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The Interaction between soil moisture and evapotranspiration at dry region of Lowland Dipterocarp forest in Peninsular Malaysia

Noor Atiqah Badaluddin[1], Marryanna Lion[2], Sheriza Mohd Razali[3], Saiful Iskandar Khalit[1]*, Yoshiko Kosugi[4], Siti Aisah Shamsuddin[2], and Ahmad Zaidi Hampden[5]

[1]Faculty of Bioresources and Food Industry, Universiti Sultan Zainal Abidin, Besut Campus, 22200, Besut, Terengganu, **Malaysia**
[2]Forestry and Environment Division, Forest Research Institute Malaysia (FRIM), 52109 Kepong, Selangor, **Malaysia**
[3]Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, M**alaysia**
[4]Graduate School of Agriculture, Kyoto University, 606-8502, **Japan**
[5]School of Civil Engineering, UniversitiTeknologi MARA, Kampus Samarahan, Jalan Meranek, 94300 Kota Samarahan, Sarawak, **Malaysia**

***Correspondence:** saifuliskandar@unisza.edu.my **Received: 06-10-2022, Revised: 19-11-2022, Accepted: 14-12-2022 e-Published: 18-12-2022**

Evapotranspiration (ET) is responsible for nearly 60% of global precipitation. Understanding the behaviour of ET under the influence of some meteorological variables is essential to predict how tropical rainforests will react to climate change. Research was conducted in lowland dipterocarp forest in Peninsular Malaysia, known as Pasoh Forest Reserve (FR), to assess the ET rate using the eddy covariance method (EC). Meteorological variables such as rainfall amount, soil temperature, volumetric soil water content (VSWC), vapor pressure deficit (VPD), and solar radiation are recorded and divided into the monsoon season. Rainfall varies throughout the season as Malaysia experiences a weak El Niño event in late 2019 and an early La Niña stage in mid to late 2020. The soil temperature shows consistent values in both the wet and dry seasons, varying between 24.75°C (±0.33) and 26.39°C (±0.14). Soil moisture is an important relationship between rainfall, surface water, and soil water, with spatiotemporal variations caused by various hydrologic processes such as evapotranspiration. The results show that rainfall and VSCW are synchronized in all seasons, even in the dry season with low rainfall, such as February 2019 indicating. This illustrates that precipitation does not affect the stability of ET since the forest can transpire and exchange water throughout the dry season. The findings of this study could serve as a benchmark to better understand the behaviour of tropical forests and resistance to the potential impacts of climate change in the future

Keywords: Rainfall, Monsoon, Tropical Forest, Sustainability

INTRODUCTION

Evapotranspiration (ET) is a combined process of evaporation from bare soil and exposed water with the transpiration process of plants through stomata. The role of both evaporation and transpiration in ecosystems is unlikely because transpiration is usually correlated with plant productivity, while evapotranspiration has no significant relationship with production (Katul et al. 2012). In the process of natural evapotranspiration, energy is required to convert liquid to water vapor and transport water from the earth's surface to the atmosphere (Badaluddin et al. 2021b). Many factors such as radiation, wind, vapor pressure, ambient temperature, and others can affect the evapotranspiration rate (Marryanna et al. 2012). Accurate quantification of evapotranspiration is critical for better understanding of various hydrologic, climatic, and ecosystem processes, as well as for multiple applications such as water resource management, drought monitoring, hydrologic model improvement, weather forecasting, and wildfire risk (Bastiaanssen et al. 2005).

Tropical rainforest responses to environmental stresses are essential because of their long-term sustainability and potential to counteract climate change. Changes in rainfall amount and pattern are the most significant ecological stresses on forests. Knowing how evapotranspiration varies with fluctuating moisture content is critical to predicting how tropical rainforests adapt to climate change more efficiently (Mohd Razali and Nuruddin, 2011). Evapotranspiration is usually considered close enough to the transpiration process to allow, for example, a correlation between biomass and evapotranspiration in a complete canopy system. However, because of the vast areas of exposed soil in vegetation-poor regions, evapotranspiration can account for a high percentage of evapotranspiration.

