ = -39.7 ± 26.3‰). No differences were detected between monsoon seasons.

The relationships between $\delta^{2}H$ and $\delta^{18}O$, defined as the Local Meteoric Water Line (LMWL), were $\delta^{2}H$ (‰) = 7.9 $\delta^{18}O$ (‰) + 11.6 (r^2 = 0.98) for SW monsoon season and 7.8

$\delta^{18}O$ (‰) + 9.3 (r^2 = 0.99) for NE monsoon season (Figure 2.3). The intercept d (deuterium excess) value was slightly lower during the NE monsoon season than during the SW monsoon season. Both values fit the GMWL well (r^2 = 0.98). Generally, the regression lines between the NE and SW seasons including all data points were indistinguishable.

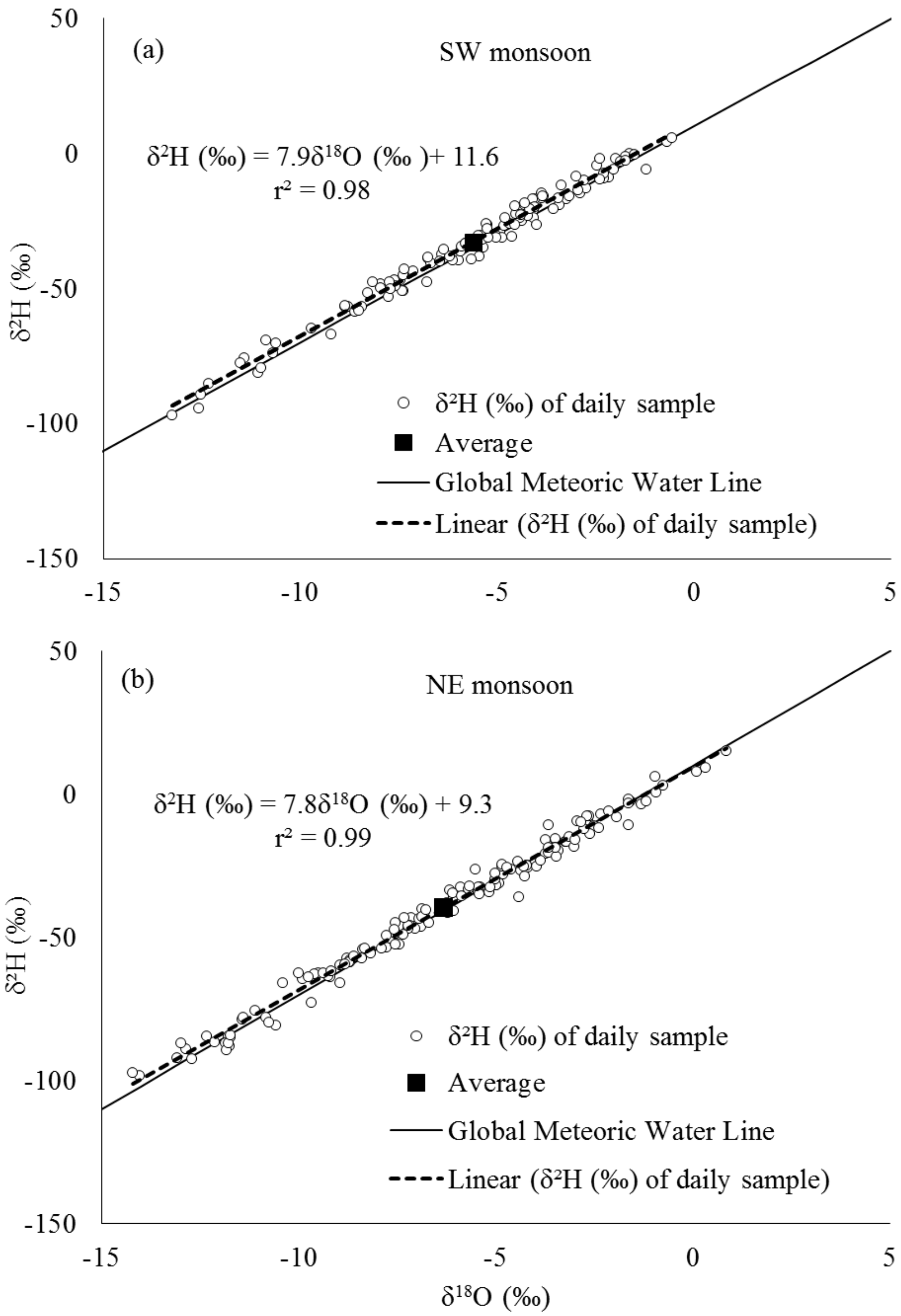

Figure 2.3 Relationship between δ^2H and $\delta^{18}O$ in daily rainfall samples fitted with the local linear regression line and Global Meteoric Water Line, SW = south-west, NE = north-east.

2.3.3 Comparison of long-term average monthly isotope signal with GNIP stations in neighbouring countries

The long-term monthly mean rainwater $\delta^{18}O$, $\delta^{2}H$ and deuterium excess values and monthly rainfall amount at Pasoh FR (Figure 2.4, 2.5 and Table 2.2) had a similar bimodal rainfall pattern to those at Kuala Lumpur and Singapore, but received less rainfall at the beginning of the year compared with those at the other two stations. The rainfall isotope patterns at Pasoh FR were also bimodal. Pasoh FR showed more positive isotope values during months with less rainfall. Cameron Highlands, located at a high altitude, showed more negative isotope values. Kota Bahru, located on the east coast of Peninsular Malaysia, showed less negative isotope values compared with Pasoh FR with heavier rainfall during the NE monsoon season (Figures 2.5a and b). Alor Setar and Langkawi showed isotope patterns similar to those of Bangkok, which were unimodal in shape and decreased in September and October.

Most of the sites had comparable relationships between the long-term mean rainfall and isotope values (Figure 2.4). The slope of the relationship between the isotope values and monthly rainfall was steep and similar to that reported elsewhere in the maritime continents by Kurita et al. (2009). By contrast, isotopes at the Cameron Highlands station were more negative than those at the other sites. Kota Bahru during the NE monsoon season and Langkawi during the SW monsoon season showed less negative isotope values under heavy rainfall conditions.

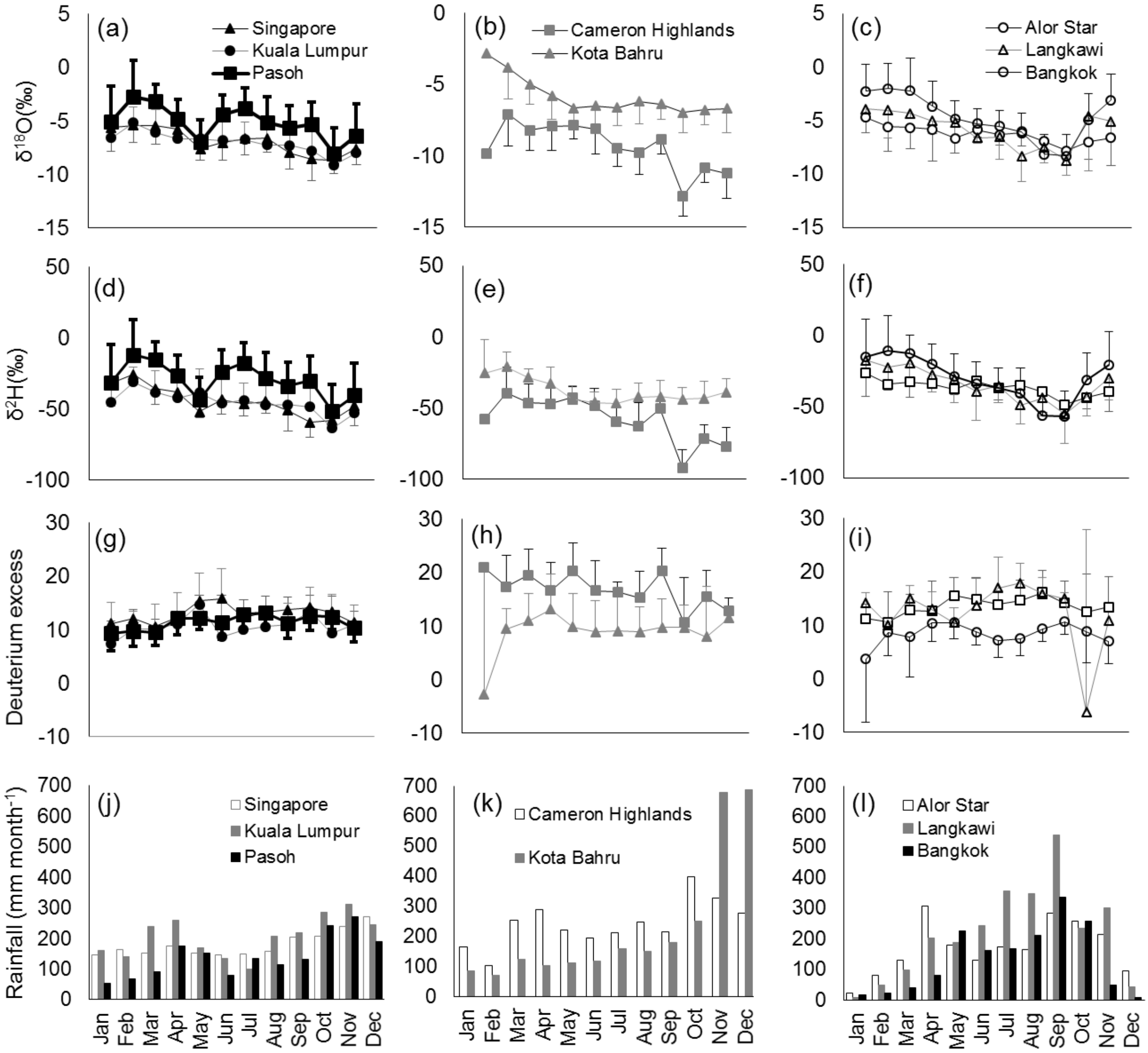

Figure 2.4 Long-term monthly average rainwater (a–c) $\delta^{18}O$, (d–f) $\delta^{2}H$, (g–i) deuterium excess, (j–l) monthly rainfall amount; error bars show standard deviations, long-term monthly values for Pasoh FR were calculated based on monthly statistics for 3 or 4 years (n = 3 or 4)

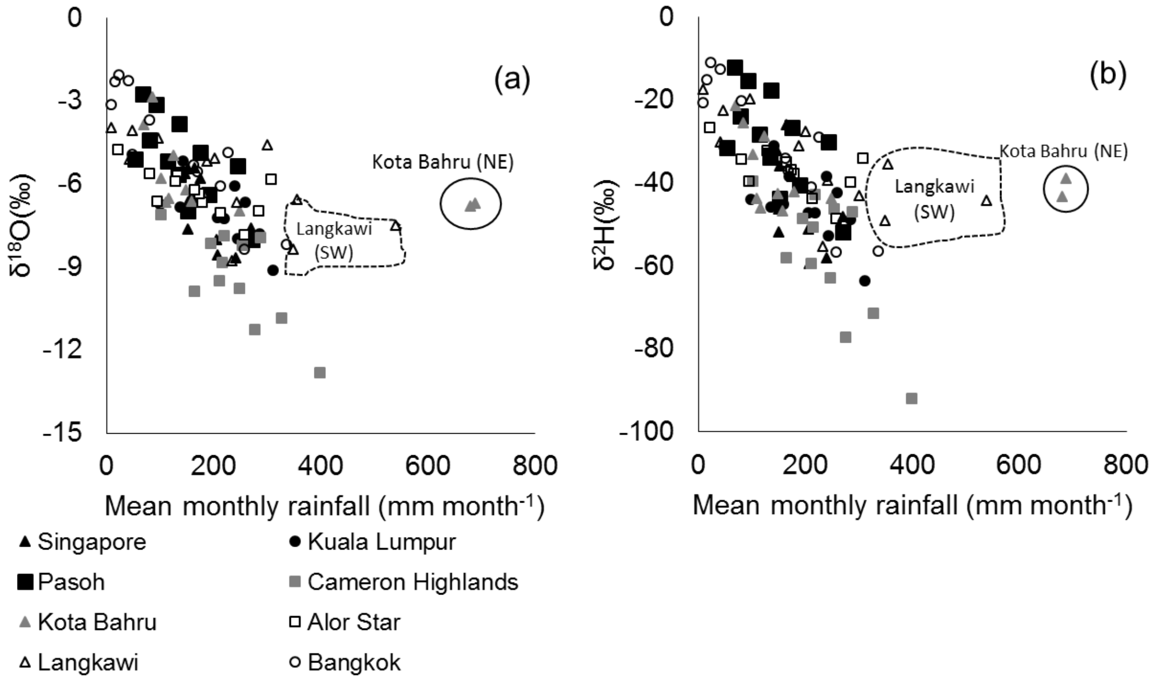

Figure 2.5 The relationship between monthly rainfall amount of $\delta^{18}O$ (a) and $\delta^{2}H$ (b) at Pasoh FR and nearby Global Network of Isotopes in Precipitation stations.

2.3.4 Daily and seasonal variation in isotopes in precipitation

A time series of rainwater $\delta^{18}O$, $\delta^{2}H$ and deuterium excess in the daily rainfall samples and the 30-day running average from September 2012 to December 2015 are shown in Figures 2.6a–c to examine the detailed daily and seasonal variation in the isotopes in precipitation at Pasoh FR (details observation data are listed in Appendix 1). The isotope values varied considerably during the day, seasons and between years. The $\delta^{18}O$ and $\delta^{2}H$ values detected during monsoon onset in May (SW) and November (NE) tended to decrease but this tendency was mitigated compared with the long-term mean monthly trend. The isotope values tended to be lower during the middle of the rainy season compared with those in the beginning of the rainy and drier seasons, and the pattern of dry and wet seasons differed between years. Deuterium excess increased in correspondence with the decrease in $\delta^{18}O$ and $\delta^{2}H$. The relationship between monthly average over four years and isotope values is shown in Figures 2.6d and e. The $\delta^{18}O$ and $\delta^{2}H$ values showed the amount effect during the NE monsoon seasons but were scattered during the SW monsoon season and especially the intermonsoon season.

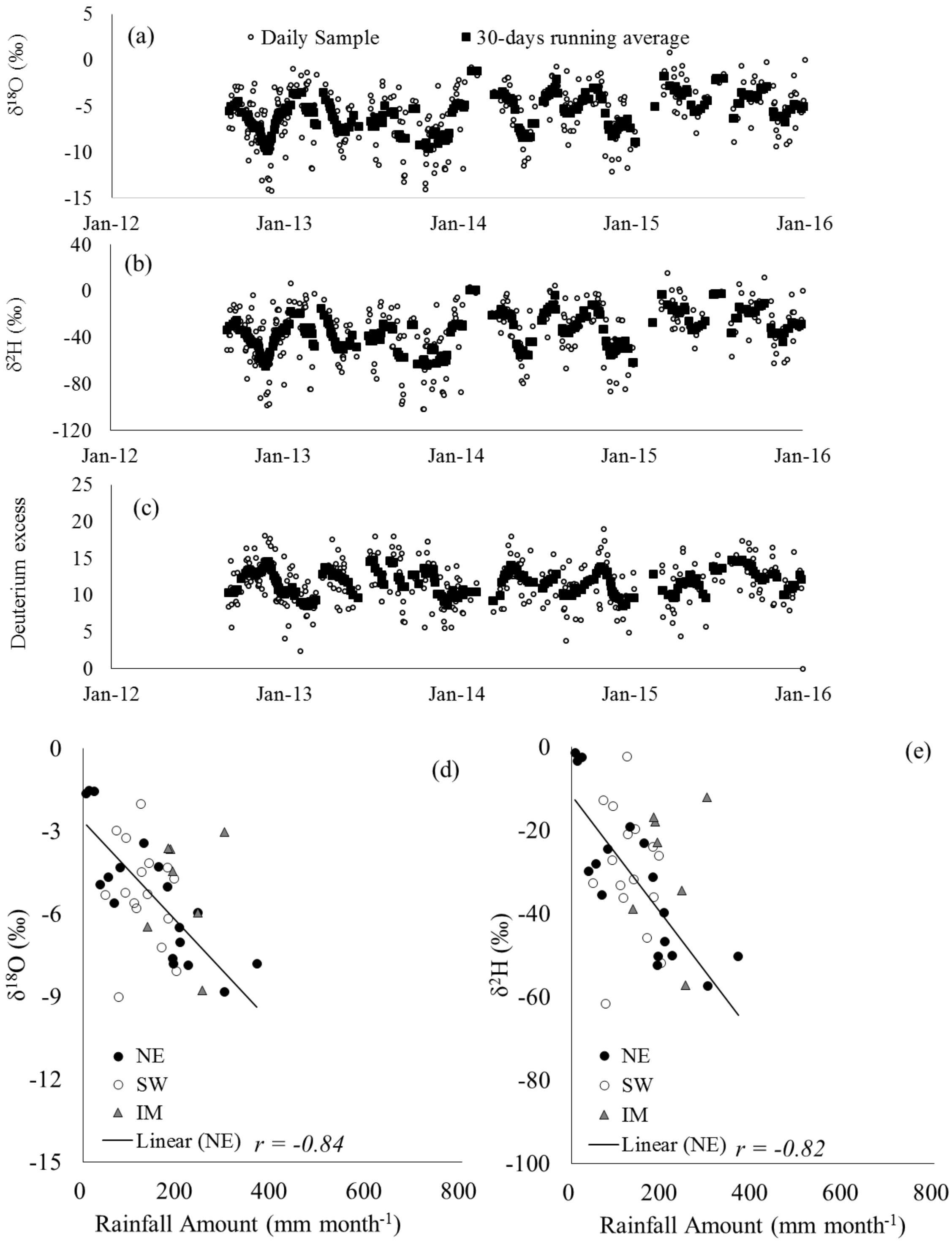

Figure 2.6 Time series of rainwater (a) $\delta^{18}O$, (b) $\delta^{2}H$, and (c) deuterium excess in daily rainfall samples with 30-day running average, and the comparison between monthly rainfall amount and monthly average of rainwater (d) $\delta^{18}O$ and (e) $\delta^{2}H$ at Pasoh FR from September 2012 till December 2015; lines in (d) and (e) show linear regressions for the relationship between $\delta^{18}O$ and monthly rainfall amount during the north-east (NE) monsoon season; SW = South-west; IM = intermonsoon

Both $\delta^{18}O$ and $\delta^{2}H$ were significantly related to daily rainfall amount (r = -0.218 to -0.391), maximum rainfall intensity (r = -0.206 to −0.386) and duration (r = -0.247 to -0.333) for both monsoon seasons ($p < 0.05$) (Figures 2.7a–f). However, the relationships included considerable scatter. No better relationships were found for maximum rainfall intensity or duration compared to daily rainfall amount. The larger deuterium excess values were not detected during small rain events, small maximum rainfall intensity and short-duration rainfalls (Figures 2.7g–i), although they were occasionally observed during larger-scale rain events. No clear differences were detected between the seasons, although values were slightly lower during the NE monsoon season because more data fell within the high rainfall range.

