INTERACTIONS BETWEEN WATER, SOIL AND FOREST HEALTH IN LOWLAND TROPICAL FORESTS

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ABSTRACT

The severe drought that hit Malaysia was caused by the El-Niño Southern Oscillation (ENSO). Studies have shown that tropical forests depend heavily on evapotranspiration during the dry season, which is influenced by factors such as rainfall quantity and vapour pressure deficit (VPD). The objective of this research is to investigate the interaction between soil, water and forest health by measuring water content and evapotranspiration. The research aimed to understand how the forest ecosystem responds to severe dryness by monitoring soil water content and evapotranspiration, comparing them to rainfall and VPD during the research period. Forest health was determined by satellite indices such as the Normalized Difference Vegetation Index (NDVI) and soil moisture index (SMI). The study took place at the Pasoh Forest Reserve (FR) in Jelebu, which has the lowest annual rainfall, making it an ideal location to study the potential effects of climate change on the forest ecosystem. The results revealed that the forest's evapotranspiration uses a significant amount of rainfall in Pasoh, while less than 10% helps replenish the soil's water content. Due to the high intensity and brief duration of rainfall, between 20 and 45% of it contributes to surface runoff. Despite a consistent VSWC pattern throughout the observation period, the observation in 2019 and 2020 demonstrates that the forest in Pasoh FR responded favourably to the amount of rainfall. Several dry spells with very low monthly rainfall (less than 60 mm per month) were recorded in 2019. February 2019 was one of the driest months on record, with only 3.56 mm of rain falling. January 2022 was also classified as dry, with less than 60 mm of monthly rainfall. The publication of these findings has significantly enhanced and updated forest hydrology information in this region. This information is vital for improving research ideas and can be utilized for climate change mitigation plans. Understanding how soil moisture and evapotranspiration react to dry conditions in tropical forests is crucial research. It provides valuable insights into the ecosystems' vulnerability to climate change, which can inform adaptive management strategies and ensure long-term resilience and sustainability.

Keywords: *Tropical forest, climate change, water use, Vapour pressure deficit*

INTRODUCTION

In tropical forests, the interaction between water and soil is crucial for maintaining the health of the forest. However, the demands of a growing population have led to the rapid conversion of forests for agriculture and infrastructure development. Tropical forests are important in regulating water availability in the region, contributing to rainfall formation through transpiration and evaporation. Disrupting these ecosystems will affect the entire ecosystem. Climate change from global warming will worsen impacts such as changing rainfall patterns and more frequent droughts. Thus, investigating the nexus between forest water-soil is crucial for understanding these effects. Conservation and restoration of tropical forests are necessary to maintain the interconnected functions of forests, water, and soil and support sustainable development in tropical regions.

Previous research has found that tropical forests maintain consistent evapotranspiration (ET) even during dry periods, while certain areas increase ET (Kosugi et al., 2012; Marryanna, Kosugi, Itoh, et al., 2017). Rainfall in Pasoh Forest Reserve (FR) varies according to a monsoon-like pattern. It exhibits strong inter-annual fluctuations, with two separate peaks from March to May and October to December (Marryanna, Kosugi, Itoh et al., 2017). During the El Niño events of 2014-2015, the research site suffered from two drought episodes in February and March of that year (Marryanna, Kosugi, Itoh et al., 2017). As previous studies have shown, rainfall of high intensity and short duration can reduce the potential for rainfall penetration to the extent that groundwater storage is not sufficiently restored during the wet season, resulting in a significant decrease in dry season runoff (Bruijnzeel, 2004). Extreme events can have strong impacts on tree growth and survival, due to typically stronger responses and shorter response times than for normal climatic events (Hanson et al., 2006; Kreyling et al., 2011).