Recent research has shown that the tropical rainforest controls evapotranspiration rates even in a dry season (Marryanna et al. 2017). Pasoh Forest Reserve is located in the driest part of Peninsular Malaysia, with the lowest annual rainfall among the neighbouring tropical rainforests in Southeast Asia. Based on a seven-year continuous Eddy Covariance study, the water content is almost the same even during dry conditions. This paper analyses the interaction between the surface and deeper soil moisture variation and the ET rates in Pasoh Forest Reserve during the study period. We expected the finding from this study would enhance the understanding of dry tropical forests that can be used to manage the potential climate change effects on the tropical forest.

MATERIALS AND METHODS

Site description

The study was conducted at the 6 hectares of Pasoh Forest Reserve, Negeri Sembilan, at 2°58'N, 102°18'E, and 75m to 150m above sea level (Figure 1). The soil at this locality is derived from the Durian series, indigenous to the region. They are categorized as ultisol with a yellowish 40 to 80 cm slit-clay layer, covering a blocky harden lateritic horizon of 30 to 40 cm thick, overlaying the speckled white clay to a depth of 130cm to 150cm (Leigh, 1982). In 1994, a 6-hectare research area was established for long-term ecological studies, and a 52-meter-tall meteorological observation tower was built (Noguchi *et al.* 2016).

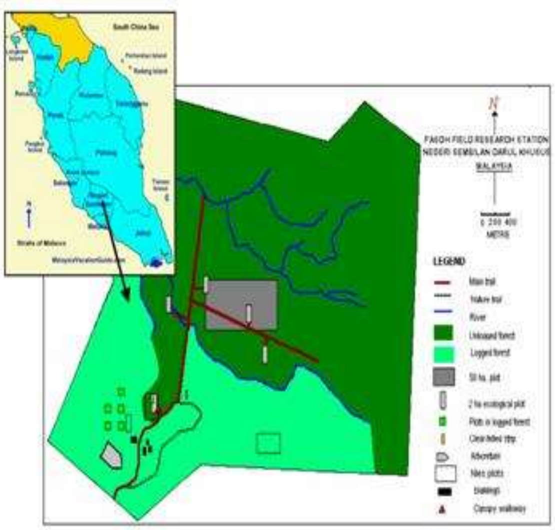

Figure 1: The location of the study site (Marryanna et al. 2012)

Micrometeorologyand Evapotranspiration

The data collected from October 2019 to October 2020 were analyzed. The sensible heat and water vapor of Eddy covariance were measured at the 52m height flux tower. Table 1 shows the sensors that were used to measure their expected properties. Latent heat (λE, Wm-2), sensible heat (H, Wm-2), and momentum fluxes were determined at an average of 30 minutes. To account for the influence of changes in air density, the Webb-Pearman-Leuning (WPL) was applied, and the linear trends in temperature and water vapor were obtained. Soil and interception evaporation and transpiration were included in the eddy covariance measurements of evapotranspiration. All recorded latent heat flux data were ignored during and after the rain. The gap was covered with sensible heat flux and available energy collected using a three-dimensional (3D) ultrasonic anemometer capable of recording data throughout the rain.

Table 1: The sensors installed at the study site and data readings.

Sensors	Readings
Sonic anemometer (SAT-550; Kaijo, Tokyo, Japan)	- Wind velocity - Temperature
Open path CO_2/H_2O analyser (LI-7500; Li-Cor, Lincoln, NE, USA)	- Water concentration
Radiometer Sensor (MR22, EKO, Japan, or CMA6, Kipp and Zonen, The Netherlands)	- Radiation, shortwave, downward and upward
Time Domain Reflectometry (TDR) sensor (CS615 or CS616, Campbell Scientific)	- Volumetric soil water content (VSWC)
Vaisala sensor (Vaisala, Vantaa Finland)	- Air temperature - Humidity
Assmann psychrometer (SY-3D, Yoshino Keiki, Japan)	- Calibrate Vaisala sensor periodically
Tipping bucket rain gauge (Ota Keiki 34-T, Japan)	- Rainfall amount

Incoming and reflected shortwave and longwave radiation from the flux tower and measurement of heat flux in the soil at a depth of 0.02 m were monitored at three locations near the tower and the available energy was calculated. The energy released by differences in air, vapor, and bark water storage was projected using vapor pressure variations and temperature at the height of 52 m. The tipping bucket rain gauge was placed 430 m from the flux tower. The rainfall data is then compared and matched with the measured rainfall data from the gauge at the observatory (Marryanna et al. 2017). TDR sensors were placed at three points around the tower and recorded at 30-min intervals at the depths of 0.1, 0.2, and 0.3 m, where most of the layer contains fine roots (Noguchi et al. 2016). The API60 is the tested pre-antecedent precipitation index and has a remarkable relationship with VSWC (Noguchi et al. 2016). The precipitation index was applied as the wetness index as it was defined as $\sum_{i=1}^{60} P_i/i$where $\boldsymbol{P_i}$is the daily precipitation (mm) and i is the number of consecutive days (Kosugi et al. 2008).