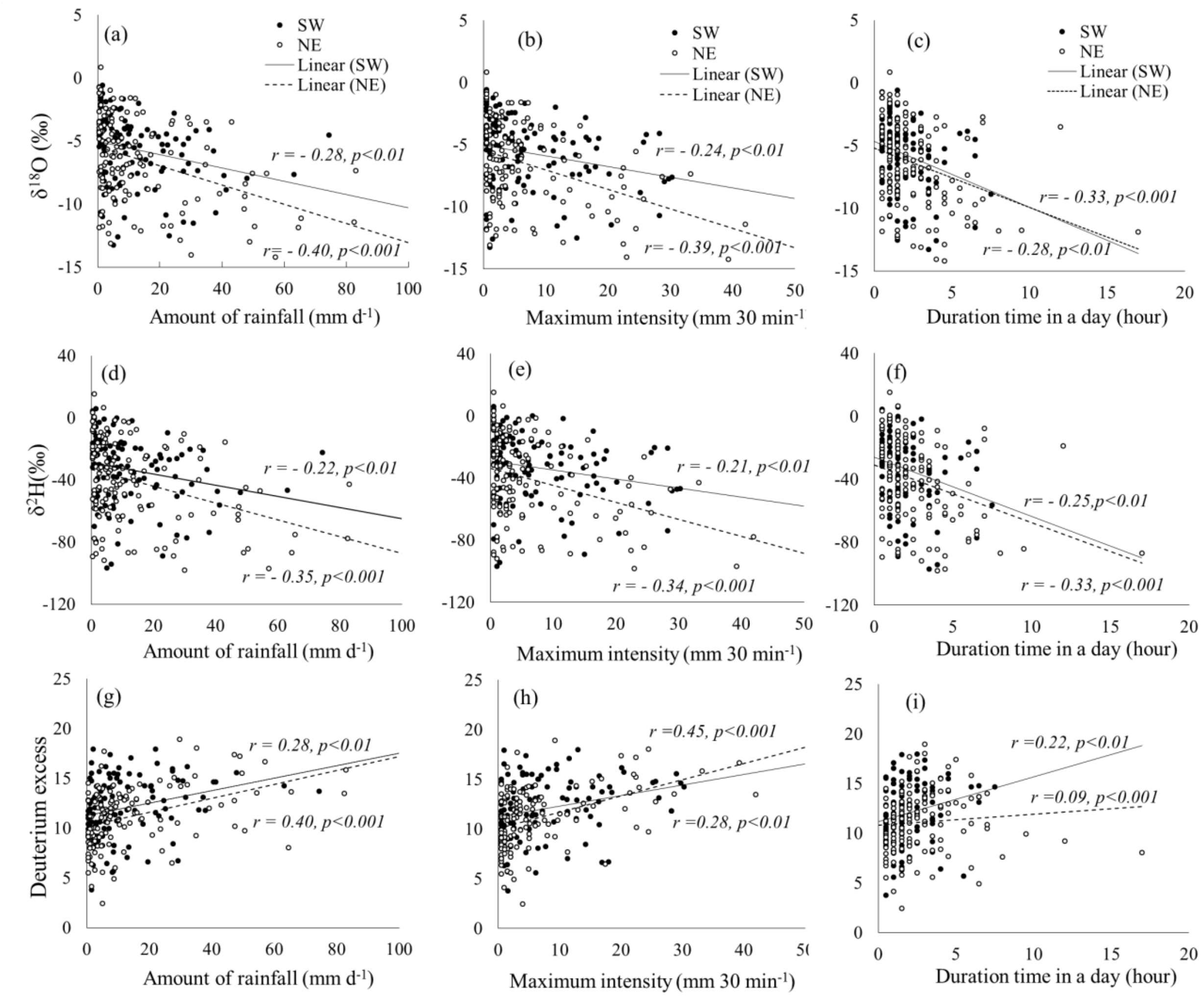

Figure 2.7 Comparison between (a–c) $\delta^{18}O$, (d–f) $\delta^{2}H$ and (g–i) deuterium excess and daily rainfall amount (mm day^{-1}); maximum rainfall intensity per 30 min (mm 30 min^{-1}) for each day; and rainfall duration (hours) for each day during the north-east (NE) and south-west (SW) monsoon seasons

Figure 2.8a and b show a comparison of $\delta^{18}O$ values with amounts of daily rainfall and the API60, which was calculated as cumulative rainfall and was used as a wetness index for this study. In this analysis, the data did not divided into seasons. There were significant correlations detected for amount of rainfall and AP160. However, the correlation was stronger with the latter ($r = -0.44$, $p < 0.001$) than with the amount of rainfall each day ($r = -0.30$, $p < 0.001$). The seasonal trend in $\delta^{18}O$ can be produced by using the relationship between the 30-day running average of $\delta^{18}O$ and the 30-day running average of API60 (Figure 2.8c, $r = -0.49$, $p < 0.001$).

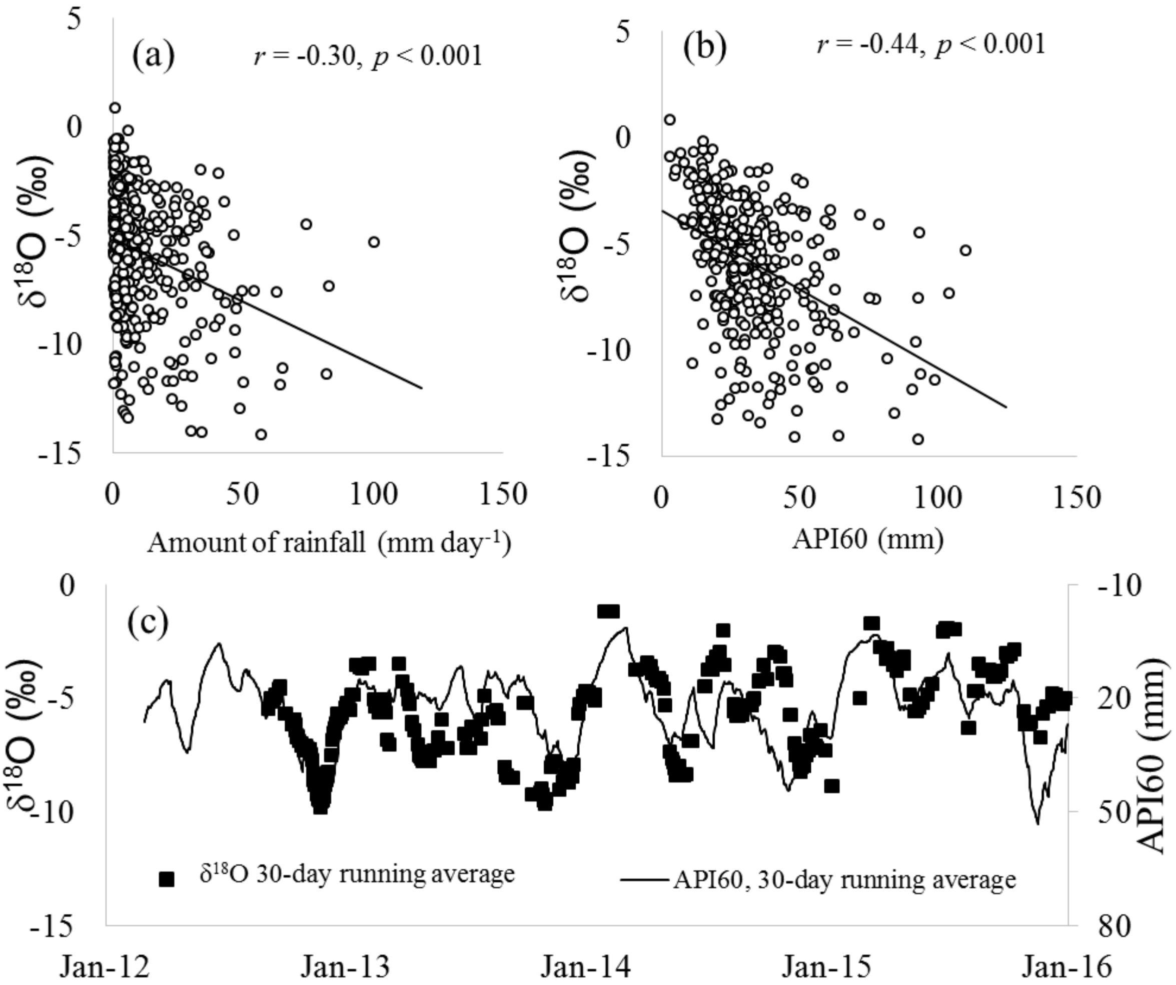

Figure 2.8 Comparison between $\delta^{18}O$ and (a) daily rainfall amount (mm day^{-1}) and (b) the 60-day antecedent precipitation index (API60); lines show linear regressions; (c) the 30-day running average of daily $\delta^{18}O$ and API60 from September 2012 till December 2015

2.4 Discussion

2.4.1 Rainfall characteristics

The rainfall characteristics in Pasoh FR generally corresponded to typical weather in Peninsular Malaysia, which is characterised by two monsoon regimes (Figure 2.2a, b). This condition results in a bimodal rainfall pattern on the west coast and a unimodal rainfall on the east coast (Suhaila & Abdul Aziz 2009). Most rain fell in the Pasoh FR during the late afternoon to midnight and was intense and of short duration (Figure 2.2e, f), indicating that precipitation at the study site was mainly caused by a convective process.

2.4.2 Distribution of isotope values in precipitation

The results showed no difference in the distribution of isotope values in precipitation between the NE and SW monsoon seasons (Figure 2.3). The best fit equation for the GMWL is $\delta^2H = 8 \times \delta^{18}O + 10$, as reported by Dansgaard in 1964. Similar result with other areas within the tropical region means that the precision of data in this study is high and acceptable. Thus, data from Pasoh FR can be used for studies of forest water use estimation, water quality and tracing water source. The value of 10 is an offset called the deuterium excess under the condition that the slope of the line is fixed at 8. The global average is 10 but varies according to local conditions known as the LMWL. The LMWL approximates the $\delta^{18}O$ and δ^2H values at a local scale and the slope value varies with local isotope values. Increases in deuterium excess of rainwater originate from re-evaporated moisture from continental basins and moving of water vapour (Kondoh & Shimada 1997). The relationship between $\delta^{18}O$ and δ^2H at Pasoh FR was defined as $\delta^2H = 7.9\ \delta^{18}O + 11.6$ (SW monsoon) and $\delta^2H = 7.9\ \delta^{18}O + 9.0$ (NE monsoon), which is similar to that in Borneo, which has been defined as $\delta^2H = 7.9\ \delta^{18}O + 10.3$ (Moerman et al. 2013). The slope was close to 8, which was near equilibrium. The slope for Pasoh FR was very similar to several continental stations in Indonesia, although other Indonesian stations located near the coast and small islands showed slopes near 7 (Rozanski et al., 1993; Clark & Fritz 1997; Belgaman et al., 2016). With a slope near 8, Pasoh FR corresponded to the theoretical results obtained under isotopic equilibrium conditions (Belgaman et al., 2016).

2.4.3 Comparison of long-term average monthly isotope signals with the nearby GNIP stations

Pasoh FR showed a seasonal trend in isotope values similar to those in Kuala Lumpur and Singapore, but different from those at the northern Peninsular Malaysia stations, mainly due to the different rainfall patterns (Figure 2.4). Rainfall pattern for most of the east coast of Peninsular Malaysia is unimodal, in which extreme rainfall occurs during particular months of the NE monsoon season (Suhaila et al., 2010). In Cameron Highlands (1430 m.a.s.l), the relationship between isotope values and rainfall is be influenced altitude effect (Dansgaard 1964). The different seasonal rainfall trends in Langkawi, Alor Setar and Bangkok could be associated with the different seasonal isotope patterns (Figure 2.4).

The slope for the relationship between long-term average of monthly $\delta^{18}O$ and monthly rainfall was steeper in the maritime continental region of Indonesia than in marine subtropical island stations, namely, Palau and Bali (Kurita et al., 2009). They reported that lower $\delta^{18}O$ values during the rainy season could not be explained by the local rainout effect because the intensity of atmospheric convergence during the rainy season was similar in the two regions. The factors underlying this situation are the spatial distribution of vapour during the movement of moisture from adjacent regions. The slopes obtained at Pasoh FR and the nearby GNIP stations in Peninsular Malaysia were also rather steep and similar to those at maritime continental stations in Indonesia (Kurita et al., 2009), except for Kota Bahru during the NE monsoon season and Langkawi during the SW monsoon season (Figures 2.5 a, b). The amount effects of the Cameron Highlands were excluded from the slope analysis as this site might be influenced by the altitude effect. At Kota Bahru, which is located on the east coast of Peninsular Malaysia, the slope was less steep during extreme (> 600 mm month^{-1}) rainfalls in November and December. Langkawi, an island located on the west coast of Peninsular Malaysia, also experienced a similar trend during the SW monsoon season (Figure 2.5 a, b). These results suggest that the rest of the sites, which had steeper slopes similar with those found by Kurita et al. (2009), could be affected by distillation during land transport from source regions.

2.4.4 Daily and seasonal variation in isotopes in precipitation

The daily isotope values and rainfall characteristics were significantly correlated (Figures 2.6

and 2.7), but the correlation coefficients were considerably scattered. Post-condensation process considerably influenced the amount effect on a short timescale (Moerman et al., 2013). Intense rainfall in the tropics, mainly result of convective air mass, depletes isotopes in precipitation (Cole et al., 1999). Although the relationship between isotopes and rainfall characteristics are often not strongly correlated at a shorter timescale, amount effects may still be observed (Risi et al., 2008; Kurita et al., 2009). Rainwater isotopes at Pasoh FR were significantly related to the daily-scale local rainfall (Figures 2.9a–f). The relationship between detailed rainfall characteristics were examined, such as rainfall intensity and duration but did not detect any stronger correlations between these parameters and isotopes compared with daily rainfall amount. This may have occurred because the study site is characterised by a typical rainfall pattern with high intensity and short duration, which varied little. It was assumed that rainwater isotopes in a small rain event caused by small-scale local convection might be influenced by land-originating re-evaporated moisture, and that this was one of the reasons why the isotopes varied on a daily timescale. However, there was no increase in deuterium excess in such rainwater detected. Rather, smaller deuterium excess values were detected for smaller-scale rainfall events (Figures 2.4g–i). This suggested that scatters of isotope values in small rain events were not the main result of adding re-evaporated moisture from the land surface. It also suggested that land was not the major determining factor for the variability of isotopes in this area.

The amount effect on a longer timescale may be associated with large-scale atmospheric conditions such as movement of the Inter-Tropical Convergence Zone (Kurita et al., 2009). The isotope values in precipitation during the rainy season were lower than those during the dry season. Therefore, a negative correlation was observed between rainfall and the isotope values. Distillation during land transport of water vapour caused low isotope values in precipitation (Kurita et al., 2009). The combination of continental and amount effects may contribute to the complexity of seasonal rainfall isotope values, which leads to relatively high rainfall isotope values in February–April and August–October (shoulder seasons). The bimodal seasonal pattern and amount effect at Pasoh FR became clearer in the long-term average monthly data (Figures 2.4–2.7). Variation in isotope signals was more closely correlated with the 60-day antecedent rainfall index than with the amount of rainfall each day (Figures 2.8a and b), therefore it was able to roughly reproduce the seasonal trend in $\delta^{18}O$ using the antecedent rainfall index (Figure 2.8c). Results for Pasoh FR also suggested that the effects of rainfall amount on isotope composition at the study site resulted from the degree of rainout on a larger scale, including upstream transport pathways of water vapour, antecedent conditions and local-scale and specific rain events.

2.5 Conclusions

Most of the rain events at Pasoh FR were characterised as convective rainfall and no differences in rainfall characteristics and isotope signature were detected between the SW and NE monsoon seasons. Pasoh FR showed a similar seasonal trend in isotope values compared with those at nearby GNIP stations such as Kuala Lumpur and Singapore, while differing from those at stations in northern Peninsular Malaysia, which was mainly due to the different rainfall patterns. The amount effect was clearly detected and comparable with those of the nearby GNIP stations for the long-term mean monthly statistics, while it was obscured on the daily timescale and for the monthly rainfall not averaged over the long-term. The daily isotope values at Pasoh FR were negatively correlated with rainfall amount, maximum rainfall intensity and duration but the correlation coefficients were small. As it did not detect any increase in the deuterium excess in such rainwater, the scatter in the isotope values from small rain events did not mainly result from adding re-evaporated moisture from the land surface. The seasonal isotope values were more closely correlated with the 60-day antecedent rainfall index than with the amount of rainfall each day. Overall, the results strongly suggested that rainfall amount effects of isotope composition at the study site resulted from the degree of rainout on a larger scale, including upstream and antecedent conditions, in addition to that on a local scale and on specific rain events. These results will be useful to understand the mechanisms for the variability in rainfall isotope signals in Malaysian tropical rainforests and improving climate change forecasts. The availability of rainwater isotope data serves as fundamental information for forestry research and management. This result becomes very useful when paired up with isotope in xylem and soil water, ET and soil water content for the estimation of forest water use.

CHAPTER 3

Effect of soil moisture on evapotranspiration and water source

3.1 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 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 dry period. In Pasoh FR, which is located in a dry zone of Peninsular Malaysia and received 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 et al., 2012a). 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 et al., 2012a) compared to other Southeast Asian tropical rainforests (e.g., Kume et al., 2010; Vernimmen et al., 2007; Noguchi et al., 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 et al., 2012a).

Several other EC flux studies conducted in Amazonian and Southeast Asian tropical rainforests have also consistently demonstrated this characteristic (e.g., Malhi et al., 2002; da Rocha et al., 2004; Costa et al., 2010; Kume et al., 2011). In the Amazonian rainforests ET did not drastically decrease and sometimes increased during the dry season (e.g., da Rocha et al., 2004; Costa et al., 2010). 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 (Tani et al., 2003; Kosugi et al., 2008). 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 ($\delta^{18}O$ and $\delta^{2}H$) provide a powerful tool for determining plant water resources under a number of environmental conditions (Dawson and Ehleringer, 1991; Eggemeyer et al., 2009; Brooks et al., 2010; West et al., 2012; Yang et al., 2015; Evaristo et al., 2015). Using isotope indices, soil water, and streamflow and plant transpiration can be investigated whether all are 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 utilise only one of the dual stable isotopes of $\delta^{18}O$ (Querejeta et al., 2007; Nie et al., 2011) or $\delta^{2}H$ (Jackson et al., 1995; Filella and Peñeulas, 2003). However, the dual isotopes method (e.g., Cramer et al., 1999; Li et al., 2006; West et al., 2007, Eggermeyer et al., 2009; Wang et al., 2010, Rossatto et al., 2012; Orlowski et al., 2013; Evaristo et al., 2015) 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 does not contribute to stream flow, or mobile water that is unrelated to the water used by trees (i.e. groundwater, streamflow, infiltration, and hill slope runoff) (McDonnell, 2014). This approach can improve an understanding of the ecohydrological processes controlling water flows in soil-plant-atmosphere continuums (Berry et al., 2016).

Study of ET and water sources in the Pasoh FR comprised of three objectives: i) measure and calculate ET using the EC method over a 4-year period (2012 – 2015); ii) determine spatial and temporal patterns of water uptake and provenance, using water budget methods combining ET, precipitation and soil moisture data; and iii) 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.

3.2 Material and Methods

3.2.1 Site description

The study was conducted in a lowland dipterocarp forest within the 6 hectares plot of Pasoh FR (Figure 1.2). The detail description of the study site was explained in section 1.3.

3.2.2 Micrometeorology and eddy covariance evapotranspiration

Continuous EC flux observations commenced in September 2002. The four years of data from January 1, 2012 to December 31, 2015 were analysed, 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 CO_2/H_2O analyser (LI-7500; Li-Cor, Lincoln, NE, USA). Data were sampled at 10 Hz and sent to a data logger (CR-5000, or CR-1000; Campbell Scientific, Logan, UT, USA). 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 (WPL) correction for the effect of air density fluctuations (Webb et al., 1980) was also applied, and linear trends in temperature and water vapour were retained. The EC measurements of ET included transpiration, interception evaporation, and soil evaporation. All latent heat flux data recorded during and after rainfall were discarded; however, this gap was filled using available energy and sensible heat flux data measured using a three-dimensional (3D) ultrasonic anemometer, which can collect data during rainfall. A detailed description of these methods and instruments is provided in Kosugi et al. (2008, 2012a). 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 et al., 2012a). Gaps were further filled using a second-order polynomial relationship between 30-min λE after the energy budget correction method, and the available energy (R_n – G – S) was determined. Available energy is composed of net radiation (Rn), net soil heat flux (G), and net change in the storage term (S). Net radiation (Rn) refers to the balance of all the incoming and outgoing radiation at 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 shortwave radiation (MR22, EKO, Japan, or CMA6, Kipp and Zonen, The Netherlands) and longwave radiation (PIR, Eppley, USA; or CGR3, Kipp and Zonen, The

Netherlands) at a height of 52 m, and soil heat flux (HFP01, Hukseflux Thermal Sensors B.V., 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 the top of the tower based on Ohtani et al. (1997). Air temperature and humidity at the height of 52 m were observed using an HMP45A or HMP45C 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 (TDR) 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-minute 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). The daily average value of nine sensors was used as a reference VSWC for the surface layer between 0 and 0.5 m. The TDR 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 et al., 2012a). 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 daily precipitation (mm), and $\boldsymbol{i}$ is the number of preceding days (Kosugi et al., 2007).

3.2.3 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 hours after rainfall (4 April, 17 June, 29 October, and 9 December 2015), while five samples were collected 48 to 72 hours after rainfall occurrence (5 August, 23 September, 15 October, 19 November, and 15 December 2015); however, these samples were not taken during the rainfall. Eight samples were collected when there had been no rainfall for more 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 1.2). 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 3.1). 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 freezing in the laboratory. The tree species selected from emergent trees to the forest floor trees were *Dipterocarpus sublamellatus*, *Xanthophyllum stipitatum*, *Ptychopyxis caput-medusae*, *Syzygiium rugosum* (Kelat), *Diplospora malaccensis*, *Homalium dictyoneurum*, *Baccaurea parviflora* and *Macaranga lowii* (Table 3.2). Soil samples were collected on the same day or the next day with xylem samples near the flux tower (Figure 1.2) at soil depths of 0.05, 0.3, 0.75, 1.5, and 3.0 m. There was no presence of groundwater found 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 to –20°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 et al., 2006). Cryogenic vacuum extraction is the most widely utilised method for plant and soil water extraction

(Ingraham and Shadel, 1992; West et al., 2006; Vendramini et al., 2007; Koeniger et al., 2011; Orlowski et al., 2013). The water extracted from plants were treated 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 one week before transfer into measurement vials.