Malaysia's monsoon season is notorious for its heavy rainfall, which can occasionally give way to droughts, particularly during El-Niño events. The Pasoh region, in particular, has been known to experience dry conditions and receive less than 2,000 mm of precipitation annually. It is imperative to conduct research on the correlation between soil water content and evapotranspiration in the lowland tropical forest of Pasoh Forest Reserve, Negeri Sembilan during periods of dryness. Our research aims to gain a more thorough understanding of the impact of meteorological droughts on forest ecosystems by developing spectral indices that can accurately estimate soil water content and forest health. We also strive to investigate the relationship between soil water content and evapotranspiration. By doing so, we hope to gain insights into how forest ecosystems adapt to droughts, as well as how we can better manage and protect these vital ecosystems amidst changing climatic conditions. Such an investigation would provide invaluable insights into the dynamics of this ecosystem and could inform future management strategies.

MATERIALS AND METHODS

Location of the study area

The study was conducted at Pasoh Forest Reserve, Negeri Sembilan. The Pasoh Forest Reserve (PFR) located in a drier region of Peninsular Malaysia experience extreme and prolonged dryness during the El Niño Southern Oscillation events (Marryanna et al. 2017b). The study was conducted from 2019 to 2020 by utilising both field and satellite remote sensing data to monitor meteorological variables such as rainfall, soil temperature, Volumetric Soil Water Content (VSWC), vapour pressure difference, and solar radiation. Sensors such as Photosynthetically Active Radiation sensor (PAR), Open-path gas analyzer (Li7550), 3D Ultrasonic anemometer (Wind speed and direction) and Solar Radiation were placed at the 52-m flux tower for this purpose. In addition, remote sensing data obtained from a high-resolution Worldview-2 satellite image with eight multispectral bands provided a better understanding of drought effects on forest ecosystems. The Normalized Difference Vegetation Index (NDVI) and Soil Moisture Index (SMI) were used to calculate soil moisture levels and improve knowledge of drought effects. The indices of a spectral bands were calculated based on the equation below:

(i) NDVI = (NIR – Red) / (NIR + Red) Equation (1) (Rouse et al. 1973)
(ii) SMI = NIR / Visible Blue Equation (2) (Dupigny-Giroux & Lewis 1999).

Soil moisture sampling

Field observation of soil water content data from the study site was obtained from the 39 soil water content access tubes described as ground points in this study. Soil water content was obtained from six depths from 0.1, 0.2, 0.3, 0.4, 0.6, and 1.0 m using the PR2 Soil moisture sensor. The NDVI and SMI indices were then extracted based on the 39-tube data for further analysis. A map for the indices was developed to characterise vegetation vigour and soil water content availability in the study site. Two types of data are obtained in this study; measured data and calculated indices. Measured data is the soil water content data obtained from six depths at the 39 observation points. The calculated indices are the data from remotely sensed images interpolated using a model.

RESULTS

Rainfall characteristic

Pasoh Forest Reserve, located in the Jelebu district, is classified as a dry region in Peninsular Malaysia due to its low annual rainfall of below 2500mm. As seen in Figure 1, during the moderate El Niño in 2014, Pasoh FR received only 1851mm (±81.75 std) of annual rainfall. In the recent moderate El Niño event in 2018 – 2019, Pasoh FR recorded annual rainfall of 1928mm (±101.70 std) and 1737mm (±124.14 std). The strong El Niño event in 2014-2015 also impacted Malaysia and Pasoh FR received only 1563mm (±93.39 std) and 1510mm (±103.92 std) of annual rainfall. Over an 11-year period (Figure 2), Pasoh FR has received an average monthly rainfall of 158.00mm (±91.00 std). The maximum monthly rainfall recorded was 488mm in October 2019, while the minimum monthly rainfall was only 3.5mm in February 2019.

Figure 1: Annual rainfall distribution for Pasoh FR from 2012 – 2022. The red bar indicates rainfall during a very strong El Niño event, while the brown bar indicates a moderate El Niño event.