RESULTS

Rainfall variations in 2019 and 2020

Rainfall trends seemed to change between 1990 and 2020, especially in Peninsular Malaysia, according to Malaysia Meteorological Department (MMD). Historical meteorological data reveal that rainfall patterns change dramatically over time. The annual rainfall from 2019 to 2020 increased from 1827.95 mm to 2004.28 mm, respectively. In 2019, the highest rainfall was recorded in October, November and December, while in 2020, the highest rainfall was in April, July and November. Rainfall characteristics in Malaysia are divided into three seasons: Northeast monsoon (NEM), which starts from November to March, Intermediate Monsoon (IM), which occurs in April and October and Southwest Monsoon (SWM), which starts from May to September. NEM, characterized by north-easterly strong winds from the tropical western Pacific towards the South China Sea between November and February and associated with moist air throughout the area, has been blamed for increasing rainfall intensity and duration (Chang et al. 2005). Changes were expected in the form of increasing frequency of heavy rainfall, particularly during the NEM and the last quarter of every year (Rahman et al. 2013).

Weak El Niño was occurred in Malaysia in 2019, with only 3.6 mm of precipitation falling in Pasoh FR in February (Figure 2). Very little rainfall also fell in January and August, with 15.76 mm and 40.17 mm, respectively. A sequence of interactions between the atmosphere and the oceans, particularly in the tropical Pacific Ocean, produce the El Niño Southern Oscillation (Oettli et al. 2018). This interaction impacted various parts of the planet at different times or over the years. Variations in air-sea surface interaction and changes in the Walker circulation caused by the regional El Niño's effects (Oettli et al. 2018). Malaysia has shown a sharp decrease in rainfall and a rise in temperature during El Niño, leading to a drought crisis. La Niña, on the other hand, caused significant cooling in the eastern and central Pacific Ocean and the equatorial zone. The meteorological phenomenon often occurs in the period from October to January. It causes shifts in climatic patterns and affects the climate of tropical rainforests (Khalit et al. 2017). According to MMD, the La Niña phenomenon, known for wet and rainy weather, is expected to continue until May 2021. Table 2 summarizes the El Niño events in Malaysia according to their strength for each year. In 2019, Malaysia had weak El Niño events while La Niña was beginning to occur. The NEM phase, which started in November 2020, is expected to last until March 2021. The peak rainfall in Pasoh FR was recorded in November 2020 with 304.04 mm. NEM season received only 621-mm (November to March) precipitation, while SWM season received 846 mm (May to September) for each season during the same 5-month period. IM season in October 2019, April 2020, and October 2020 received 488 mm, 289 mm, and 184 mm precipitation, respectively.

Table2: The El Niña strength for each year that occurs in Malaysia.

Very strong	Strong	Moderate	Weak
1997/98	1987/88	1986/87	2004/05
2015/16	1991/92	1994/95	2006/07
		2002/03	2014/15
		2009/10	2018/19