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

Table 3.1 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	8.0
12-13 March 2014	12 March 2014	13 March 2014	Very Dry	0.4 (12 Mar) 0.4 (13 Mar)
28-29 November 2014	28 November 2014	29 November 2014	Wet	41.8 (28 Nov) 30.0 (29 Nov)
8 January 2015	8 January 2015	8 January 2015	Wet	31.8

3.3 Results

3.3.1 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 3.1a). 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 3.1a, Marryanna et al., 2017). The annual rainfall from 2012 to 2015 fluctuated between 1624 and 1850 mm on average ± SD of 1720 ± 101 mm. The number of rainy days for four years was an average of 158 ± 13.3 days per year and the average ± SD of the yearly maximum length of rainless periods was 21.5 ± 8.8 days. These years were characterised as rather dry periods compared with the 21-year statistics on annual rainfall (1805 ± 280 mm), the number of rainy days (162.38 ± 16.3 days), and the average ± SD 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 March 15, 2014, coinciding with a very small monthly rainfall amount (7.7 mm month^{-1}, February 2014) and API60(0.2 mm) (Figure 3.1b). 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), respectively (Figure 3.1c). The annual average ET value was 1,182 ± 26 mm for the four 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 3.1d) 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}, respectively (Figure 3.1d). Daily ET increased in proportion to available energy when VSWC was high, and it decreased with a low VSWC (Figure 3.2a). The ET reaches a ceiling at high VPD, while at low VSWC during drier periods a small decrease in ET was observed with high VPD indicating stomatal closure (Figure 3.2b).

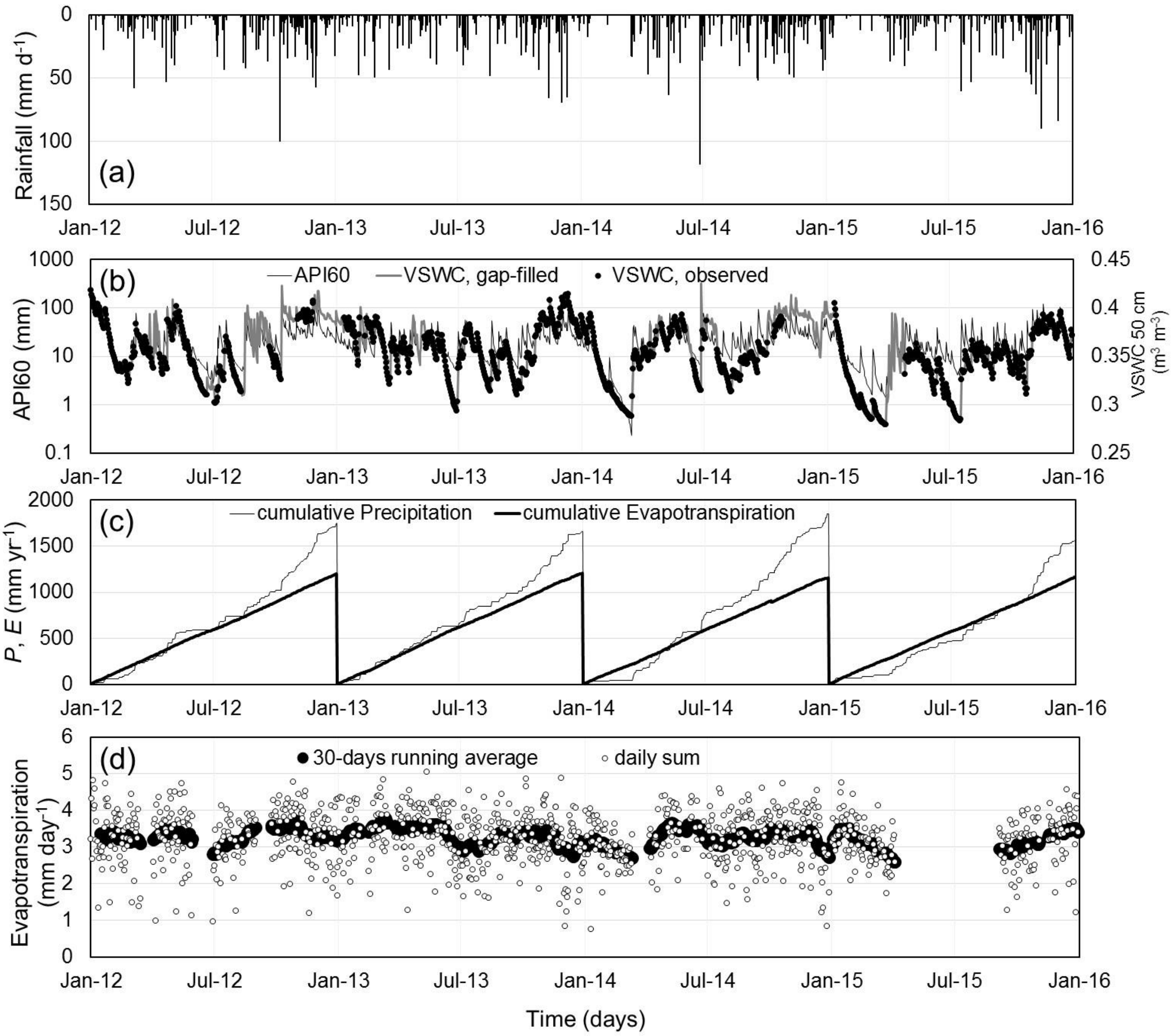

Figure 3.1 Time-series fluctuation of rainfall, soil water status and ET at Pasoh Forest Reserve from 2012-2015. (a) Daily rainfall amount (mm). (b) Antecedent Precipitation Index (API60), and observed and interpolated daily average volumetric soil water content (VSWC) from 0 to 50 cm (m^3 m^{-3}). (c) Annual cumulative rainfall amount and ET. (d) Daily and 30-day running average of ET (mm day^{-1}).

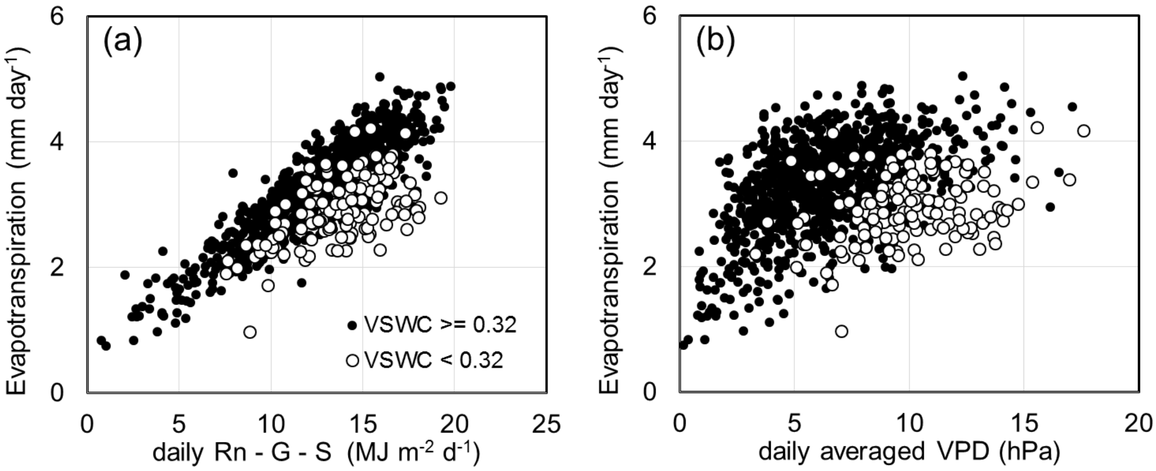

Figure 3.2 Comparison between daily ET (mm day^{-1}) and (a) daily available energy (MJ m^{-2} day^{-1}), and (b) daily average vapor pressure deficit (VPD) (hPa). Black and white dots represent daily average volumetric soil water content (VSWC) values that were more than and less than 0.32, respectively. The daily available energy is the sum of net radiation, net change in heat flux to soil, and heat flux to stem air and vapor in the canopy space

3.3.2 Soil water budget

Comparing ET with water budget in the soil provides some insight into the source of water for ET (Figures 3.3, 3.4). Figure 3.3 compared the cumulative ET and precipitation for several antecedent time scales to evaluate the minimal storage period of water for ET during dry condition. If water for ET is supplied from one-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 3.3a). In this case, the one-month antecedent water supply was not sufficient for plant consumption. Even if a further preceding month had been included (two-month antecedent water supply), there was insufficient water to accommodate plant water use for the period between (12 – 13 March 2014; Figure 3.3b), and even the four-month antecedent water supply was insufficient for plant water use. During the severe dry period (12 – 13 March 2014), at least four 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 (Peh, 1978; Leigh, 1978). However, some portion of such overland flow is assumed to infiltrate before reaching the stream. If this flow was 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.

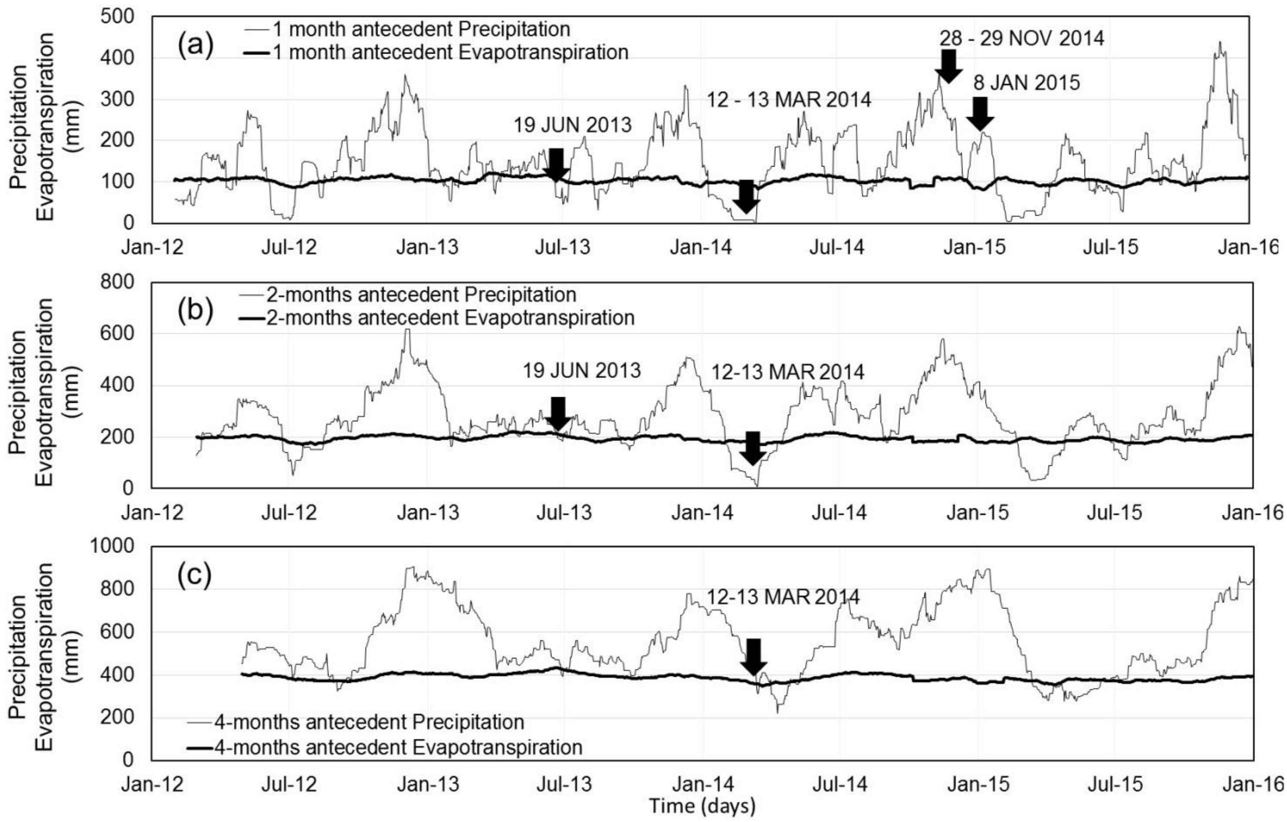

Figure 3.3 Comparison between cumulative ET (mm) and precipitation (mm) for (a) one month, (b) two months and (c) four months previously. The arrow indicates the four sampling periods for plant and soil water.

Figure 3.4 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 the budget was above 0 then the rainfall portion was not included. The soil water storage differential in soils at depths of 0–0.5 m was calculated using the VSWC, assuming uniform soil water content between 0 to 0.5 m. If both decline slopes are similar, this indicates that most water was supplied from this surface layer, 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. Since there was no drainage portion were accounted, it should be expected some overestimation if the differential considered was used only for transpiration and soil evaporation. It should also be noted 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 3.4a 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 3.4b). 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 was 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.

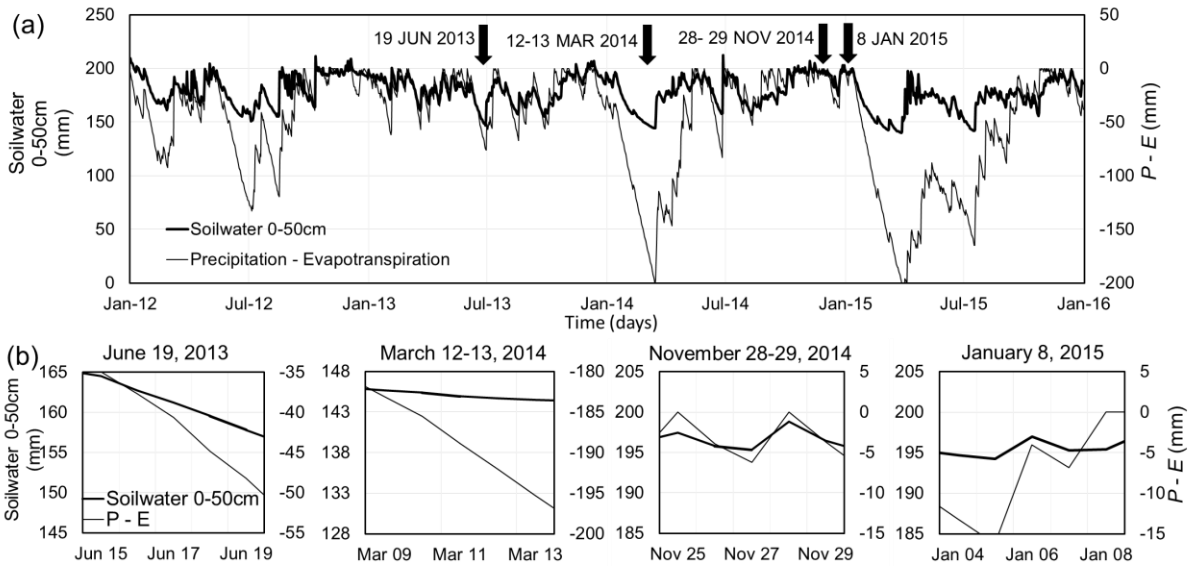

Figure 3.4 Comparison between ET demand (mm) and water budget in the surface soil layer (0–0.5 m) (mm). (a) Time series comparison from 2012 to 2015. The arrow indicates the sampling period at 19 June 2013, 12–13 March 2014, 28–29 November 2014 and 08 January 2015. (b) Short-term comparison for 15–19 June 2013, 09–13 March 2014, 25–29 November 2014 and 04–08 January 2015.

Table 3.2 The list of species and heights selected in this study. Species were selected based on accessibility from the flux tower

ID	**Species**	**Height (m)**	**DBH (cm)**
Group 1			
D.s.	*Dipterocarpus sublamellatus (Keruing)*	45	42.5
S.r.	*Syzygiium Rugosum (Kelat)*	25	23.0
B.p.	*Baccaurea parviflora*	5	2.9
M.l.	*Macaranga lowii*	3	2.1
Group 2			
X.s.	*Xanthophyllum stipitatum*	33	52.5
D.m.	*Diplospora malaccensis*	17	12.5
H.d.	*Homalium dictyoneurum*	12	7.0
Group 3			
P.c.	*Ptychopyxis caput-medusae*	32	38.2

3.3.3 Stable isotope signatures of plants, soil and stream water

Figure 3.5 provides an overview of how water is compartmentalised for different uses in the forest ecosystem. The daily $\delta^{18}O$ in precipitation in Pasoh FR varied considerably (Figure 3.5a, Marryanna et al., 2017). The $\delta^{18}O$ value in precipitation during the monsoon onset in May (SW) and November (NE) 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 $\delta^{18}O$ 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 $\delta^{18}O$ in stream water were detected, corresponding well to those in precipitation. The $\delta^{18}O$ 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 $\delta^{18}O$ and $\delta^{2}H$ (Figure 3.5b), stream waters had isotope values corresponding more closely to rainwater, while 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 3.5c) 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 3.5d) 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 3.2): group 1 with medium isotope values that fell within or near the range of soil water isotopes [*D. sublamellatus* (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 $\delta^{18}O$ and $\delta^{2}H$ 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 that as can be seen from the standard deviations of plant water isotope values ($\delta^{18}O$) for each species in Figure 3.5d, were similar in size to the temporal fluctuations in isotope values for upper layer soil water (0.05, 0.3 and 0.75 m, Figure 3.5c), 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.

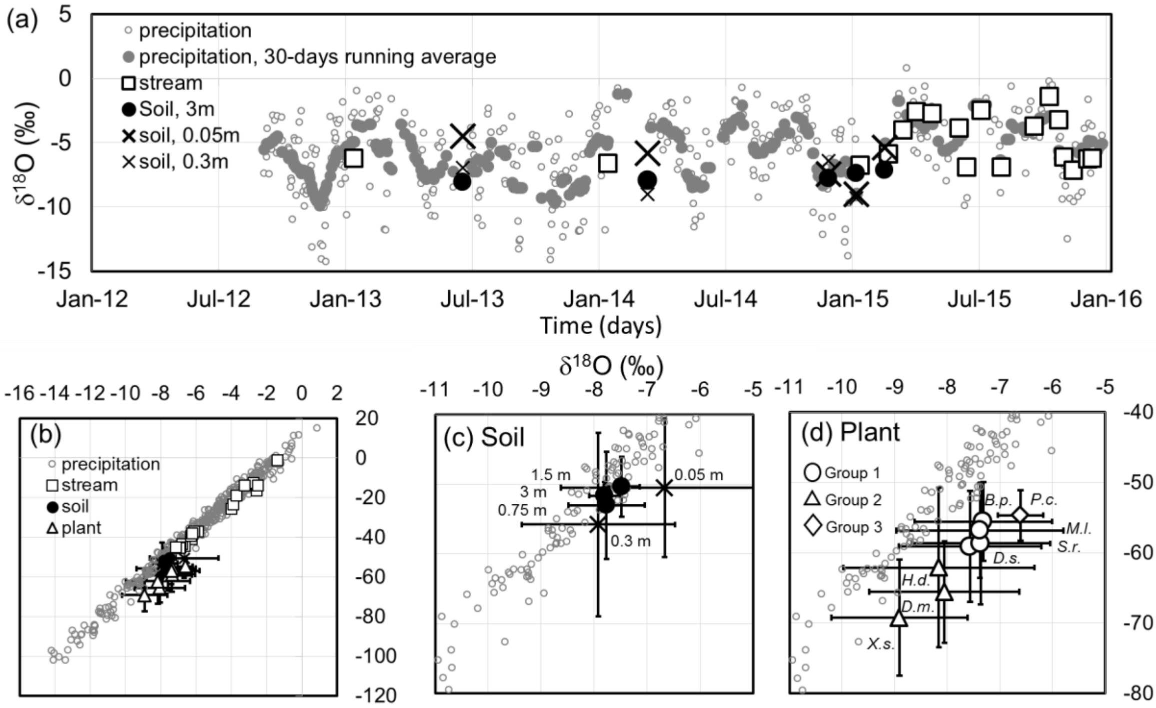

Figure 3.5 Isotope signatures of precipitation, stream, soil and plant water at Pasoh Forest Reserve. (a) Time-series fluctuation in $\delta^{18}O$ of precipitation, stream and soil water at 0.05, 0.3 and 3.0 m. Isotope signatures are also shown in the relationship between $\delta^{18}O$ and $\delta^{2}H$ for (b) rainfall, stream, soil and plant water, (c) soil water and (d) plant water. Plant water is depicted as circles for Group 1, triangles for Group 2 and diamonds for Group 3.