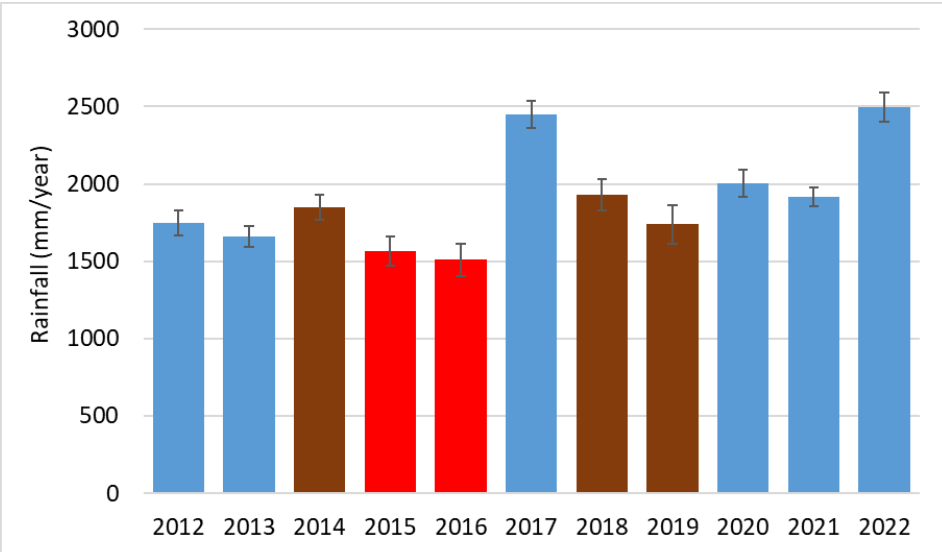
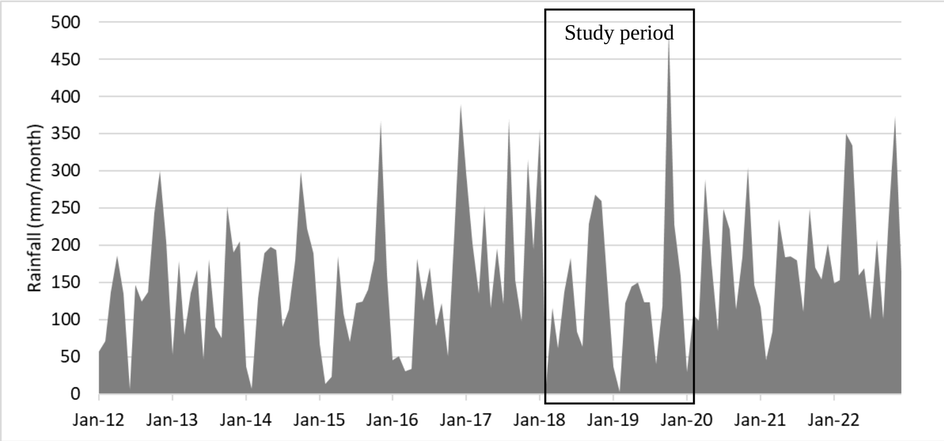


Figure 2: Monthly rainfall distribution for Pasoh FR from 2012 – 2022.



The soil moisture in Pasoh forest reserve

The topsoil depths of 10 cm and 20 cm, show a constant soil moisture content value of reading range from 10% to 25%. The topsoil water content could be less due to the soil porosity that leads to surface water runoff. In the intermediate soil horizon (30 cm – 40 cm), the soil moisture increased from 15% to 33% and at the deep soil horizon (60cm – 100 cm), which gives a very high percentage of soil moisture content from 18.22% in the dry season and 51.64% during the wet season. According to Malaysia Meteorology Department (2007), soil moisture can be categorized into very wet (> 30%), Wet (25 - 30%), Moderate (20 - 25%), Dry (15 - 20%) and Very dry (<15%). Based on this classification, we have discovered some interesting findings. Our observations indicate that soil moisture at depths ranging from the surface to one meter below ground varies from very dry to moderately moist. Specifically, the topmost layer (between 0.1 to 0.3 meters) typically exhibits a soil water content of less than 15% to 25%. Interestingly, we observed that the very surface layer (at 0.1 meters) consistently remained dry, never reaching the very wet classification (Figure 3).