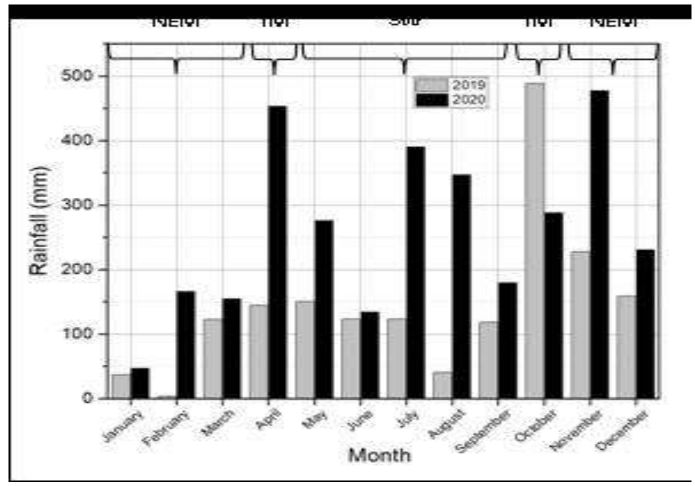

Figure 2: The monthly amount of rainfall in Pasoh FR from 2019 to 2020

The interaction between Evapotranspiration and other meteorological factors

As shown in Figure 3, the other meteorological variables such as soil temperature, VSWC, vapor pressure difference (VPD) and solar radiation are divided into the monsoonal season. The changes in ET depend on these meteorological variables and their interactions. Regardless of the wet or dry period, soil temperature varies consistently between constantly ranging average (± standard deviation) from 24.75°C (±0.33) to 26.39°C (±0.14). A study investigated the effects of soil temperature and water content on soil respiration rates and their spatial and temporal variations at this site (Kosugi et al. 2007; Marryanna et al. 2019). The study monitored soil respiration rate, temperature, and water content in a 50 m plot using a nested sampling technique with increasing grid size. Soil respiration rates were low when the soil water content was high (Kosugi et al. 2007). Conversely, respiration rates were low when the soil was dry. Even during the dry season, soil respiration was lower at wetter sites. As a result, seasonal variations in average daily soil temperature were minor, and no significant relationship with soil respiration was discovered.

The variations in seasonal precipitation and VSWC are synchronous. From Figure 2 and 3(c), the VSWC ranges from 0.33 % (± 0.01) to 0.37 % (± 0.03) during the entire monsoon period from October 2019 to October 2020. These variations agree with the rainfall average of the respective months. The highest soil moisture is recorded in October 2019 in the season IM, where the rainfall is highest (15.75mm ± 22.74). In the dry season, which is at the end of the NEM season, low rainfall was recorded in March 2020 (3.19mm ± 11.27) thus the soil moisture content is the lowest. Soil absorption decreases as the soil moisture content increases, but the remaining soil moisture is available to be absorbed by the plant roots., therefore ET increases (Badaluddin et al. 2021a). Several parameters influence the relationship between soil moisture and evapotranspiration.

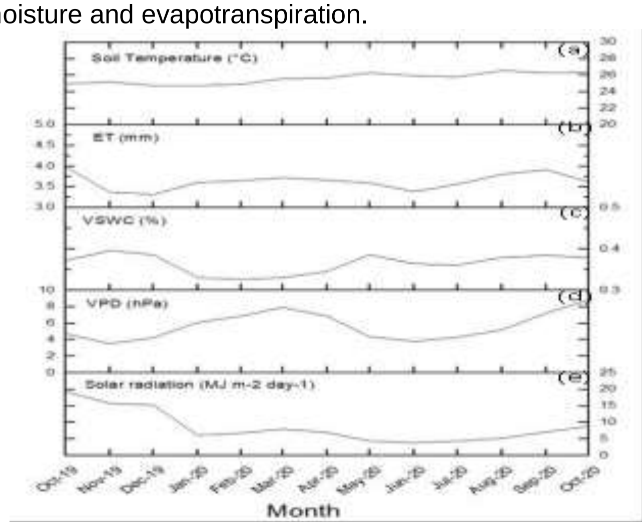

Figure 3: Time series fluctuation of soil temperature, ET, VSCW, VPD and solar radiation

The VPD or vapor pressure deficit and solar radiation are important variables for studying CO2 flux in the tropical forest. In this study, VPD was measured highest in November 2019 (3.55hPa ± 1.74) and lowest in October 2020 (8.81hPa ± 2.65). Solar radiation is radiation in the electromagnetic form emitted by the sun. In Pasoh FR, solar radiation was the highest in October 2019 (19.28 MJ m-2 day-1 ± 3.43 MJ m-2 day-1) and lowest in June 2020 (3.84 MJ m-2 day-1 ± 1.87 MJ m-2 day-1). The higher the VPD, the drier the regime. Although the VPD was highest in November 2019, when the quantity of precipitation was highest, solar radiation and VPD are affected by the measurement time. Morning, midday, and night-time readings varied and were affected by other variables such as tree canopy height, cloud cover, wind speed, and others (Mohd Razali et al. 2016).