During the dry period (Figure 3.6a; 19 June 2013), for 30-day antecedent rainfall, most plant water isotopic contents were different from rainwater, while for longer (60-day) antecedent rainfalls, 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 3.6b), most rainwater 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 3.6c; 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 3.6d; 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 3.6). 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.

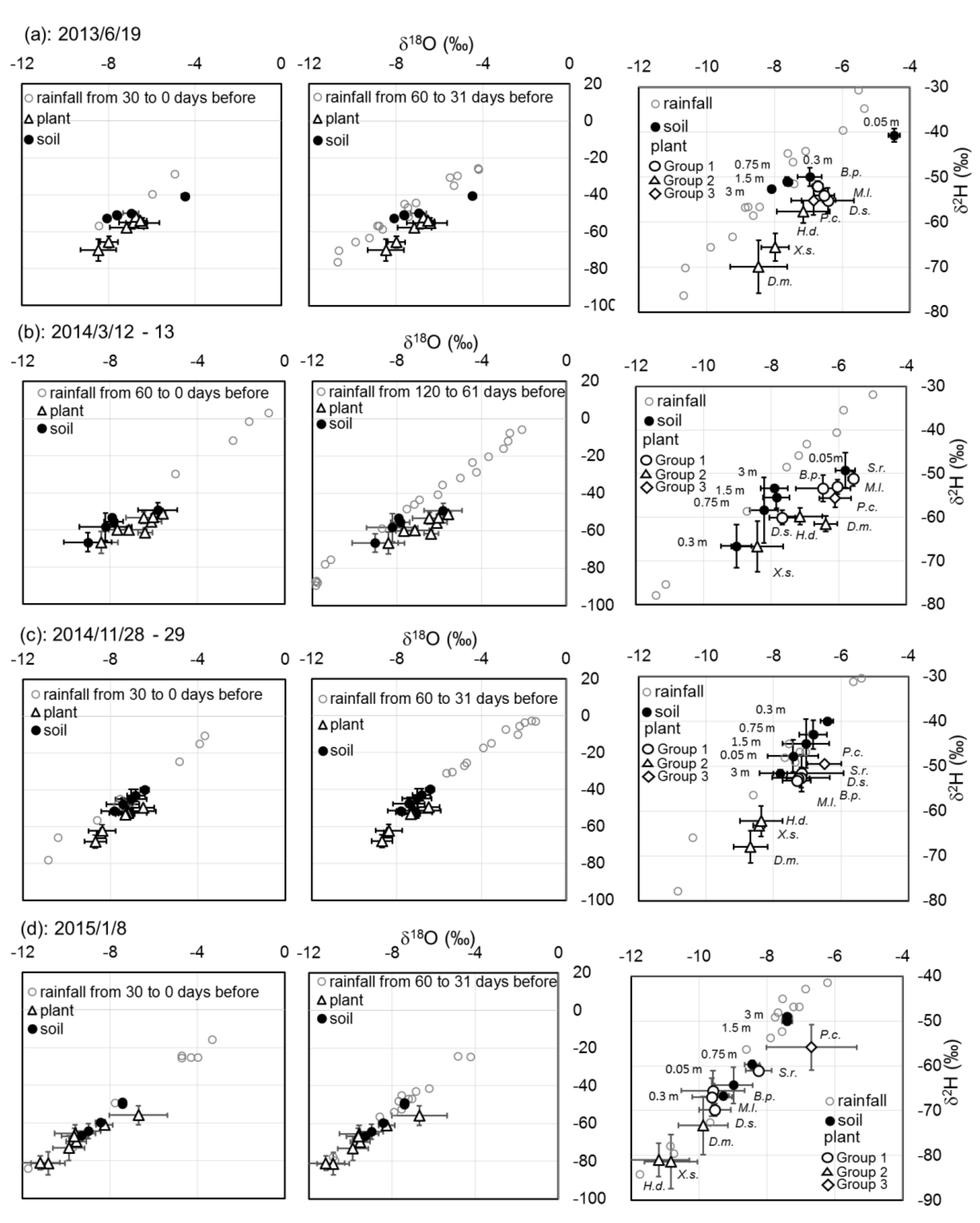

Figure 3.6 The relationship between $\delta^{18}O$ (‰) and $\delta^{2}H$ (‰) of rainwater, soil water and plant water for (a) 19 June 2013 (dry, API60 = 8), (b) 12-13 March 2014 (very dry, API60 = 0.4), (c) 28-29 November 2014 (wet, API60 = 30 – 42), and (d) 08 January 2015 (wet, API60 = 32). Individual 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. *Syzygiium rugosum* (S.r) was not sampled in 19 June 2013. Antecedent rainfall is also plotted to identify water sources

3.4 Discussion

3.4.1 Micrometeorology and eddy covariance evapotranspiration

Pasoh FR has typical monsoon-type rainfall variations (Figure 3.1ab). It has significant inter annual 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 et al., 2012a). The seven-year average annual value of ET found by Kosugi et al., (2012a) 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 parameterised with occasional EC measurements. Indonesian peat swamp forests show larger values (1,636 ± 53 mm, Hirano et al., 2015), and one semi-deciduous tropical forest in Xishuangbanna, southwest China, showed a smaller value (1,029 ± 29 mm, Li et al., 2010). Here, the values cited only based on EC measurement and after correction or consideration of energy budget imbalances. EC methods often suffer energy imbalance problems, while 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 3.1cd). Similar ET stability was seen in several other EC flux studies conducted in Amazonian and Southeast Asian tropical rainforests (e.g., Malhi et al., 2002; da Rocha et al., 2004; Costa et al., 2010; Kume et al., 2011). 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). Based on energy-imbalance filtering data, ET was stable with a slight increase in the dry season in central Amazonian rainforest sites, whereas in drier semi deciduous 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; Li et al., 2010) and stomatal control (e.g., Cunningham, 2004), latter of which is influenced by the factors related to water supply, such as available water in the soil (e.g., Burgess et al., 1998; Rafael et al., 2005), rooting-depth (e.g., Nepstad et al., 1994; Li et al., 2010) and upward flow in the soil (e.g., da Rocha et al., 2004; Li et al., 2010). In Malaysian tropical rainforests located near the equator with indistinct dry periods, ET was relatively constant (Tani et al., 2003; Kumagai et al., 2005; Kume et al., 2011). The variability of daily ET at Pasoh was dependent on available energy and VPD, but was also moderately influenced by soil water content (Figure 3.2ab, Kosugi et al., 2012a). 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 3.2; 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 3.1cd), 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 Li et al. (2010) could be the driving factor. The drought-tolerant tree and deep root system (Hodnett et al., 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 et al., 2012a) that this forest used on average (± SD) 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 four years.

3.4.2 Water budget in the soil

Soil water content is a major control of hydrological processes such as ET, the precipitation-runoff response, energy transfer, and as a climate predictor (e.g., Betts et al., 1996). The soil water budget is a useful method for estimating total water loss from the soil caused by transpiration and soil evaporation (Wilson et al., 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 and Sheriff, 1996). This forest needs at least four months of water storage to accommodate the ET demand during extended dry periods (Figure 3.3). 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 3.3. 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 3.4b) 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 3.4 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. Based on the occasional observations of soil water content at 0.05, 0.3, 0.75, 1.0, 2.0, and 3.0 m soil depths (unpublished data by Noguchi et al.), very little fluctuation was detected at 2.0 and 3.0 m. If fluctuations in soil water content in the layer between 0.5 and 1.0 m were assumed 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 the result of this study.

3.4.3 Plant and Soil Water Isotopes

Rainwater is partitioned into three components: (a) interception loss, (b) infiltration excess overland flow, and water infiltration to soil. Infiltrated water is divided between (c) percolating water held at tension below field capacity (drainable pore space), (d) plant-available water held at tension between field capacity and permanent wilting point (water available for plant ET), and (e) immobile residual water not participating in the hydrological cycle. The results (Figure 3.5, 3.6) strongly suggest that water sources for stream, plants, and soil at this forest, corresponding to (b) + (c), (d), and (e) respectively, are separated.

Large fluctuations in isotope values in stream water corresponding with rainwater (Figure 3.5a) indicate that the portion of ‘new’ water runoff 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 (Peh, 1978; Leigh, 1978). The results are consistent with this. Generally (e.g., Clark and 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 stream flow. There was a need for more intensive data of stream water to check this consistency and to obtain more precise partitioning of runoff pathway in this site.

Soil and plant water showed different characteristics from stream water, and additionally, differed from each other (Figure 3.5, 3.6). Only in the very dry period, plant and soil isotope values became 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 this study during the driest sampling period (June 2013 and March 2014, Figure 3.6ab), 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. How tightly the water was bound to the soil was not tested in this study and this could be a significant topic for future study. However, it can at least be inferred from Figure 3.1 that the volumetric soil water content of soils from the study site was approximately 0.28 $m^3\ m^{-3}$ 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 it can be concluded 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 that 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 3.4.

It has been assumed that plants take up water according to their height (Kim et al., 2014) and rooting depth (Meinzer et al., 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 isotope signals from trees of different height and species did not show any clear tendency of water uptake depth during the study period. Based on these results, it could not be distinguished whether shorter or smaller trees use water from the shallow soil layer, while 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, while others use both layers (West et al., 2007; Eggermeyer et al., 2009). 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 and 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 et al., 2007; Orlowski et al., 2016). Despite this, there are still many factors that may influence isotopic unfractionated water and as a result, this issue remains poorly understood and there is a need for further studies (Munksgaard et al., 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.

This 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, B. parviflora)* and a middle-sized tree *(Syzgiium 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, D. malaccensis)*. The Group 3 tree *(Ptychopydix 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 *(Ptychopydix caput-medusae)* trees have small stomatal conductance and maximum photosynthesis (Kosugi et al., 2012b). 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 Group 2 and 3 are medium sized trees, which may indicate the origin of these characteristics. It was found smaller stomatal conductance and photosynthesis in middle-sized trees at this site compared with emergent trees (Kosugi et al., 2012b). These middle-sized trees might suffer from water stress, and operate in a highly protective manner (Kosugi et al., 2009). The utilisation of released water from stored compartments near the canopy may play an important role in mitigating water stress in canopy leaves, thereby maintaining stomata 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); while others have shown that stem-stored water may be used for buffering the daily water deficit even when soil water is abundant (Holbrook, 1995; Goldstein et al., 1998).

3.4.4 Impact of vegetation on hydrology

Pasoh FR used most of the available water to maintain ET particularly during dry in which there was no decrease of ET (Figure 3.1d). During dry periods, i.e. 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. The 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 runoff in response to rainfall is dominant, and the streams sometimes dry up during drier periods. This forest is mainly characterised 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. Stream flow characteristics are typically determined by soil physical traits, topography and geography. In the study area, the uptake of almost all-available water by vegetation also influenced streamflow characteristics. In many tropical rainforests with rainfall amounts of c. 2,000 mm and having occasional dry period, the amount of runoff is not large, as illustrated by several reviews of hydrology in the humid tropical region (e.g., Wohl, 2012). Rather, runoff is typically low and occasionally ephemeral during dry periods due to the large ET demands of rainforest ecosystems.

3.5. 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, indicating the dominance of 'new' water runoff. There are occasional isotopic differences between plants and soil water, probably because water source for plants is different from the 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 runoff. 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.

CHAPTER 4

Effect of soil moisture on stand dynamics

4.1 Introduction

In tropical rainforests, changes in soil moisture patterns associated with rainfall pattern have an impact on processes that affect the forest ecosystem functions, which in turn results in variations in the forest stand dynamics (e.g., Bettina et al., 2007). Temporal drought decreases soil respiration (e.g., Goulden et al., 2004; Kosugi et al., 2007), gross primary production (e.g., Kosugi et al., 2012), and increases mortality rates (e.g., Meir et al., 2015) in tropical rainforests.

In Amazonian rainforests, many studies have reported increased mortality related to temporal drought (e.g., Phillips et al., 2009; Lewis et al., 2011; Meir et al., 2015). Temporal drought has also been shown to induce the decrease of soil respiration in an eastern Amazonian rainforest (Goulden et al., 2004). However, while the effects of temporal variation in soil moisture on ecosystem processes are well-characterised, they differ from those of spatial variation in soil moisture. In a Southeast Asian tropical rainforest, Pasoh Forest Reserve (FR), surface soil water content had a positive relationship with temporal variation in soil respiration, but a negative relationship with spatial variation in soil respiration (Kosugi et al., 2007). Thus, there is a complex relationship between soil moisture and soil respiration. It is important to clarify how ecosystem processes are influenced by both temporal and spatial variations in soil moisture.

In forest ecosystems, the spatial distribution of soil moisture may influence the forest community structure. The availability of detailed data on volumetric soil water content (VSWC) is critical for classifying habitat in relation to the water gradient (Marryanna et al., 2012), because plants have different relationships with water that are also associated with topographical variation in water availability. These are likely to be important drivers of plant population dynamics and species distribution across habitats. However, such variations in water availability have rarely been examined (Liza & Bettina, 2009).

In the present study, it was hypothesised that spatio-temporal patterns of VSWC are driven by topographical spatial patterns and soil physical properties, and that spatio-temporal VSWC patterns influence spatial variability in stand dynamics such as biomass, size distribution, tree number, mortality, and species distribution in a Southeast Asian tropical rainforest. The objectives of this study were (1) to examine the spatial distribution of VSWC at different soil depths and the governing factors thereof, and (2) to determine the influence of VSWC variation on stand dynamics.

4.2 Material and Methods

4.2.1 Site description

The study was conducted at a 6 ha plot (Niiyama et al., 2003) in Pasoh FR (Figure 4.1). Pasoh FR is located at 2° 98' 20 N, 102° 31' 30 E, at approximately 75 to 150 m.a.s.l. It is a lowland dipterocarp forest with a canopy height of 30–40 m (with emergent trees ~45 m tall). The core area (600 ha) of the reserve is primary lowland mixed dipterocarp forest, consisting of various species of *Shorea* and *Dipterocarpus* (Soepadmo, 1978).

The mean annual rainfall at the study site is 1800 (±285) mm (1996 –2015, Marryanna et al., 2017), peaking from March to May and from October to December (Kosugi et al., 2008). These rainy periods are characterised by their short duration and high intensity (Noguchi et al., 2003). The mean annual air temperature is 25.4°C (1997–2011) (Noguchi et al., 2016). Typically, this area receives at least 42.6% of its annual rainfall during the northeast monsoon (November to March), 39.1 % during the southwest monsoon (April to October) and the remaining 18.4 % during the transitional months (April and October) (Noguchi et al., 2003). The study area is located within a dry zone of Peninsular Malaysia, and receives the lowest annual rainfall amount among adjacent south-eastern tropical rainforests (Noguchi et al., 2003, 2016, Marryanna et al., 2017). Pasoh experience extreme and prolong dryness during the El Niño Southern Oscillation events (Marryanna et al., 2017). Thus, the site is suitable for assessing the influence of VSWC on stand dynamics.

The soil types at the study site are of petrophlinthic haplorthox and typic paleudults, both having clay topsoil with a fine granular structure and silty loam texture in deeper layers (Yamashita et al., 2003). The A horizon in this area was thin (0–2 cm, Yoda 1978, or 0–5 cm, Yamashita et al., 2003). Lateritic gravel is abundant below depths of 30 cm and increases with depth (Yoda 1978). The soil particle size distribution is characterised by low sand and high silt content (Yamashita et al., 2003). The hydraulic conductivity (*Ks*) of the plot area ranges from 3.3×10^{-2} to 8.9×10^{-4} cm s^{-1} (Noguchi et al., 2016). The proportion of thinner fine root to total fine root is higher than reported elsewhere (Yamashita et al., 2003). Fine roots are important for absorbing water and nutrients, and for dry matter production. The fine root biomass down to a depth of 2 m was estimated at an average of 13.3 Mg ha^{-1} by the pipeline method and 16.4 Mg ha^{-1} using a pit sampling method (Niiyama et al., 2010).

The topography of this forest is less steep than that of other tropical lowland forests, such as Lambir in Sarawak (Yamakura et al., 1995). Detail topography, soil morphology and pedo-hydrology was also reported in Adzmi et al (2010). Generally, the vegetation type in this forest is lowland dipterocarp characterised by a high proportion of dipterocarpaceae species. A previous study estimated that Pasoh FR houses over 800 species, 21 of which were new to science (Christine et al., 2012).

Plot 1 (100 m × 200 m) established by Wong & Whitmore (1970), which includes a 20 m × 100 m clear-cut area under the International Biological Program (Kato et al., 1978), was expanded to the 6-ha (200 m × 300 m) plot in 1994 as a long-term ecological research site (Niiyama et al., 2003). Spatial gridding was carried out using a small grid area (5 × 5 m) for the tree census. A survey was also conducted to measure the elevation distribution within the plot. The 20 m × 20 m (400 m^2) grids was selected corresponding to VSWC measurement points. In total, 35 plots were included, each 20 m × 20 m (Figure 4.1). Relative elevation and census data within the selected 400 m^2 grid were used to assess the relationship with VSWC. Therefore, it should be noted that the data presented in this study were only for the selected grids. The clear-cut plot were excluded (Figure 4.1) from the analysis because it was reported that 59 of 82 original species failed to return after clear-cutting conducted from 1955 to 1959, (Niiyama et al., 2003).

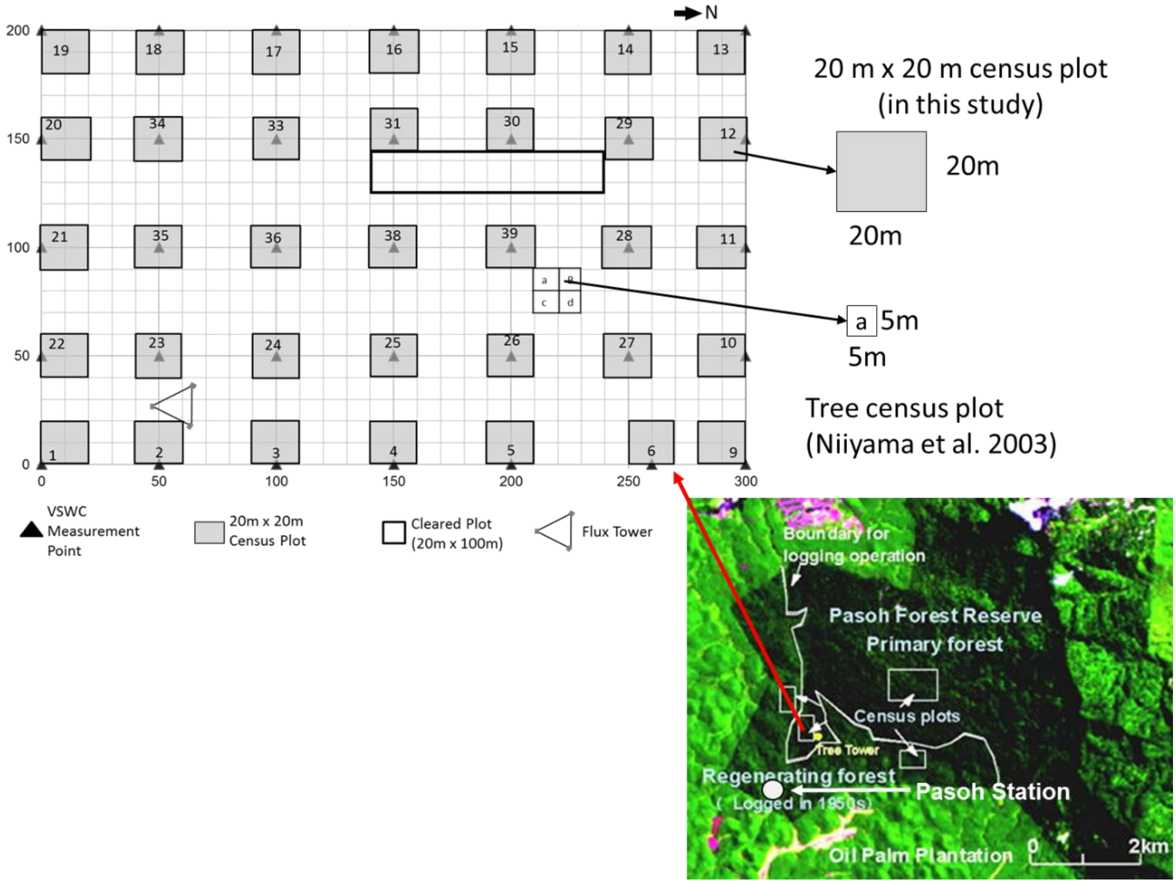

Figure 4.1 Location of 6 ha plot of Pasoh FR in Peninsular Malaysia and plot design of the measurements of VSWC and parameters of stand dynamics

4.2.2 Volumetric soil water content

The 50-m-interval spatial sampling grids were established in the 200 × 300 m plot (6 ha plot) within the Pasoh FR (Figure 4.1). An Amplitude Domain Reflectometry (ADR-type) soil moisture profile probe (PR2; Delta T Devices, Ltd.) were used to collect data from soil depths of 0.1, 0.2, 0.3, 0.4, 0.6 and 1-meter. One-meter fibreglass access tubes suitable for the PR2 sensor were buried in the ground for soil moisture measurement. Soil moisture was measured 28 times, from June 28, 2016 to May 30, 2017 at 35-access tubes across the plot (Figure 4.1). The device had a generalised mineral and organic value, which contained two parameters (a_0 and a_1). The default values (parameter $a_0 = 1.3$ and parameter $a_1 = 7.7$) were applied for the middle and deeper soil layer (0.4–1 m), while for the surface soil layer soil calibration parameters specific to mineral soil were used. Twelve soil samples were taken from the forest at the 0–10 cm soil layer at six points (6, 23, 27, 29, 34, 38), and their gravimetric values were obtained by oven drying. The soil samples were saturated, dried and weighed. Volumetric moisture valves, obtained with the gravimetric method and with the use of an ADR sensor (ML2x; Delta T Devices, Ltd.) were calculated. This sensor was used because the PR2 sensor was difficult to calibrate in the laboratory. The regression coefficients were determined between VSWC (m^3 m^{-3}) measured with the ADR method and VSWC (m^3 m^{-3}) measured with the gravimetric method and obtained values of 1.44 (parameter a_0) and 6.96 (parameter a_1).