In January 2020, there was a dry season with less than 60 mm of rainfall per month, according to the Schmidt-Ferguson classification and low soil moisture content. However, the soil water content improved with the rainfall received in the Pasoh FR (as shown in Figure 4). As the amount of rain increased, the soil moisture also increased. The deep soil horizon can act as a water storage for the tropical forest, even in the dry season, as the soil moisture content remains high. However, it remains unclear how long this forest can survive in prolonged dry conditions. Therefore, long-term monitoring that covers multiple El Niño events with different magnitudes will help us understand its resilience.

We examined two spectral indices; the Normalized Difference Vegetation Index (NDVI) and the soil moisture index (SMI). The NDVI ranged from 0.3 to 0.8, with a value of +1.00 indicating healthy vegetation in the study site. Despite the lowest value being 0.3, a canopy completely covered the site. The lower NDVI value could be due to the natural opening of the canopy caused by wind. The SMI (as shown in Figure 5) ranged from 2 to 4, with more area covered by moderate to low index values. We used Natural Breaks (Jenks) to divide the final output map from the modelling into 5 classes: very low (1.19-1.81), moderate (1.81-2.52), intermediate (2.52-2.97), high (2.97-3.32), and very high (3.32-3.84).

Figure 3: The categorization of the profile soil moisture based on the classification system provided by the Malaysia Meteorology Department in 2007 and its frequency of occurrences throughout the plot.

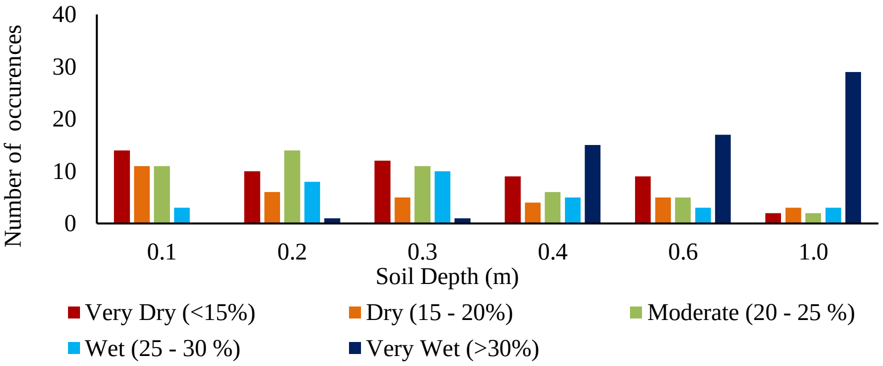
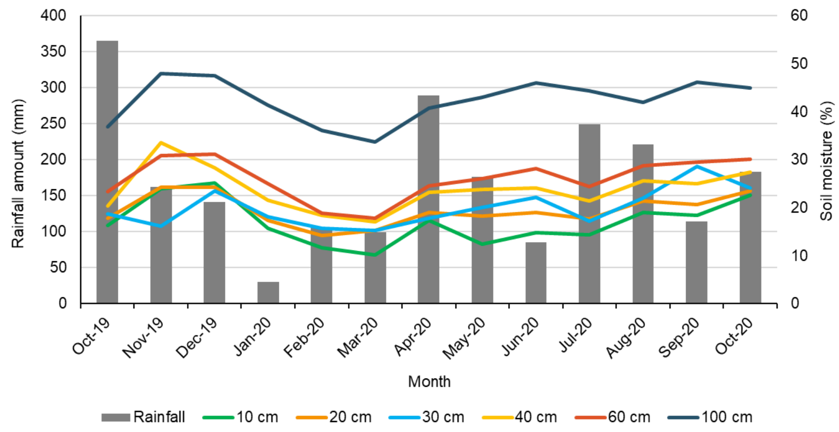
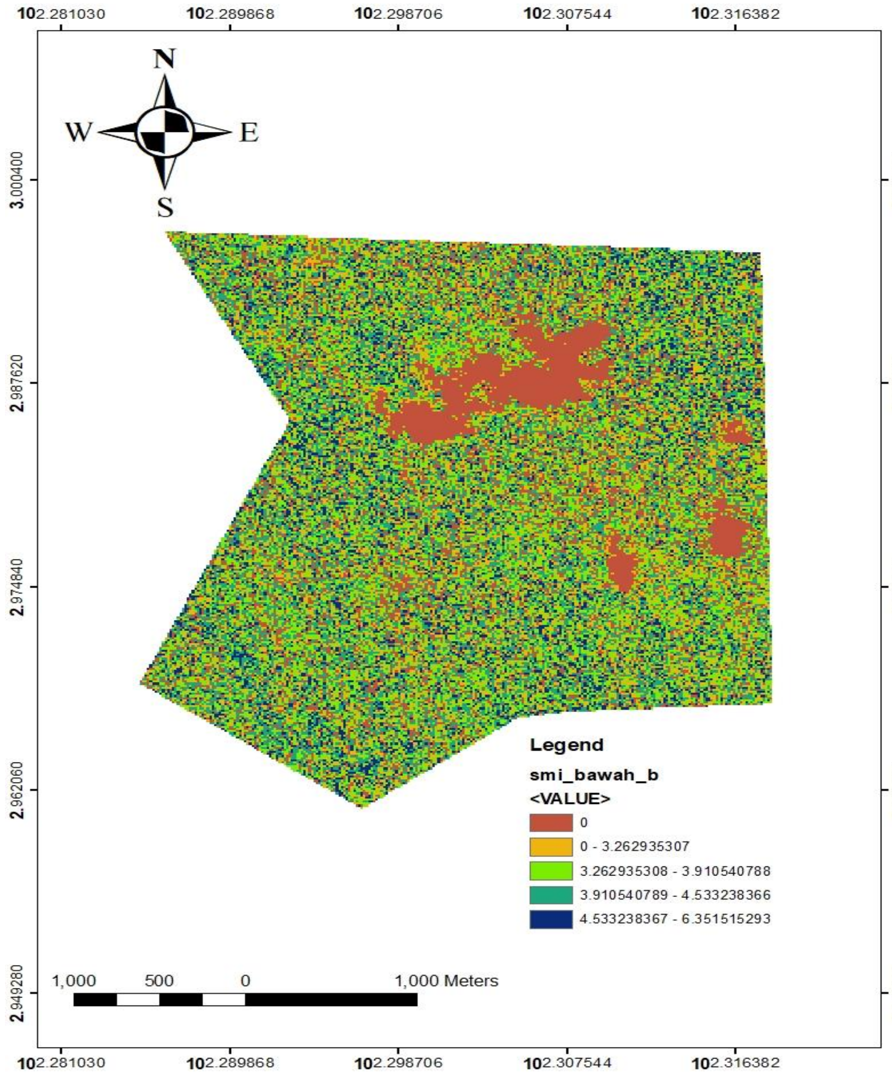