Seasonal variation in evapotranspiration from October 2019 to October 2020

Pasoh FR generally has a stable ET annual rate. The annual ET rates were 1200 mm year-1 (2012), 1208 mm year-1 (2013), 1156 mm year-1

(2014), 1163 mm year-1 (2015), 1212 mm year-1 (2018), 1237 mm year-1 (2019), and 1320 mm year-1 (2020). Figure 3(b) plots the monthly ET rates by the monsoon season. Although the rates show some fluctuating values, especially at the beginning of the NEM season and in the middle of the SWM season, the annual ET values in 2012-2015 were significantly lower than recently due to the El Niño events, especially in 2014 and 2015, as a strong El Niño occurred in these years. During the driest period, especially in the middle of the NEM season when rainfall is low, Pasoh FR's ecology still has a noticeable ET (Figure 4).

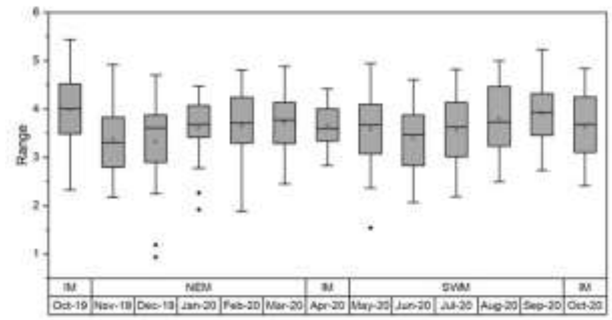

Figure 4: Boxplot of ET by seasonal variations in Pasoh FR

The rooting depth in Pasoh FR was compacted in the A horizon but stretched downward up to 4 m (Marryanna et al. 2017). Due to energy balance filtering data, ET was constant in the mid-Amazon rainforest areas, with a slight increase during the dry season. ET decreased somewhat in the drier deciduous forest areas during the dry season (da Costa et al. 2010). According to previous studies, ET is mostly affected by evaporative demand in the atmosphere and stomatal behavior, the latter being influenced by factors related to water supply, such as available water in the soil (Burgess et al. 1998; Oliveira et al. 2005), rooting depth (Li et al. 2010) and upward flow in the soil (da Rocha et al. 2004; Li et al. 2010). ET rate is almost constant in the tropical rainforests of Malaysia, which are located near the equator and have an indeterminate dry season. Although Pasoh FR experienced drought in the NEM season, especially in February 2020, when the forest received only 106 mm of rainfall, the rate of ET was still found to have an average ± standard deviation of 3.65 mm ± 0.76, though there was a slight decline. Due to the forest's capacity to evaporate water during the dry season, the stability of ET was not considerably influenced by rainfall. Under these conditions, the significant rooting depth proposed by (Li et al. 2010) for lowland rainforests on moderately weathered soils could be the driving force. Trees that are drought resistant and have deep root systems could influence. ET reduced during the rainy season due to decreased available energy and the surrounding temperature.

CONCLUSION

Pasoh FR used all the water available in the soil to keep ET stable throughout the season. ET rates in 2020 are higher than 2019 but still in a stable pattern. At least four months are required to store water to meet ET demand during dry seasons, although rainfall varies by season. ET rates remained stable in the NEM despite lower rainfall. Other meteorological variables that can affect ET, such as soil temperature, VSWC, VPD, and solar radiation, play different roles in the hydrological process in Pasoh FR. The soil moisture content has linearity to the rainfall pattern. Apparently, the higher the water content in the soil, the lower the ability of the soil to absorb water. However, ET can be enhanced by the uptake of plant roots in the soil. VPD and solar radiation are critical factors for gas exchange analysis whose values are always different and influenced by many environmental variables. In Pasoh FR, the monthly ET depends not only on the VPD and energy available but also on the soil moisture content. In conclusion, the interaction between soil moisture and ET is vital in dry tropical forests to accommodate stable ET demand.

CONFLICT OF INTEREST

The authors declared that present study was performed in absence of any conflict of interest.

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AUTHOR CONTRIBUTIONS

ML devised the project, the main conceptual ideas and proof outline. NAB contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript, with help from SMR. SIK helped supervise the project. YK, SS and AZH conceived the study and helped to draft the manuscript

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