To obtain soil physical data at the study site, including saturated and residual soil water contents, undisturbed soil samples at depths of 0–5 cm at 15 measurement points were collected inside the 6 ha plot (Itoh et al., 2012). Thin-walled steel samplers with a volume of 100 cm^3 (inner diameter: 5 cm, height: 5.1 cm) were used to collect soil samples. Soil water retention curves in the range of ψ 0 to -1000 cm were measured using pressure plates (Itoh et al., 2012) and fitted using the log-normal distribution model (Kosugi, 1996, 1997) for soil water retention. This model was used to estimate the median pore radius (r_m) and pore size distribution (Δ).

4.2.3 Precipitation

Rainfall was measured using two 0.5-mm tipping bucket rain gauges (model 34-T; Ota Keiki Seisakusho, Tokyo, Japan) at the top of the 52 m meteorological observation tower and at the station observatory from January 2016 to May 2017. The tipping bucket gauges measured rainfall at 30 minutes intervals. Rainfalls was also collected daily from a storage-type rain gauge in an observatory located 430 m away from the flux tower (Figure 4.1). The storage rain gauge was buried in the ground, to prevent heating, within a double-layered small-mouth inner glass bottle to prevent evaporation. Data collected from tipping bucket rain gauges were compared with stored rainfall to correct for possible underestimates. The antecedent precipitation index (API60) was found to have a significant relationship with the VSWC (Noguchi et al., 2016), and was therefore used as a wetness index in the study area. The API60 is defined as $\sum_{i=1}^{60} P_i/i$, where $P_i P_i$ is daily precipitation (mm), and $\boldsymbol{i}$ is the number of preceding days (Kosugi et al., 2007). The antecedent precipitation index (API60) threshold for identifying dry and wet values was obtained from the average API60 throughout the observation periods between January 01, 2016 and May 31, 2017

4.2.4 Stand dynamics

Censuses of trees in the 6 ha plot have been carried out every 2 years since 1994 (Niiyama et al., 2003). All trees with diameter at breast height (DBH) >5 cm were identified and mapped. Tree species were categorised into several ecological species groups: emergent, main canopy, understorey, and others (Manokaran & Swaine, 1994; Niiyama et al., 2003). From the census data, several parameters of stand dynamics were obtained, assessed in relation to VSWC. The census data from 2002 and 2012 were used, and calculated the mean values between these 2 years to determine the average parameters over the 10-year period. The basal area (m^2 ha^{-1}) is a sum of every tree within each 20 m × 20 m plot, and serves as an index of biomass and occupancy. The mean DBH (cm) is the average value of trees within each 20 m × 20 m plot, representing the average tree size within the plot. Tree number (N 400 m^{-2}) is the count of existing trees within each 20 × 20 m grid. The mortality (% 10 $years^{-1}$) is the percentage loss of trees in each 20 m × 20 m plot over 10 years, and was calculated based on the differences in tree numbers between 2002 and 2012. The numbers of emergent, main canopy and forest floor species (N 400 m^{-2}) were calculated based on the species classification in census data (Manokaran & Swaine, 1994; Niiyama et al., 2003). The relationships between VSWC and the number of trees of specific families were also examined within each 20 × 20 m plot. In all, 22 families that had an occupancy of more than 1% in the 6 ha plot were tested (Table 4.1).

4.2.5 Statistic

Pearson correlation was used to examine the dependencies among the variables and determine *r* and *p* values. Three thresholds of significance were used to determine the strength of each relationship: $p<0.001$, $p<0.01$ and $p<0.05$. SigmaPlot 12 (Systat. Software, Inc.) was used to map the spatial distributions of VSWC, relative elevation and stand dynamics within the plot. The 2-D scatter plots was used to compelling contour which show the spatial relationship between parameters.

Table 4.1. Percentage of tree families' occupancy in the 6 ha plot of Pasoh FR. Percentage is based on number of each family.

No	Family name	Occupancy (%)
1	Euphorbiaceae	19.1
2	Dipterocarpaceae	12.6
3	Burseraceae	5.6
4	Annonaceae	5.4
5	Sapotaceae	3.9
6	Myristicaceae	3.7
7	Leguminosae	3.3
8	Ulmaceae	3.2
9	Ebenaceae	2.6
10	Meliaceae	2.6
11	Flacourtiaceae	2.6
12	Myrtaceae	2.5
13	Anacardiaceae	2.2
14	Guttiferaceae	2.0
15	Lauraceae	2.0
16	Sapindaceae	2.0
17	Rubiaceae	1.8
18	Polygalaceae	1.8
19	Moraceae	1.5
20	Fagaceae	1.1
21	Olacaceae	1.1
22	Alangiaceae	1.0

4.3 Results

4.3.1 Physical properties of the surface soil

The saturated VSWC ($VSWC_{\psi = 0cm}$) for 15 undisturbed surface soil samples ranged from 0.441 to 0.603 with an average value (± SD) of 0.508 (±0.045) m^3 m^{-3}. The residual VSWC ($VSWC_{\psi = -1000cm}$), for which used the approximate VSWC value at the capillary pressure head at a depth of 1 m, ranged from 0.141 to 0.322 with an average value of 0.228 (±0.055) m^3 m^{-3} (Figure 4.2a). The range between $VSWC_{\psi = 0cm}$ and $VSWC_{\psi = -1000cm}$, which is an index of the effective VSWC range in soil, was from 0.09 to 0.431, with an average of 0.272 (±0.08) m^3 m^{-3}. The range became larger as the $VSWC_{\psi = -1000cm}$ decreased (Figure 4.2b). The estimated median pore size also increased as residual value decreased (Figure 4.2c).

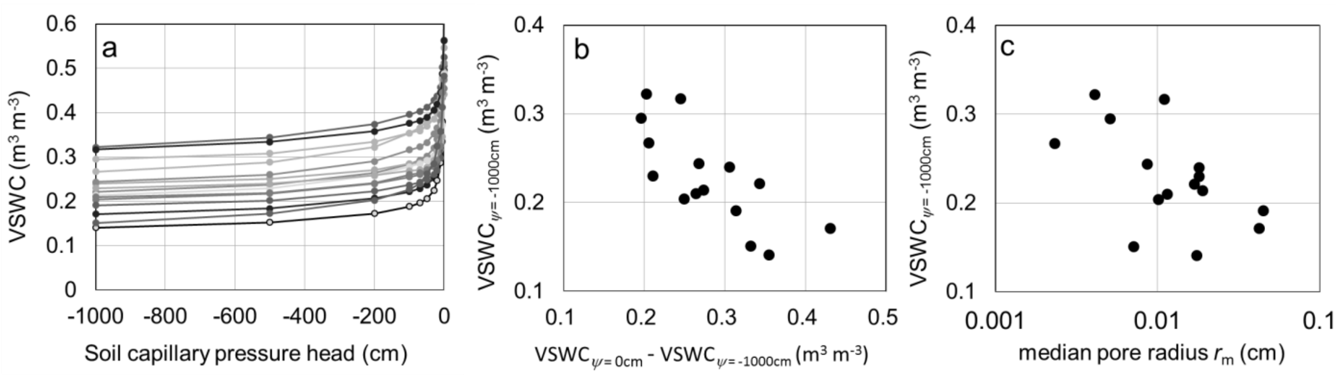

Figure 4.2 (a) The soil water retention curve, i.e VSWC ($m^3\,m^{-3}$) and soil capillary pressure head (cm) at the surface soil (0-5cm), (b) The range between VSWC$_{\psi\,=\,0cm}$ and VSWC$_{\psi\,=\,-1000cm,}$ which is an index of effective VSWC (c) The estimated median pore size using lognormal distribution model for unsaturated soil. Undisturbed soil samples were collected at depths of 0–5 cm at 15-measurement points inside the 6 ha plot.

4.3.2 Temporal variation of VSWC

The total rainfall for 2016 was 1, 495 mm year^{-1}; it was 1,070 mm for the first 5 months of 2017 (Figure 4.3a). Generally, conditions were dry before October 2016 and wet after November 2016, but conditions oscillated frequently depending on rainfall (Figure 4.3a, b). The API60 values from June 1, 2016 to May 31, 2017 ranged from 1.89 to 132.6 mm (average: 23.4 mm). The API60 value at the 28 VSWC observation point ranged widely, from very dry (5.58) to wet (75.21) conditions (Figure 4.3b). The average API60 value (23.4) was used as the threshold for distinguishing between dry and wet periods. Among 28 sampling events conducted from June 28, 2016 to May 30, 2017, 12 events were grouped into the dry period and 16 events into the wet period. Over time, the spatially averaged VSWC (an average of 35 points) ranged from 0.143 to 0.369 $m^3\,m^{-3}$, and from and 0.296 to 0.588 $m^3\,m^{-3}$, for surface (0.1 m) and deeper soil (1.0 m), respectively. The seasonal fluctuations in VSWC corresponded to changes in rainfall pattern and API60 (Figure 4.3c).

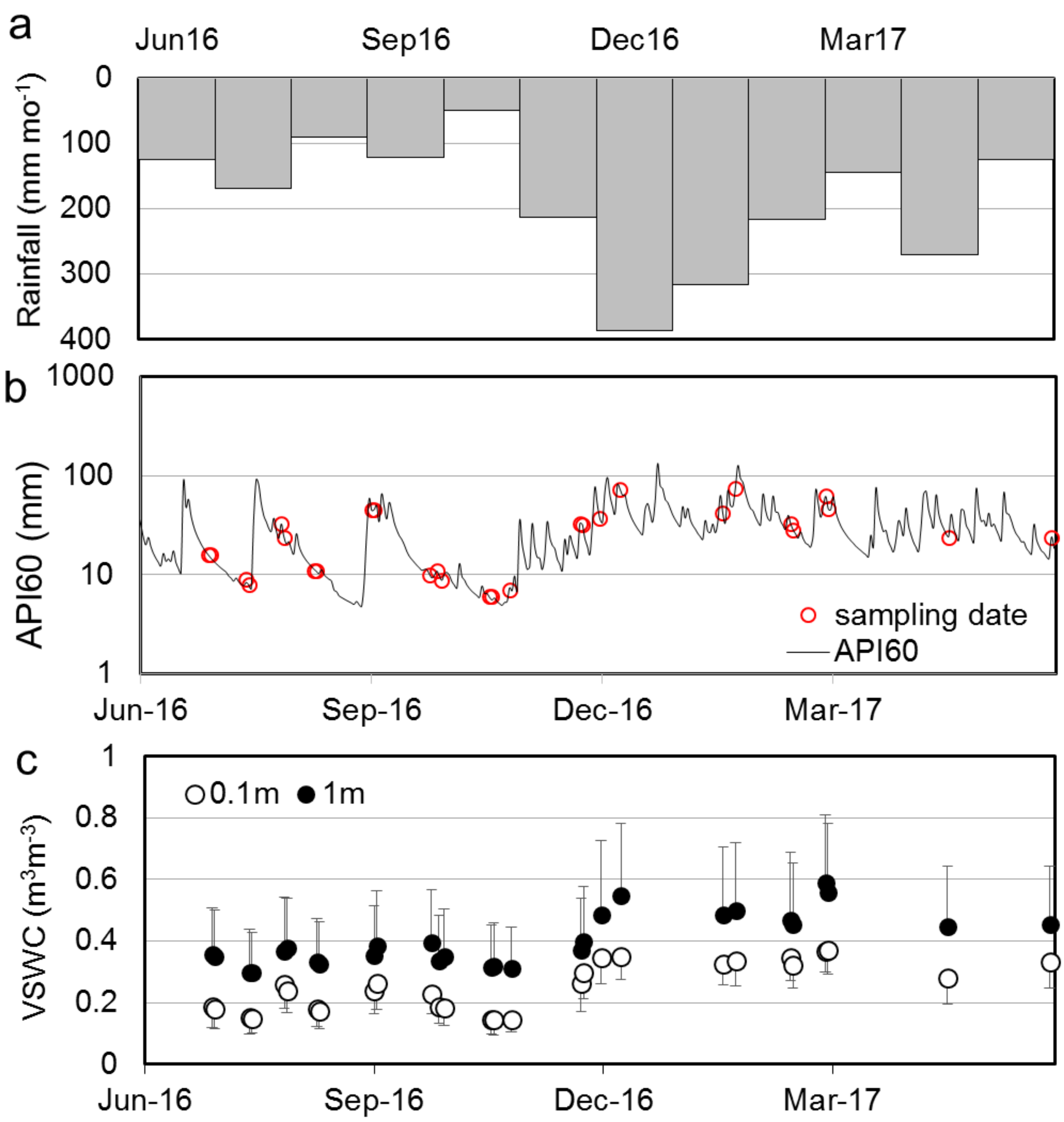

Figure 4.3. Temporal variations of (a) rainfall (b) API60 and sampling date of soil moisture (c) The average volumetric soil water content (VSWC) of 0.1m and 1m depth from 2016 to 2017 in Pasoh FR. Error bars shows the standard deviation.

4.3.3 Spatial and vertical distributions of VSWC

The range of spatial variation in surface-layer VSWC during the dry period (Figure 4.4a) resembled that of the residual VSWC ($VSWC_{\psi=-1000cm}$, Figure 4.2a, b, c). Relative elevation showed a significant negative relationship with surface layer VSWC during the dry period (r = -0.61***) and throughout the entire period (r = -0.44**) (Table 4.2, Figure 4.4a). However, relative elevation was not significantly correlated with surface-layer VSWC during the wet period (Table 4.2). Detailed analysis revealed some inconsistencies between the distribution patterns of surface-layer VSWC and relative elevation (Figure 4.5a, c, i). The wet areas near plot 6 and plot 33 (Figure 4.1; Figure 4.5a, b, c) are hollows, where overland flow is sometimes observed during rain events. Although there are two types of soil in the 6 ha plot, VSWC did not appear to depend on the soil types.

Middle-layer (0.2, 0.3, 0.4 m) VSWC showed an independent spatial pattern in the map (Figure 4.5d, e, f). Middle- and deep-layer VSWC often showed significant positive relationships with relative elevation (Table 4.2, Figure 4.4b), and negative relationships with surface-layer VSWC, during the dry period (Table 4.2, Figure 4.4c).

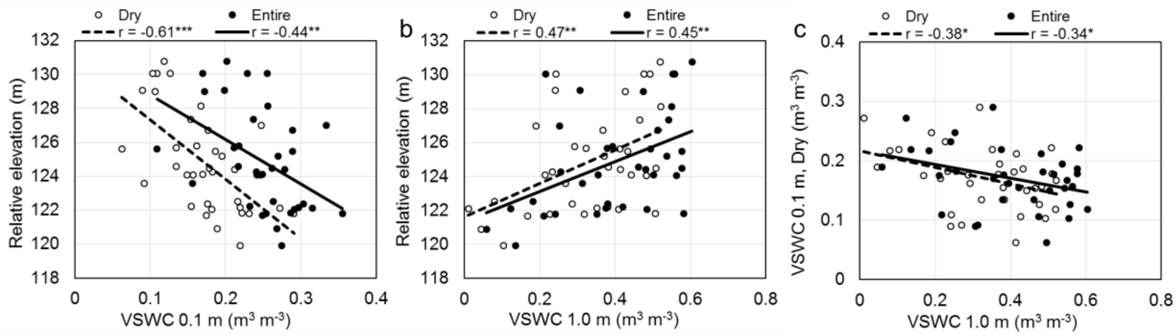

Figure 4.4. The relationship between (a) relative elevation and VSWC at surface layer (0.1m) VSWC during dry and entire periods, (b) relative elevation and VSWC at deeper layer (1.0 m) during dry and entire periods (c) relationship between VSWC at surface layer (0.1 m) and deeper layer (1.0 m) VSWC during dry and entire periods.

Table 4.2. The Pearson correlation and their level of significance resulting from a regression between altitude and volumetric soil water content (VSWC) measured at 35 points in the 6 ha plot of Pasoh FR. VSWC was measured at 6 depths (0.1, 0.2, 0.3, 0.4, 0.6 and 1.0 m) during dry (API60 <23, n=12), wet (API60 >23, n=16) and entire periods (n=28) from 28 June 2016 to 30 May 2017. The correlation between VSWC at each depths and the surface (0.1 m) VSWC during dry period are also shown.

*P<0.05, **P<0.01, and ***P<0.001, NS Not significant

Sampling Period and depth (m)	Relative Altitude (m)	VSWC 0.1 m during dry period (m^3 m^{-3})
Dry Period		
0.1 m	-0.61***	
0.2 m	NS	NS
0.3 m	NS	NS
0.4 m	0.35*	NS
0.6 m	0.52**	-0.50**
1.0 m	0.47**	-0.38*
Wet Period		
0.1 m	NS	NS
0.2 m	NS	NS
0.3 m	0.38*	-0.39*
0.4 m	0.49**	-0.39*
0.6 m	0.54***	-0.49**
1.0 m	0.43*	NS
Entire Period		
0.1 m	-0.44**	
0.2 m	NS	NS
0.3 m	NS	-0.36*
0.4 m	0.44**	-0.36*
0.6 m	0.54***	-0.50**
1.0 m	0.45**	-0.34*

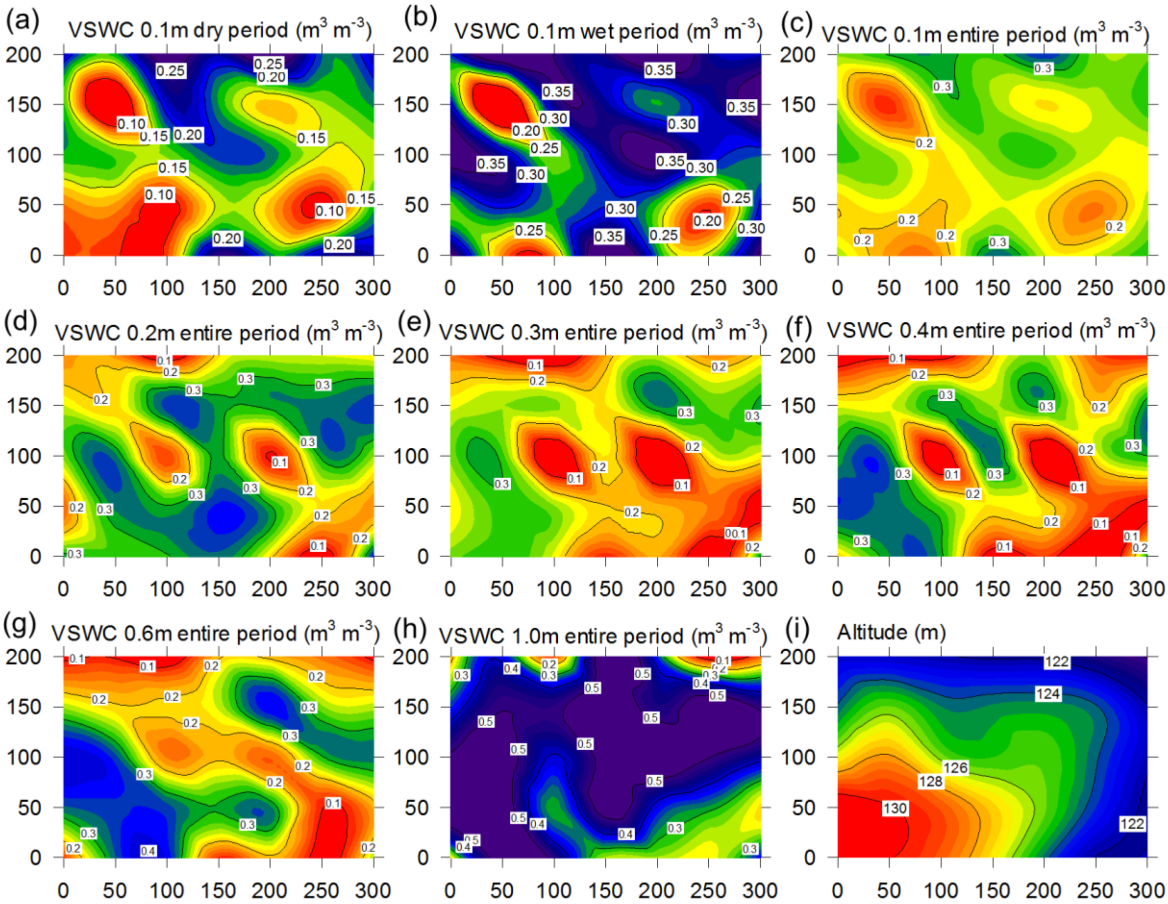

Figure 4.5. Spatial distribution of (a)VSWC at surface layer (0.1 m) during dry period (b) VSWC at surface layer (0.1 m) during wet period, (c) VSWC at surface layer (0.1 m) during entire periods, (d) VSWC at 0.2 m during entire period, (e) VSWC at 0.3 m during entire period, (f) VSWC 0.4 m during entire period, (g) VSWV at 0.6 m during entire period, (h) VSWC at deeper layer (1.0 m) during entire period, and (i) Relative altitude in the 6 ha plot of Pasoh FR (n=35). VSWC was measured at 6 depths (0.1, 0.2, 0.3, 0.4, 0.6 and 1.0 m) during dry (API60 <23, n=12), wet (API60 >23, n=16) and entire periods (n=28). Sigma plot 12 software was used to generate the spatial distribution.