Figure 4: The distribution of rainfall and soil moisture in Pasoh FR from October 2019 to October 2020.





asses.

The relationship between soil water content and evapotranspiration in Pasoh forest reserve.

Based on the rainfall amount classification by Schmidt-Fergusson, the months with the least amount of rainfall in 2019 were January, February, and August, with each month receiving less than 60mm of rainfall. The recorded rainfall values for those months were 15.76mm (±2.23 std) in January, 3.56mm (±0.35 std) in February, and 40.17mm (±4.48 std) in August. In 2020, January had the lowest monthly rainfall recorded at 30.23mm (±2.35 std). February 2019 can be categorized as an extremely dry month since it has the lowest monthly rainfall, which is below 10mm/month. However, it's important to note that Vapour Pressure Deficit (VPD) is also an indicator for measuring landscape dryness. A VPD threshold of 1.5 kPa was selected as the approximate value above which stomata close (Kurjak et al., 2012). This VPD value was used to represent the dry air during the observation period. Based on the atmospheric dryness index, March 2019 and October 2020 were the driest months.

The vapour pressure deficit used as the atmospheric dryness index was recorded to the maximum in March, 2019 (1.60 kPa) and October, 2020 (1.58 kPa). The VSWC was recorded at 7.38 % (± 0.01 std) in January 2019 and 8.56 % (±0.00 std) in February. The monthly ET during these periods was 103.00 mm (±1.20 std) in January and 88.36 mm (±0.30 std) in February 2019. In general, ET was very stable throughout the observation period in spite of some decline during the driest months. On a daily basis, the plant transpires water at 3.00mm daily. The summary in Table 1 shows that in 2019, 71% of water sources has been returned to the atmosphere through evapotranspiration. In the following year 65% of the rainfall received in Pasoh being transpired by the forest landscape.