4.3.4 The relationship of VSWC with basal area and mean DBH

Significant negative relationships were found between basal area and surface-layer VSWC (Table 4.3, Figure 4.6) for the dry ($r = -0.56^{***}$), wet ($r = -0.37^{*}$), and entire periods ($r = -0.48^{**}$). A similarity in spatial pattern between basal area and surface-layer VSWC was apparent on the map (Figure 4.7a, b), but no relationships were found between basal area and VSWC at other depths (Table 4.3).

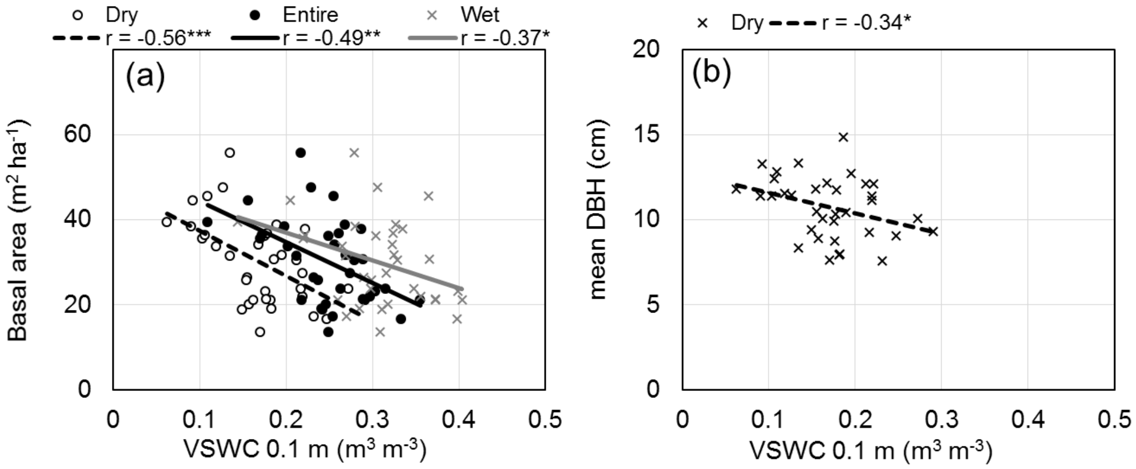

Figure 4.6. Relationship between (a) basal area (m^2 ha^{-1}) and surface layer VSWC (0.1 m) during dry, wet and entire periods (b) mean DBH (cm) and deeper layer VSWC (1.0 m) during dry period.

A weak negative relationship was found between mean DBH and surface layer VSWC, but only during the dry period ($r = -0.34^{*}$) (Table 4.3, Figure 4.6b, Figure 4.7a, c). It was also found a weak positive relationship between mean DBH and deep-layer (1 m) VSWC for the dry ($r = 0.36^{*}$), wet ($r = 0.35^{*}$) and entire periods ($r = 0.35^{*}$) (Table 4.3).

4.3.5 The relationship of VSWC with number of trees and mortality

There were no significant relationships between VSWC and either number of trees or mortality at any depth (Table 4.3), although both of number of trees and mortality showed strong relationships with stand dynamics parameters (Table 4.4).

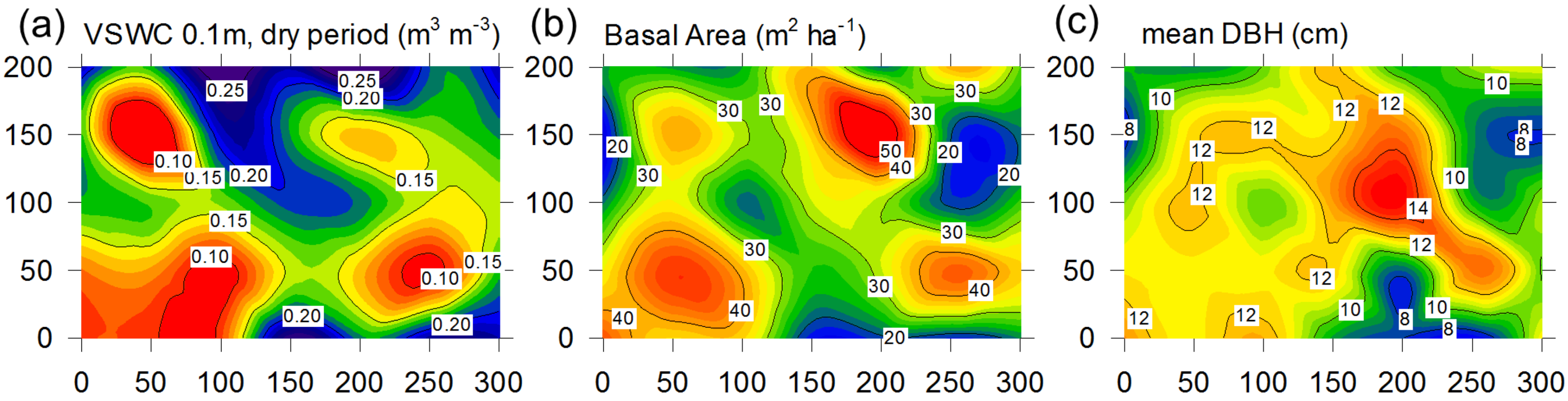

Figure 4.7. Spatial distribution of VSWC and stand dynamics parameters (a) surface layer (0.1 m) VSWC during dry period, (b) basal area, and (c) mean DBH in 6 ha plot of Pasoh FR. Stand dynamics parameters refer to basal area (m^2 ha^{-1}) and mean DBH (cm) within the 400 m^2 sampling plot from 2002 to 2012.

Table 4.3. The Pearson correlation and their level of significance resulting from a regression between the parameters of stand dynamics and volumetric soil water content (VSWC) measured at 35 points in the 6 ha plot of Pasoh FR. VSWC was measured at 6 depths (0.1, 0.2, 0.3, 0.4, 0.6 and 1.0 m) during dry (API60 <23, n=12), wet (API60 >23, n=16) and entire periods (n=28) from 28 June 2016 to 30 May 2017. The parameters of stand dynamics are obtained using tree census data at 2002 and 2012. The number of trees refer to the number of tree exist within the 20 x 20 m plot. *P<0.05, **P<0.01, and ***P<0.001, NS Not significant.

VSWC	Basal Area (m^2 ha^{-1})	Mean DBH (cm)	N trees (n in 400 m^2)	Mortality (%)	Canopy (n in 400 m^2)	Emergent (n in 400 m^2)	Understory (n in 400 m^2)	Dipterocarpaceae (n in 400 m^2)	Annonaceae (n in 400 m^2)	Ulmaceae (n in 400 m^2)
Dry										
0.1 m	-0.56***	-0.34*	NS	NS	NS	NS	NS	NS	NS	NS
0.2 m	NS	NS	NS	NS	NS	NS	NS	NS	NS	-0.38*
0.3 m	NS	NS	NS	NS	NS	NS	NS	NS	0.36*	NS
0.4 m	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
0.6 m	NS	NS	NS	NS	NS	-0.42*	NS	NS	0.33*	NS
1.0 m	NS	0.36 *	NS	NS	NS	-0.40*	-0.35*	-0.34*	NS	NS
Wet										
0.1 m	-0.37 *	NS	NS	NS	NS	NS	NS	NS	-0.35*	NS
0.2 m	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
0.3 m	NS	NS	NS	NS	NS	NS	NS	NS	0.35*	NS
0.4 m	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
0.6 m	NS	NS	NS	NS	NS	-0.45**	NS	-0.38*	NS	NS
1.0 m	NS	0.34*	NS	NS	NS	-0.50**	-0.39*	-0.46**	NS	NS
Entire Period										
0.1 m	-0.48**	NS	NS	NS	NS	NS	NS	NS	-0.37*	NS
0.2 m	NS	NS	NS	NS	NS	NS	NS	NS	NS	-0.33*
0.3 m	NS	NS	NS	NS	NS	NS	NS	NS	0.36*	NS
0.4 m	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
0.6 m	NS	NS	NS	NS	NS	-0.45**	NS	-0.37*	NS	NS
1.0 m	NS	0.35*	NS	NS	NS	-0.47**	-0.38*	-0.42*	NS	NS

Table 4.4. The Pearson correlation analysis of the relationship among parameters of stand dynamics obtained using tree census data at 2002 and 2012 in the 6 ha plot of Pasoh FR. $^{*}P<0.05$, $^{**}P<0.01$, and $^{***}P<0.001$, NS Not significant.

	Basal area (m^2 ha^{-1})	Mean DBH (cm)	N Trees (400 m^2)	Mortality (%)	Canopy (N in 400m^2)	Emergent (N in 400m^2)	Understory (N in 400m^2)
Basal area (m^2 ha^{-1})	-	0.72^{***}	0.54^{***}	-0.48^{**}	0.43^{*}	NS	NS
Mean DBH (cm)	0.72^{***}	-	NS	-0.55^{***}	NS	NS	NS
Number of Trees (400 m^2)	0.54^{***}	NS	-	-0.69^{***}	0.78^{***}	0.36^{*}	0.84^{***}
Mortality (%)	-0.48^{**}	-0.55^{***}	NS	-	-0.35^{*}	NS	-0.61^{***}
Canopy (N in 400 m^2)	0.43^{*}	NS	0.78^{***}	-0.35^{*}	-	NS	0.49^{**}
Emergent (N in 400 m^2)	NS	NS	0.36^{*}	NS	NS	-	NS
Understory (N in 400 m^2)	NS	NS	0.84^{***}	-0.61^{***}	0.49^{**}	NS	-

4.3.6 The relationship of VSWC and tree species

Significant negative relationships were found between the number of emergent tree species and deep-layer (0.6, 1.0 m) VSWC for the dry (r = -0.42*, r = -0.40*) wet (r = -0.45**, r = -0.50**), and entire periods (r = -0.45**, r = -0.47**) (Table 4.3, c, Figure 4.8a, b). Similar but weaker negative relationships were also found between the number of understory tree species and deep-layer VSWC for the dry (r = -0.35*), wet (r = -0.39*) and entire periods (r = -0.39*) (Table 4.3, Figure 4.7c, Figure 4.8a, d). However, these negative relationships not observed for the surface and middle layers. No relationships were found between the number of canopy tree species with VSWC at any depth or period (Table 4.3).

There was no relationship between VSWC and 19 tree families out of the 22 most abundant families in the 6 ha plot (Table 4.1). Dipterocarpaceae had a significant negative relationship with VSWC at depths of 0.6 and 1 m. Annonaceae, had weak a positive correlations with VSWC at 0.3 and 0.6 m and a weak negative correlation with surface-layer VSWC during the wet and the entire period. For Ulmaceae, a weak negative correlation was found with 0.2 m VSWC during the dry period and the entire period (Table 4.3).

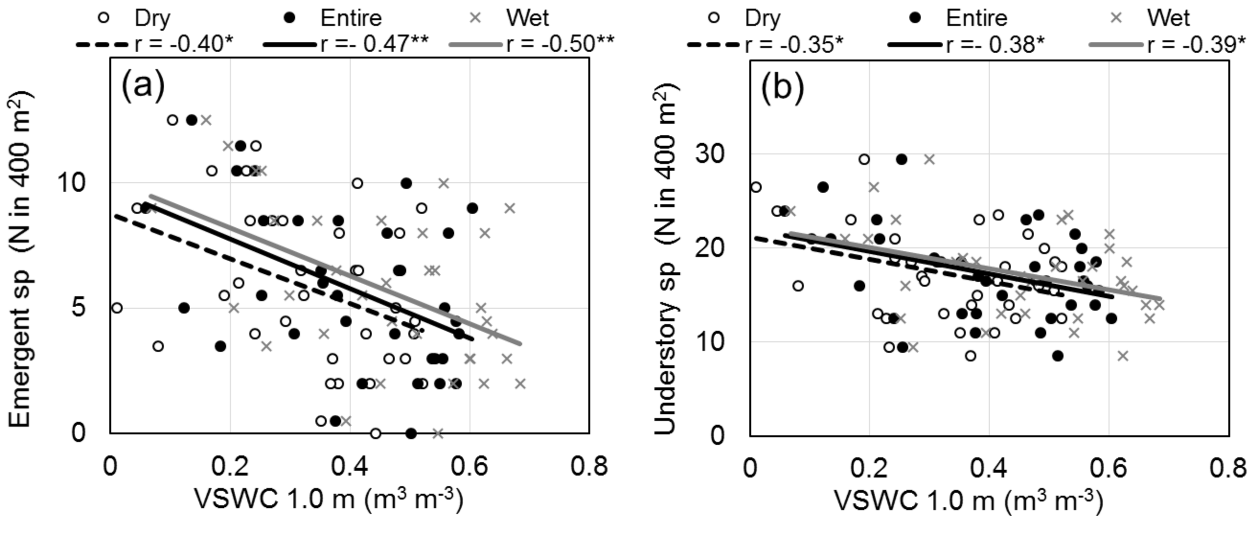

Figure 4.8. The relationships between VSWC at deeper layers (1.0 m) and stand dynamics parameters (a) correlation between deeper layer VSWC (0.1 m) and the number of trees of emergent species during dry, wet and entire periods (b) correlation between deeper layer VSWC (1.0 m) and the number of trees of understory species during dry, wet and entire periods in the 6 ha plot of Pasoh FR. Stand dynamics parameters refers to number of tree of emergent and understory species within the 400 m^2 sampling plot from 2002 to 2012.

4.4 Discussion

4.4.1 Physical properties of the surface soil

Soil moisture content is often related to soil physical properties, which are described with the soil water retention curve. The relationship between capillary pressure and soil water content depends on the soil pore size distribution (Kosugi, 1997). Large saturated and residual VSWC values (Figure 4.2a) are typical for clay soil with small pore sizes, which is the type found in the 6 ha study plot in Pasoh FR.

In the surface soil layer, the decrease in residual VSWC was accompanied by an increase in effective VSCW (Figure 4.2b), which attributed to an increase in the median pore size of the soil (Figure 4.2c). Log-normal distribution model analysis for unsaturated soil hydraulic properties showed that changes in soil pore size were related to forest soil development (Kosugi 1996, 1997). It was concluded that median pore size increased with the development of forest soil at the surface layer.

4.4.2 Spatial and vertical distributions of VSWC

The observed spatial variation of surface-layer VSWC during the dry period (Figure 4.4a) may have resulted from the differences in residual VSWC, and thus soil physical structure (Figure 4.2, Figure 4.4a). The 'drier' plots, with lower surface-layer VSWC during the dry period, might also be areas with lower residual VSWC and larger soil pore size.

A clear relationship between surface-layer VSWC and relative elevation (Table 4.2, Figure 4.4a) indicates that surface-layer VSWC during the dry period was determined mainly by relative elevation. However, topographical details, such as hollows or valleys near plot 6 and plot 33 may also have influenced the distribution of VSWC (Figure 4.5). The fact that there were no relationship found between surface-layer VSWC and relative elevation during the wet period (Table 4.2) indicates that relative elevation influenced surface-layer VSWC mainly during the dry period. As overland flow was frequently observed in this forest (Leigh, 1978), smaller particles in clay soil may have accumulated in hollows/valleys, creating packed clay soil with larger residual VSWC. Conversely, soil with larger pore structure and lower residual VSWC was present in ridge areas.

The gravel layer exists between 0.2 and 0.4 m, and sometimes deeper layer, and VSWC depends strongly on the existence of large pores caused by the gravels. The intermittent existence of the gravel layer caused an independent pattern in middle-layer VSWC.

Although the existence of the gravel layer obscured the relationship, middle- and deep-layer VSWC tended to be higher in plots with lower surface-layer VSWC during the dry period (Table 4.2, Figure 4.4c). It can be inferred that this relationship also led to the apparent positive relationships between middle- and deep-layer VSWC with relative elevation (Figure 4.4b), as there was no other plausible explanation for the inverse relationship between VSWC and relative elevation.

Consider the lower surface-layer VSWC during the dry period to be the results of lower residual VSWC and larger median soil pore size, it can be said that this type of soil has greater water permeability. This may explain why higher middle- and deep-layer VSWC corresponded with lower surface-layer VSWC during only the dry period. In areas that had higher surface-layer VSWC during the dry period, residual VSWC tended to be larger, and the median soil pore size smaller. This type of soil is less permeable, and is often associated with excess overland flow. This lower level of permeability may have created drier conditions in the middle and deep soil layers.

4.4.3 The relationship of VSWC with basal area and mean DBH

The negative relationship between basal area and surface-layer VSWC (Figure 4.6a, Figure 4.7a, b) shows that areas with lower surface-layer VSWC tend to have greater biomass, as basal area is a direct index of biomass. Forest biomass generally increases with stand age, and plateaus at maturity owing to a decline in net primary productivity. In primary forests, such as the study site, fluctuations in biomass are largely due to the death of large trees (Hoshizaki et al., 2004). However, no relationship were found between surface VSWC and other stand dynamics parameters (such as tree mortality or number of trees), in spite of clear correlations between basal area and these parameters. This strongly suggests that basal area and surface-layer VSWC simply had a direct relationship in the study site. Areas with lower surface VSWC are considered to have larger median pore size, and thus less compact soil texture. This might be beneficial for trees.

A negative relationship between surface VSWC and N content was also observed at the study site (Kosugi et al., 2007). In dry surface soil, plant roots may be more prolific because of wide nutrient coverage, loose structure and sufficient air. These may be the reasons for the negative correlation between basal area and surface VSWC seen in this forest. It is also possible that this negative relationship caused the observed spatially negative relationship between soil respiration and surface-layer VSWC (Kosugi et al., 2007). In addition, there may be feedback effects of basal area on surface-layer VSWC. Larger root biomass increases soil cultivation, which eventually loosens clay soil texture and helps to increase soil pore size. The existence of more roots would also stimulate the absorption of water from the soil.

The weak relationship between mean DBH and surface-layer (0.1 m) VSWC during the dry period (Table 4.3, Figure 4.6b, Figure 4.7a, c) may have resulted from the strong positive relationship between mean DBH and basal area, as it was found spatial similarity between both parameters (Figure 4.7b, c). Mean DBH also had a weak relationship with deep-layer (1.0 m) VSWC. This may be associated with the negative relationship between surface-layer VSWC and deep-layer VSWC during the dry period. Mean DBH was not related to the number of canopy, emergent or understory species (Table 4.4). Therefore, the relationship between VSWC and tree size was unlikely to have resulted from any species group preference.

4.4.4 The relationship of VSWC with tree number and mortality

Spatial distribution of trees number and mortality were not dependent on VSWC in this forest. Many studies have considered tree mortality to be associated with temporal drought or lower level of soil water (e.g. Allen et al., 2010; Meir et al., 2015). In the Amazonian tropical rainforest (Tapajos), there was a significant increase in mortality as relative plant-extractable water decrease below to 0.5 (Meir et al., 2015). The discrepancy between the findings of this study and those of previous studies may be due to different modes of assessment: previous studies focused on temporal effects of VSWC on mortality while, the present study focused on the spatial dependence of tree mortality on VSWC. Spatially, several studies conducted in the Amazonian forest found weak negative relationships between tree mortality and topography, although not between tree mortality and VSWC (e.g. Madelaine et al., 2007; Ferry et al., 2010). It has been shown that mortality is high in low-lying areas owing to shallow water tables, which provide low adherence and prevent roots from penetrating deep into soil (Madelaine et al., 2007; Ferry et al., 2010). Conversely, the results of this study did not support the possibility that saturated soil conditions increased tree mortality. The intensity of the dry period may also have differed between the study site and the sites in Amazon. Amazonian rainforests have a distinct and longer dry period compared with Southeast Asian tropical rainforests, although dry and wet periods do exist in the study site as part of seasonal fluctuations with considerable variability between years (Kosugi et al., 2008).

4.4.5 The relationship of VSWC with tree species

The emergent tree species did not thrive when the deep layer was saturated, as demonstrated by the negative relationship between the number of emergent species trees and deep-layer VSWC during all periods (Table 4.3, Figure 4.8a,b). Similarly, the number of Dipterocarpaceae trees had a negative relationship with deep-layer VSWC (Table 4.3). In this forest, emergent tree species were mainly within the Dipterocarpaceae family (Soepadmo, 1978). The relationship between these trees and deep-layer VSWC can be explained based on their rooting system. Emergent tree species use hairy roots to obtain surface water, and taproots to obtain water from deeper soil. Near-saturated conditions in deep soil layers reduce the availability of oxygen, leading to reduction and anaerobic conditions that decrease soil nutrients. Anaerobic conditions also suffocate plant roots. Thus, emergent tree species with deep rooting systems are negatively affected by the saturation of deep soil layers.

Understory species also had a negative relationship with wet conditions in deep soil layers, although the effect was weaker than for emergent species (Table 4.3, Figure 4.8b, Figure 4.9a, c). Since there was no relationship between the number of emergent species trees and understory species trees (Table 4.4), these are likely to have been independent trends. It is likely that some understory species also have deep rooting systems and prefer aerobic conditions in the deeper layers of soil.

However, it maybe speculated that not all trees in the study site were negatively affected by wet conditions in the deeper soil layers. For instance, trees with shallower rooting systems should be less affected by deep soil conditions. Some flowering plant families, such as *Ulmaceae* and *Annonaceae*, do not prefer wet surface soil conditions. This may be due to their anatomies: water-conducting xylem cells are expected to contribute to variations in plant water preferences. In an adjacent 50 ha plot in Pasoh FR, *Annonaceae* and *Ulmaceae* were found to be abundant on ridges or slopes and in dry alluvial soil (Marryanna et al., 2012).

It should be noted that the effects of deep-layer VSWC on emergent and understory species trees were independent of the negative relationships between surface-layer VSWC and basal area or mean DBH: areas with lower surface-layer VSWC tended to have higher deep-layer VSWC. There were no relationship between basal area and the number of emergent or understory species trees found. Therefore, it can be concluded that forest biomass was greater in areas with drier surface soils having looser structures, and that some emergent and understory species prefer drier, well-aerated deep-soil layers; these two trends were independent.

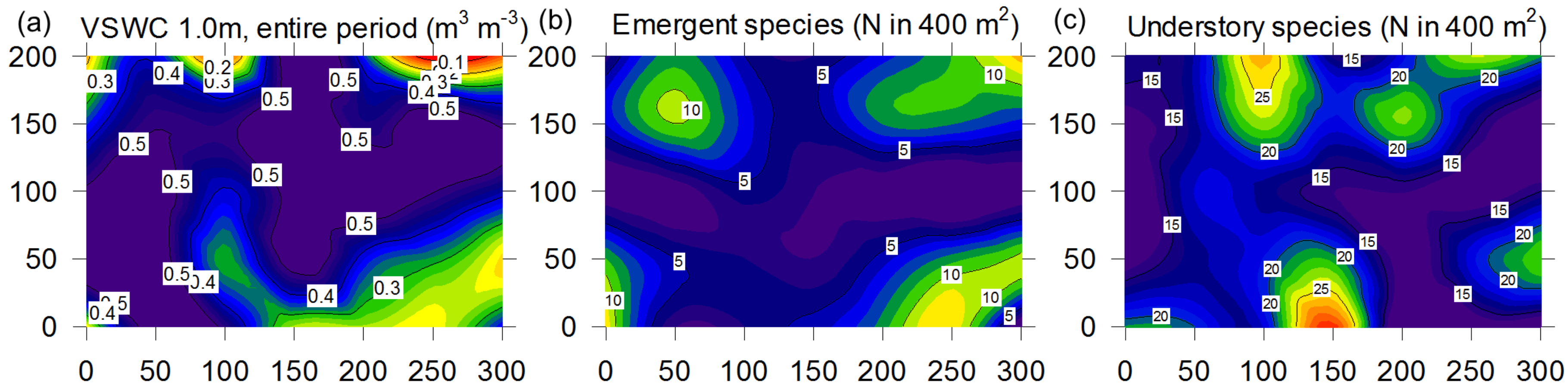

Figure 4.9. Spatial distribution of VSWC and stand dynamics parameters (a) deeper layer VSWC (1.0 m) during entire period, (b) number of trees of emergent species, and (c) number of trees of understory species. Stand dynamics parameters refers to number of tree of emergent and understory species within the 400 m^2 sampling plot from 2002 to 2012.

4.5 Conclusion

Understanding how the distribution of VSWC affects stand dynamics in tropical rainforests is particularly important given research suggesting that VSWC controls ecosystem processes, and is in turn likely to be affected by climate change. To gain insight into these phenomena, the relationships between VSWC and stand dynamics in Pasoh FR, which is located in a dry zone of Peninsular Malaysia and has the lowest annual rainfall among adjacent south-eastern tropical forests were analysed.

In this forest, surface-layer VSWC was determined largely by relative elevation, although the data also suggested that areas of drier surface soil had a coarser soil texture with larger pore size. Drier surface soil conditions corresponded to wetter conditions in the deeper soil layers. This study rejected the hypothesis that variability in VSWC affected tree number or mortality. However, there was a significant negative relationship between surface-layer VSWC and basal area (i.e. biomass), which may be explained by 1) the preference of many trees to develop the roots in drier surface conditions and coarser soil textures, and 2) feedback effects that increased root distribution in such areas for water absorption. An independent trend for deep-layer VSWC was found: it was negatively correlated with the number of *Dipterocarpaceae* or emergent species trees. This may have been due to the preference of the trees with deep rooting systems for drier aerobic conditions.

The findings of the present study are interesting given that this forest has relatively low precipitation and a high usage of available water (Kosugi et al., 2008; Marryanna et al., 2017, Chapter 3). The depth of soil and existence of a large soil water reservoir may explain the complex relationship between tree species and soil conditions.

CHAPTER 5

Summary and conclusion

5.1 Summary

This study examined the effects of spatio-temporal distribution of soil moisture and hydrological processes on ET, water sources and stand dynamics in a lowland dipterocarp forest at Pasoh Forest Reserve in Peninsular Malaysia.

The temporal variability of oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) isotope signatures in precipitation at Pasoh FR are reported in Chapter 2. The daily and seasonal variability of stable isotope signatures in precipitation were analysed, particularly in relation to the effects of monsoon seasons, rainfall characteristics, and larger scale trends compared with those at nearby Global Network of Isotopes in Precipitation (GNIP) monitoring stations. The isotope signatures did not differ between monsoon seasons but were correlated with amount of rainfall and its intensity and duration. An effect of rainfall amount on isotope composition was clearly detected and comparable to long-term mean monthly statistics from the nearby GNIP stations. Unfortunately the effect was obscured at the daily timescale and, for monthly rainfall, not averaged over the long-term. No large deuterium excess was detected at the daily timescale for small-scale rainfall events. The amount of $\delta^{18}O$ in precipitation was more closely correlated with the 60-day antecedent rainfall index than with the daily amount of rainfall. These findings suggest that the isotopic composition in the study area was the result of a rainout on a larger scale in addition to the local scale and specific rain events, and not the result of re-evaporated moisture added from the land surface.

Chapter 3 evaluated water use and the supporting water sources of the tropical rainforest using a 4-year assessment of ET in Pasoh FR. The eddy covariance method and isotope signals from 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 to identify isotopic signals. The 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 to 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 50–90% was supplied from the deeper soil layer, below a depth of 0.5 m. This water originated from water precipitated in this forest several months previously. 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 soil particles. Plants showed no preference for soil depth with size, whereas the existence of storage water in the xylem was suggested. The ET at this forest was balanced and maintained using most of the available water sources except for a proportion of rapid-response runoff.

In Chapter 4, the spatial distribution of VSWC measured over 1 year was analysed in the context of stand dynamics in a Southeast Asian tropical rainforest. Forest surface-layer VSWC was determined largely by relative elevation and soil physical properties. Patterns of spatial variation in surface-layer VSWC and residual VSWC during the dry period suggested that drier surface soil areas had developed forest soil texture with a larger pore size. Drier surface soil areas were associated with wetter deep soil. There were no relationships between VSWC and tree mortality or number of trees for any soil layer; however, a significant negative relationship was found between surface-layer VSWC and tree basal area, and therefore also biomass. This finding could be due to the preference of trees for drier surface areas with coarse soil texture, and to feedback processes increasing root distribution in such areas. The number of trees in the *Dipterocarpaceae* family, as well as of emergent tree species, was negatively correlated with VSWC in the deep soil layer. This finding may have been due to the preference of trees with deep rooting systems for drier aerobic conditions.

5.2 Conclusion

Understanding the response of forests to climate change is crucial because forests cover approximately 28% of the land surface, and regulate water and climatic conditions (WBGU, 1998; Buchmann, 2002). In tropical forests, soil moisture is closely related to rainfall patterns, and is among the most important environmental factors determining gas exchange and stand dynamics. To clarify the effect of these environmental factors and their future changes on each process, the actual range of their fluctuations as affected by seasonal and inter-annual climate variability should be evaluated. Tropical rainforests contain abundant moisture; however, after investigating water sources for ET in a Southeast Asian tropical rainforest in Peninsular Malaysia, it can be concluded that this tropical rainforest experiences water stress, particularly during dry periods. The temporal and spatial distribution of soil moisture affects

ET, water sources and stand dynamics differently, suggesting that a simple model or simulation of the impact of future climate change on tropical rainforests, without data collected in the field, will result in poor estimates. This study is anticipated to contribute to the understanding of the hydrology of tropical rainforests and provide baseline data describing the stable isotope signatures of precipitation, soil, plants, and stream water for further research at this study site. Baseline data obtained in this study are important for environmental modelling for diverse applications, including water-use policy and forest conservation. The significance of this study is summarised as follows.

i. Pasoh FR experienced considerable land use change when the region surrounding the forest area allotted for research lost 37% of its forest cover for alternative land use (i.e., oil palm and rubber cultivation) within a period of 10 years. This anthropogenic disturbance may have contributed to changes in soil water status, affecting forest function. This study provides supporting information quantifying changes in soil water status and their effects on ET, water use and stand dynamics.

ii. Pasoh FR is located in a drier region than other Southeast Asian tropical rainforests. Therefore, the findings of this study contribute to the literature by improving the understanding of the possible impacts on tropical forests of drier conditions due to future climate change in other Southeast Asian tropical rainforests.

iii. The data and information obtained during this study are highly important for the conservation of water resources and land use management in Peninsular Malaysia.

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APPENDIX

Appendix 1 The details values of each isotopes contents in precipitation observed from Pasoh FR (September, 2012 – December, 2015)

Date	Rainfall Amount (mm)	Max Intensity (mm 30^{-1})	Duration (Hour)	$\delta^{18}O$	$\delta^{2}H$	Deuterium excess
Mean	13.02 (±15.68)	7.11 (±8.33)	2.23 (±1.87)	-5.90 (±3.03)	-35.41 (±24.11)	11.76 (±3.01)
Max	100.46	42.00	17.00	0.85	15.20	18.94
Min	0.50	0.50	0.50	-14.21	-101.90	2.44
Median	7.00	3.59	1.50	-5.40	-31.50	11.90
05/09/2012	27.54	14.28	1.50	-7.38	-50.60	8.44
09/09/2012	27.03	12.75	1.50	-6.09	-37.70	11.02
10/09/2012	10.71	2.55	6.00	-3.87	-16.30	14.66
11/09/2012	8.16	6.12	1.00	-5.46	-38.10	5.58
12/09/2012	2.04	0.51	2.00	-7.42	-50.60	8.76
16/09/2012	11.73	11.22	1.00	-5.51	-31.10	12.98
18/09/2012	4.08	2.04	2.50	-2.84	-12.10	10.62
21/09/2012	2.55	2.04	1.00	-3.26	-16.90	9.18
23/09/2012	37.23	14.79	3.50	-5.80	-33.30	13.10
24/09/2012	3.57	3.57	0.50	-2.90	-14.50	8.70
01/10/2012	0.51	0.51	0.50	-2.98	-13.40	10.44
02/10/2012	16.83	8.16	2.50	-4.82	-25.90	12.66
11/10/2012	100.46	40.80	6.00	-5.34	-29.90	12.82
12/10/2012	3.06	1.02	2.50	-5.48	-29.10	14.74
13/10/2012	13.77	3.06	2.50	-8.43	-51.10	16.34
14/10/2012	1.02	1.02	0.50	-7.74	-50.40	11.52
15/10/2012	5.10	3.06	1.00	-7.96	-48.70	14.98
16/10/2012	23.46	12.75	3.00	-10.95	-75.20	12.40
17/10/2012	0.51	0.51	0.50	-5.78	-35.00	11.24
18/10/2012	6.63	4.59	1.50	-6.68	-41.10	12.34
19/10/2012	4.08	3.57	1.00	-4.63	-22.70	14.34
20/10/2012	3.57	1.02	2.50	-4.83	-25.90	12.74
22/10/2012	34.17	21.42	2.00	-9.06	-60.60	11.88
25/10/2012	1.53	1.53	0.50	-4.80	-25.40	13.00
26/10/2012	6.12	4.59	1.50	-3.37	-14.50	12.46
29/10/2012	9.69	4.08	1.50	-2.51	-3.70	16.38
01/11/2012	15.81	6.63	4.50	-8.78	-57.30	12.94
02/11/2012	28.05	16.83	3.50	-9.92	-64.30	15.06
03/11/2012	3.57	3.06	1.00	-8.38	-54.10	12.94
04/11/2012	12.75	6.12	2.00	-5.96	-34.70	12.98
05/11/2012	3.57	2.55	1.50	-8.97	-59.70	12.06
06/11/2012	6.12	2.55	3.50	-8.70	-57.70	11.90
07/11/2012	1.02	0.51	1.00	-8.71	-58.40	11.28
08/11/2012	15.30	11.22	1.50	-7.71	-50.20	11.48

09/11/2012	8.16	5.61	2.50	-7.07	-44.60	11.96
10/11/2012	8.16	4.59	1.50	-7.16	-43.10	14.18
12/11/2012	10.20	4.59	3.00	-6.79	-40.90	13.42
13/11/2012	4.08	1.02	3.00	-13.10	-91.80	13.00
14/11/2012	10.20	9.69	1.00	-5.41	-32.40	10.88
18/11/2012	23.46	15.30	2.00	-5.91	-32.50	14.78
20/11/2012	35.19	24.48	3.00	-5.53	-26.20	18.04
21/11/2012	2.55	2.55	0.50	-9.20	-63.60	10.00
24/11/2012	5.10	1.53	3.50	-9.52	-62.20	13.96
26/11/2012	26.52	12.75	4.50	-12.88	-88.80	14.24
27/11/2012	30.09	22.95	4.00	-14.05	-98.20	14.20
29/11/2012	48.96	22.44	2.50	-13.00	-86.80	17.20
01/12/2012	5.61	3.06	2.00	-10.00	-62.30	17.70
02/12/2012	3.57	1.02	2.50	-11.45	-78.40	13.20
03/12/2012	57.11	39.27	4.50	-14.21	-97.00	16.68
04/12/2012	32.13	12.75	4.50	-9.62	-62.60	14.36
10/12/2012	3.06	1.53	1.50	-2.94	-9.30	14.22
12/12/2012	4.59	1.53	2.50	-6.18	-33.20	16.24
14/12/2012	2.04	2.04	0.50	-6.91	-46.00	9.28
15/12/2012	2.55	1.02	2.00	-6.07	-35.90	12.66
16/12/2012	1.53	1.02	1.00	-4.21	-24.60	9.08
17/12/2012	7.14	1.53	3.00	-4.83	-27.70	10.94
18/12/2012	17.34	12.75	3.00	-4.62	-26.10	10.86
19/12/2012	4.59	2.55	2.00	-3.24	-16.50	9.42
20/12/2012	6.12	5.10	1.50	-5.44	-34.00	9.52
21/12/2012	4.59	3.06	1.50	-3.50	-15.90	12.10
23/12/2012	7.65	5.10	2.00	-3.21	-16.60	9.08
24/12/2012	5.10	2.55	2.00	-6.26	-38.70	11.38
25/12/2012	1.53	0.51	1.50	-8.18	-55.50	9.94
26/12/2012	2.55	0.51	2.50	-6.70	-44.60	9.00
31/12/2012	34.68	22.44	1.50	-6.88	-39.80	15.24
01/01/2013	1.02	0.51	1.00	-7.77	-53.30	8.86
02/01/2013	1.50	1.00	1.00	-10.59	-80.60	4.12
06/01/2013	0.50	0.50	0.50	-4.37	-26.40	8.56
07/01/2013	13.50	13.00	1.00	-6.24	-38.00	11.92
10/01/2013	2.50	1.50	1.50	-3.01	-18.30	5.78
12/01/2013	7.50	4.00	3.00	-4.85	-25.10	13.70
13/01/2013	0.50	0.50	0.50	-2.67	-8.60	12.76
17/01/2013	4.00	2.00	1.50	-0.95	6.40	14.00
22/01/2013	2.00	1.00	1.50	-3.74	-20.70	9.22
25/01/2013	9.50	3.00	4.00	-2.72	-9.20	12.56
04/02/2013	5.00	4.00	1.50	-1.63	-10.60	2.44
05/02/2013	47.50	22.50	5.50	-8.41	-57.10	10.18
06/02/2013	1.50	0.50	1.50	-4.99	-31.50	8.42
13/02/2013	7.50	3.00	3.00	-5.46	-32.50	11.18