Table 1: Observed weather conditions and volumetric soil water content for Pasoh in 2019 and 2020

(a) 2019	Rainfall (mm)	API60 (mm)	Solar Radiation (MJ m^{-2} day^{-1})	VPD(kPa)	VSWC (%)	ET(mm)
Sum	1737.47	-	-	-	-	1237.47
Average	4.76	22.23	18.29	0.69	0.34	3.42
Max	95.09	137.00	27.65	1.60	0.41	5.44
Min	0.00	0.86	0.89	0.00	0.30	0.94
Std	12.49	20.63	4.00	0.30	0.03	0.62
(b) 2020	Rainfall (mm)	API60 (mm)	Solar Radiation (MJ m^{-2} day^{-1})	VPD(kPa)	VSWC (%)	ET(mm)
Sum	2004.28	-	-	-	-	1319.58
Average	5.15	12.91	12.11	0.65	0.35	3.51
Max	110.25	7.32	15.82	1.58	0.42	5.23
Min	0.00	2.07	0.08	0.01	0.31	1.36
Std	12.90	17.35	7.02	0.29	0.03	0.67

DISCUSSION

Assessing the character of tropical forests, in terms of moisture availability and forest health, requires comprehensive field and remote sensing observations. The advancement of technology through satellite imagery and geographical information system (GIS) software as a tool has made it possible to achieve a reliable assessment of vegetation life and health on the ground based on spectral indices.

Observations from 2019 and 2020 show that the forest in Pasoh FR responded positively to the amount of rainfall, despite a stable VSWC pattern throughout the observation periods. It was found that the forest was able to perform evapotranspiration (ET) at an average rate of 3.44 mm per day, even when there was a shortage of rainfall. However, several dry conditions were recorded in 2019, marked by very little monthly rainfall (less than 60 mm per month). February 2019 was extremely dry with a monthly rainfall amount of only 3.56 mm. January 2020 was also considered a dry period due to less than 60 mm of monthly rainfall.

The forest's ET processes depend on the fluctuation in VPD, and recent studies show a positive trend in global terrestrial evapotranspiration, with varying rates of increase among datasets (K. Zhang et al., 2015). There is high confidence that global terrestrial annual evapotranspiration has increased since the early 1980s. The rate of increase in datasets varies, with an ensemble mean terrestrial average rate of 7.6 ± 1.3 mm per year per decade observed for 1882-2011(Z. Zeng et al., 2018a). However, the lack of trend in evapotranspiration post-1998 was partially due to ENSO variability (Miralles et al., 2014b).

Soil moisture and rainfall are also associated, although sometimes negligible due to no prolonged dry period during the observation. The study demonstrated the use of satellite indices of NDVI (Normalized Difference Vegetation Index) and SMI (Soil Moisture Index) in water stress studies, which can be employed for other locations with similar area characteristics.

Satellite remote sensing indices indicate the presence of live vegetation on the ground, which can potentially be managed as an early warning of water stress in the tropical forest. The observation in 2019 and 2020 shows that the forest in Pasoh FR responded positively to the amount of rainfall in spite of a stable VSWC pattern throughout the observation periods. This is an important finding because tropical forests play a crucial role in regulating global climate and biodiversity.

It is crucial to conduct long-term research on the relationship between water and climate to fully understand the potential impact and resilience of the forest. The strength of the association between NDVI, SMI, and soil water content can be supplemented with references to different temporal data in the future. Understanding the behaviour of tropical forests towards climate change requires long-term observations of various aspects. Addressing the effects of climate change in the future requires research input as a basis for policy formation. Therefore, this type of study becomes an essential input in supporting decision-makers in the formation of policies to deal with the effects of climate change at the local, regional, or global level. The findings of this study could also provide a basis for policymakers to develop strategies to mitigate the impact of climate change on tropical forests.

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