14/02/2013	29.00	6.50	7.00	-3.15	-14.70	10.50
15/02/2013	4.00	1.50	2.50	-2.51	-11.00	9.08
16/02/2013	1.00	0.50	1.00	-1.31	-3.40	7.08
17/02/2013	4.50	2.00	2.00	-2.61	-13.70	7.18
19/02/2013	5.00	3.00	2.00	-2.34	-6.90	11.82
26/02/2013	21.00	8.00	4.00	-11.74	-84.60	9.32
28/02/2013	50.50	24.50	3.50	-11.78	-84.50	9.74
02/03/2013	9.00	5.00	2.50	-8.95	-65.60	6.00
04/03/2013	3.50	3.00	1.00	-4.91	-31.10	8.18
08/03/2013	10.50	6.00	1.50	-1.59	-2.40	10.32
22/03/2013	43.00	15.50	3.00	-3.49	-15.60	12.32
27/03/2013	0.50	0.50	0.50	-2.64	-7.60	13.52
04/04/2013	26.50	19.50	2.00	-5.05	-26.30	14.10
05/04/2013	9.00	5.00	2.50	-4.84	-24.80	13.92
07/04/2013	8.50	3.50	2.00	-3.54	-16.90	11.42
11/04/2013	24.00	8.00	3.00	-6.17	-31.80	17.56
12/04/2013	0.50	0.50	0.50	-5.76	-33.40	12.68
15/04/2013	0.50	0.50	0.50	-5.91	-36.30	10.98
20/04/2013	26.50	16.00	3.50	-8.14	-50.90	14.22
22/04/2013	2.00	1.50	1.00	-5.53	-30.60	13.64
23/04/2013	2.50	2.00	1.00	-4.23	-25.50	8.34
24/04/2013	23.00	13.00	3.00	-7.61	-44.70	16.18
25/04/2013	1.50	0.50	1.50	-7.09	-44.10	12.62
26/04/2013	4.00	1.00	3.00	-9.24	-63.20	10.72
27/04/2013	0.50	0.50	0.50	-7.43	-51.50	7.94
29/04/2013	5.00	1.00	3.50	-9.89	-65.50	13.62
04/05/2013	1.00	0.50	1.00	-10.64	-70.10	15.02
05/05/2013	2.50	1.50	1.50	-7.47	-46.60	13.16
06/05/2013	4.50	2.50	1.50	-8.79	-56.60	13.72
07/05/2013	18.50	8.00	3.50	-8.87	-56.70	14.26
08/05/2013	3.00	2.50	1.00	-8.63	-58.50	10.54
14/05/2013	1.00	1.00	0.50	-5.19	-29.60	11.92
16/05/2013	13.50	6.50	3.50	-5.35	-34.70	8.10
21/05/2013	6.00	6.00	0.50	-4.93	-28.80	10.64
26/05/2013	2.00	1.00	1.50	-5.98	-39.50	8.34
05/06/2013	7.00	1.50	3.50	-8.45	-56.60	11.00
30/06/2013	27.50	9.50	4.50	-5.26	-26.10	15.98
01/07/2013	1.50	0.50	1.50	-3.82	-15.80	14.76
03/07/2013	10.00	7.00	2.00	-4.44	-20.10	15.42
05/07/2013	9.00	5.50	3.50	-5.94	-36.20	11.32
09/07/2013	17.00	16.50	1.00	-6.77	-38.80	15.36
11/07/2013	22.00	13.00	2.50	-10.87	-69.00	17.96
12/07/2013	2.00	1.50	1.00	-9.25	-62.60	11.40
17/07/2013	27.50	20.50	2.00	-11.43	-75.70	15.74
25/07/2013	3.50	3.00	1.00	-2.76	-12.90	9.18

26/07/2013	1.00	0.50	1.00	-2.29	-9.20	9.12
30/07/2013	0.50	0.50	0.50	-4.19	-20.70	12.82
12/08/2013	1.00	1.00	0.50	-4.10	-22.40	10.40
17/08/2013	1.50	1.00	1.00	-3.88	-14.50	16.54
19/08/2013	48.00	29.00	4.00	-7.97	-48.20	15.56
20/08/2013	2.00	1.00	1.50	-8.18	-47.50	17.94
29/08/2013	3.00	1.00	2.50	-2.96	-13.40	10.28
30/08/2013	22.50	9.50	3.00	-5.29	-25.80	16.52
01/09/2013	11.00	10.50	1.00	-6.69	-40.40	13.12
02/09/2013	7.50	6.50	1.00	-8.30	-51.40	15.00
05/09/2013	4.00	4.00	0.50	-6.76	-38.40	15.68
07/09/2013	8.50	4.50	2.00	-11.09	-81.10	7.62
08/09/2013	5.00	1.00	3.50	-13.26	-96.90	9.18
09/09/2013	6.50	1.50	4.00	-12.59	-94.30	6.42
10/09/2013	23.00	15.00	1.50	-12.53	-89.00	11.24
12/09/2013	2.00	1.00	1.50	-5.65	-38.90	6.30
28/09/2013	18.00	16.50	1.50	-4.39	-24.70	10.42
03/10/2013	9.50	9.00	1.00	-4.48	-23.60	12.24
11/10/2013	29.00	9.00	2.50	-6.88	-39.40	15.64
23/10/2013	34.50	5.50	8.00	-14.10	-101.90	10.90
24/10/2013	6.00	5.50	1.00	-13.42	-101.80	5.56
25/10/2013	15.00	8.00	2.50	-11.33	-78.60	12.04
26/10/2013	10.50	6.00	2.50	-10.20	-67.80	13.80
28/10/2013	3.00	1.00	2.50	-7.65	-47.60	13.60
29/10/2013	4.00	2.50	2.00	-6.39	-35.40	15.72
30/10/2013	1.50	1.50	0.50	-7.45	-42.30	17.30
31/10/2013	43.50	21.00	2.50	-8.14	-47.80	17.32
01/11/2013	17.00	6.00	3.00	-6.10	-34.40	14.40
09/11/2013	0.50	0.50	0.50	-7.45	-52.20	7.40
10/11/2013	8.50	5.00	1.50	-9.75	-63.70	14.30
11/11/2013	3.50	2.00	1.50	-12.33	-84.40	14.24
14/11/2013	82.50	42.00	6.00	-11.41	-77.80	13.48
15/11/2013	6.50	3.00	2.50	-7.19	-45.80	11.72
20/11/2013	3.50	2.50	1.50	-2.76	-12.10	9.98
26/11/2013	14.50	7.50	2.00	-6.96	-43.20	12.48
29/11/2013	1.50	1.00	1.00	-6.08	-40.50	8.14
03/12/2013	64.50	5.00	17.00	-11.87	-86.90	8.06
04/12/2013	1.50	0.50	1.50	-11.76	-87.70	6.38
05/12/2013	0.50	0.50	0.50	-11.85	-89.30	5.50
10/12/2013	5.50	3.50	1.00	-5.87	-35.40	11.56
11/12/2013	65.50	21.50	6.50	-11.12	-75.30	13.66
12/12/2013	1.50	1.50	0.50	-8.72	-58.60	11.16
19/12/2013	5.00	2.00	3.50	-4.26	-28.50	5.58
22/12/2013	5.00	1.00	3.50	-5.01	-31.80	8.28
27/12/2013	2.00	1.50	1.00	-2.99	-15.90	8.02

29/12/2013	0.50	0.50	0.50	-3.68	-20.30	9.14
30/12/2013	14.50	2.00	7.00	-2.70	-7.60	14.00
31/12/2013	4.50	3.50	1.50	-4.45	-23.30	12.30
02/01/2014	1.03	1.03	0.50	-2.13	-5.80	11.24
05/01/2014	7.70	3.59	1.50	-7.55	-48.40	12.00
11/01/2014	11.80	2.05	8.00	-11.80	-86.80	7.60
13/01/2014	6.67	5.13	1.00	-5.02	-29.60	10.56
14/01/2014	2.57	1.03	2.00	-2.39	-11.60	7.52
29/01/2014	0.51	0.51	0.50	-0.75	3.30	9.30
10/02/2014	7.70	7.18	1.00	-1.64	-1.50	11.62
17/03/2014	34.89	9.24	12.00	-3.49	-18.70	9.22
18/03/2014	24.11	11.29	4.50	-3.41	-19.60	7.68
01/04/2014	12.31	8.21	1.50	-4.43	-24.60	10.84
04/04/2014	1.54	0.51	1.50	-5.54	-36.20	8.12
09/04/2014	1.03	0.51	1.00	-2.18	-9.30	8.14
11/04/2014	46.69	40.02	1.50	-4.98	-26.20	13.64
15/04/2014	0.51	0.51	0.50	-1.88	-4.10	10.94
17/04/2014	1.54	0.51	1.50	-1.93	-2.50	12.94
18/04/2014	24.63	19.50	1.50	-4.03	-15.50	16.74
19/04/2014	2.05	1.03	1.50	-2.67	-8.90	12.46
21/04/2014	19.50	13.34	4.50	-4.15	-20.20	13.00
24/04/2014	32.32	9.24	3.50	-4.64	-21.50	15.62
25/04/2014	18.98	10.77	2.50	-7.09	-38.70	18.02
28/04/2014	33.86	21.04	2.50	-6.50	-39.50	12.50
01/05/2014	2.05	1.03	1.50	-5.40	-30.30	12.90
08/05/2014	8.72	4.62	2.00	-4.05	-16.90	15.50
11/05/2014	63.11	30.27	3.00	-7.63	-46.80	14.24
13/05/2014	0.51	0.51	0.50	-5.43	-31.70	11.74
15/05/2014	20.52	15.39	1.50	-7.39	-44.90	14.22
16/05/2014	7.18	3.59	1.50	-8.52	-58.20	9.96
18/05/2014	5.64	5.13	1.00	-9.72	-64.80	12.96
19/05/2014	30.79	11.80	6.50	-11.52	-77.40	14.76
21/05/2014	1.54	0.51	1.50	-11.01	-79.30	8.78
29/05/2014	37.97	28.22	4.00	-10.70	-73.80	11.80
02/06/2014	1.54	1.54	0.50	-7.76	-53.00	9.08
05/06/2014	10.26	8.21	2.00	-4.11	-16.80	16.08
11/06/2014	2.57	2.57	0.50	-5.04	-30.20	10.12
29/06/2014	15.91	12.83	1.50	-4.10	-19.90	12.90
30/06/2014	35.92	28.22	1.50	-4.09	-20.90	11.82
01/07/2014	8.72	7.70	1.50	-3.42	-19.10	8.26
04/07/2014	25.14	14.37	1.50	-4.84	-26.80	11.92
11/07/2014	2.05	1.54	1.00	-4.09	-23.70	9.02
12/07/2014	15.39	11.29	1.50	-6.46	-39.90	11.78
17/07/2014	8.21	6.67	1.50	-1.66	-0.10	13.18
18/07/2014	4.10	2.57	1.50	-1.76	-1.00	13.08

23/07/2014	1.54	1.54	0.50	-3.39	-11.60	15.52
27/07/2014	0.51	0.51	0.50	-0.69	4.40	9.92
29/07/2014	24.63	16.42	1.50	-2.81	-9.70	12.78
12/08/2014	21.04	16.93	3.00	-7.13	-43.30	13.74
13/08/2014	12.83	7.18	2.00	-7.58	-48.80	11.84
14/08/2014	1.03	0.51	1.00	-4.88	-31.00	8.04
15/08/2014	3.08	2.05	1.50	-3.58	-20.40	8.24
17/08/2014	0.51	0.51	0.50	-4.24	-22.90	11.02
18/08/2014	1.54	1.54	0.50	-1.21	-5.90	3.78
20/08/2014	12.83	11.29	1.50	-9.23	-66.80	7.04
25/08/2014	40.53	29.76	3.50	-7.74	-47.30	14.62
26/08/2014	5.64	4.62	1.50	-4.68	-26.00	11.44
31/08/2014	10.77	5.64	3.50	-7.71	-50.20	11.48
05/09/2014	22.06	11.29	1.50	-4.42	-23.80	11.56
08/09/2014	29.25	17.96	1.00	-6.79	-47.60	6.72
10/09/2014	8.21	6.16	1.50	-5.39	-31.70	11.42
12/09/2014	1.03	0.51	1.00	-2.06	-5.90	10.58
19/09/2014	19.50	16.93	1.50	-4.64	-30.50	6.62
20/09/2014	74.40	18.47	6.50	-4.51	-22.40	13.68
26/09/2014	7.18	4.10	2.00	-4.54	-22.30	14.02
03/10/2014	33.86	26.68	1.50	-1.98	-3.60	12.24
13/10/2014	24.63	12.31	5.00	-4.83	-26.80	11.84
17/10/2014	14.37	11.80	2.00	-4.71	-25.30	12.38
22/10/2014	0.51	0.51	0.50	-1.64	-2.60	10.52
26/10/2014	16.42	12.83	1.50	-2.86	-7.10	15.78
27/10/2014	18.47	9.24	1.00	-3.55	-14.80	13.60
28/10/2014	0.51	0.51	0.50	-1.45	-2.90	8.70
29/10/2014	5.13	2.57	1.00	-2.29	-10.20	8.12
31/10/2014	32.84	14.37	5.00	-3.92	-14.90	16.46
06/11/2014	29.76	9.24	3.00	-3.68	-10.50	18.94
07/11/2014	47.20	20.01	5.00	-10.40	-65.80	17.40
12/11/2014	0.51	0.51	0.50	-4.85	-24.30	14.50
14/11/2014	49.77	22.06	4.00	-7.55	-44.90	15.50
20/11/2014	1.03	1.03	0.50	-10.85	-77.80	9.00
21/11/2014	13.85	8.21	1.50	-12.14	-86.60	10.52
23/11/2014	1.03	1.03	0.50	-7.06	-46.70	9.78
24/11/2014	4.62	2.57	2.00	-7.23	-46.80	11.04
25/11/2014	9.24	4.62	2.50	-6.87	-42.80	12.16
27/11/2014	1.03	0.51	1.00	-7.36	-49.00	9.88
28/11/2014	19.50	13.85	1.50	-8.61	-56.30	12.58
01/12/2014	7.18	2.05	4.00	-6.22	-41.40	8.36
03/12/2014	1.54	1.03	1.00	-7.90	-53.70	9.50
04/12/2014	27.19	17.44	6.00	-10.75	-79.50	6.50
07/12/2014	4.62	1.03	3.00	-7.56	-52.30	8.18
09/12/2014	1.03	1.03	0.50	-4.22	-24.60	9.16

15/12/2014	7.70	5.64	1.00	-4.73	-25.30	12.54
16/12/2014	0.51	0.51	0.50	-4.29	-25.20	9.12
17/12/2014	0.51	0.51	0.50	-3.98	-25.10	6.74
23/12/2014	23.60	3.59	9.50	-11.75	-84.10	9.90
29/12/2014	8.72	2.57	6.50	-9.69	-72.60	4.92
08/01/2015	10.99	3.14	5.00	-7.77	-49.10	13.06
09/01/2015	10.47	1.57	7.00	-9.27	-63.30	10.86
19/02/2015	12.56	6.28	2.00	-5.03	-27.40	12.84
09/03/2015	13.08	7.33	1.50	-2.85	-9.60	13.20
10/03/2015	4.19	2.62	2.00	-3.74	-15.90	14.02
11/03/2015	0.52	0.52	0.50	-1.18	-2.40	7.04
22/03/2015	1.05	0.52	1.00	0.85	15.20	8.40
31/03/2015	1.05	0.52	1.00	-0.93	0.60	8.04
01/04/2015	2.62	1.57	1.50	-1.80	-8.20	6.20
02/04/2015	13.08	6.28	3.00	-5.61	-32.60	12.28
03/04/2015	2.09	1.05	1.50	-3.97	-24.20	7.56
06/04/2015	37.68	30.87	2.00	-5.79	-32.50	13.82
11/04/2015	32.97	24.60	2.50	-4.48	-24.60	11.24
12/04/2015	6.80	5.76	1.50	-4.66	-26.30	10.98
16/04/2015	3.14	1.57	1.50	-1.46	1.20	12.88
17/04/2015	2.62	2.62	0.50	-0.58	-0.20	4.44
22/04/2015	19.89	12.56	3.00	-6.19	-33.10	16.42
23/04/2015	1.57	1.05	1.00	-3.61	-13.00	15.88
27/04/2015	42.39	25.12	2.00	-2.15	-6.00	11.20
28/04/2015	18.32	9.94	3.50	-3.38	-15.00	12.04
06/05/2015	2.62	2.09	1.00	-5.03	-31.20	9.04
13/05/2015	21.98	6.28	6.50	-5.80	-33.30	13.10
15/05/2015	0.52	0.52	0.50	-3.45	-16.30	11.30
18/05/2015	5.76	5.76	0.50	-7.97	-49.50	14.26
21/05/2015	7.33	3.14	2.00	-6.21	-38.00	11.68
27/05/2015	9.94	9.42	1.00	-5.23	-31.10	10.74
03/06/2015	4.71	2.09	2.50	-4.05	-19.80	12.60
10/06/2015	8.90	1.57	5.50	-4.01	-26.40	5.68
26/06/2015	13.61	12.04	1.00	-1.99	-1.80	14.12
29/06/2015	2.62	2.09	1.00	-1.88	-3.00	12.04
04/07/2015	7.33	4.19	2.50	-2.48	-4.40	15.44
14/07/2015	1.05	0.52	1.00	-1.53	-0.40	11.84
03/08/2015	21.46	18.84	2.50	-5.27	-27.90	14.26
04/08/2015	42.91	26.17	7.50	-8.87	-56.30	14.66
12/08/2015	14.13	5.76	4.50	-6.36	-35.40	15.48
17/08/2015	30.35	26.69	2.50	-4.80	-23.60	14.80
20/08/2015	1.57	0.52	1.50	-0.58	6.00	10.64
25/08/2015	7.85	4.71	3.00	-2.41	-1.90	17.38
05/09/2015	32.97	27.21	1.50	-4.19	-20.40	13.12
09/09/2015	14.65	12.04	1.00	-4.56	-19.40	17.08

10/09/2015	33.49	20.93	2.50	-7.36	-42.70	16.18
14/09/2015	5.76	5.23	1.00	-2.41	-9.30	9.98
17/09/2015	1.05	0.52	1.00	-1.76	-2.60	11.48
18/09/2015	9.94	6.80	3.00	-3.85	-15.80	15.00
22/09/2015	1.05	0.52	1.00	-4.40	-22.70	12.50
23/09/2015	6.28	3.66	1.50	-4.30	-18.20	16.20
30/09/2015	0.52	0.52	0.50	-4.56	-26.10	10.38
02/10/2015	6.80	2.62	2.50	-2.39	-8.40	10.72
06/10/2015	20.93	17.79	1.50	-2.75	-12.60	9.40
13/10/2015	6.28	6.28	0.50	-0.18	11.80	13.24
27/10/2015	3.14	1.57	2.00	-2.76	-8.60	13.48
28/10/2015	5.23	4.19	1.00	-4.68	-21.00	16.44
29/10/2015	6.28	2.09	2.00	-6.16	-34.00	15.28
30/10/2015	1.05	1.05	0.50	-4.53	-27.60	8.64
31/10/2015	1.57	0.52	1.50	-5.48	-35.00	8.84
01/11/2015	49.19	26.69	5.50	-9.38	-62.30	12.74
02/11/2015	56.52	29.83	3.00	-7.58	-47.10	13.54
04/11/2015	14.13	3.66	3.50	-6.77	-40.40	13.76
06/11/2015	8.37	3.66	4.00	-8.32	-53.80	12.76
21/11/2015	2.62	1.05	2.00	-5.14	-32.40	8.72
24/11/2015	40.82	21.46	4.50	-9.19	-61.50	12.02
30/11/2015	16.75	10.47	2.50	-8.83	-59.10	11.54
03/12/2015	1.05	1.05	0.50	-3.87	-23.00	7.96
09/12/2015	12.56	4.71	2.00	-1.63	-2.90	10.14
10/12/2015	0.52	0.52	0.50	-3.50	-18.40	9.60
12/12/2015	86.34	34.54	6.00	-7.34	-42.90	15.82
14/12/2015	24.60	7.85	4.00	-3.67	-18.50	10.86
25/12/2015	3.14	1.57	2.00	-5.67	-32.00	13.36
29/12/2015	18.32	4.71	6.00	-4.42	-24.40	10.96

ACKNOWLEDGEMENT

Many people have contributed in a myriad of ways to both this thesis and its supporting research. Although words cannot fully express the depths of my heartfelt gratitude to all those who have assisted me throughout this journey, I would like to acknowledge those who have made significant contributions. I am greatly indebted to Professor Yoshiko Kosugi for providing countless hours of guidance and support for completing my research and for creating a pleasant work environment. I would like to thank and express my gratitude to a committee members, Professor Shinya Funakawa and Professor Kanehiro Kitayama for their critical reviewing of my thesis.

Highly appreciation and gratitude for those who have provided invaluable assistance and advice throughout my research, especially Dr. Masanori Katsuyama for supporting the analyses of isotopes content and exceptional insights on isotopic interpretation. A special acknowledgment to Professor Makoto Tani, Dr. Shoji Noguchi, Dr. Satoru Takanashi, Dr. Masayuki Itoh, Dr. Naoko Matsuo, Dr. Kaoru Niiyama, Dr.Tamotsu Sato, Dr. Siti Aisah Shamsuddin & Dr. Abd Rahman Kassim for their constructive comments and suggestion towards this study and manuscript.

Furthermore, I would like to acknowledge the members of both the laboratories of Forest Hydrology Laboratory of Kyoto University and Forest Hydrology Laboratory of Forest Research Institute Malaysia (FRIM) for their assistance along this journey. I would also like to recognize those who assisted with my field research, laboratory analyses, and other activities, in particular, Mr. Ibharim Hasim, Mr. Mohamad Muflif, Mr. Mohd Md Sahat, Mr. Ahmad Awang, Mr.Yamamoto, and Mr. Kenji Tsuruta.

On a personal level, I would like to thank the countless people who provided emotional and personal support during my PhD journey. The utmost thanks goes to my parents, siblings, relatives, husband and children who encouraged and supported me in various ways along the journey of my study.

Marryanna Lion