CARBON DIOXIDE, ENERGY FLUXES AND EVAPOTRANSPIRATION OF THE OIL PALM CANOPY ON MINERAL SOIL

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by

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LIST OF ABBREVIATIONS

ABL	Atmospheric boundary layer
AET	Actual evapotranspiration
ANOVA	Analysis of variance
ASL	Atmospheric surface layer
BREB	Bowen Ratio Energy Balance evapotranspiration
EBC	Energy Balance Closure
EBR	Energy Balance Ratio
EC	Eddy covariance
FFB	Fresh Fruit bunch
FFT	Fast Fourier transforms
FTM	Fall Transitional Monsoon
FTZ	Free Trade Zone
IS	Inertial sub-layer
IRGA	Infrared Gas Analyzer
LE	Latent heat flux
LST	Local standard time
MAE	Mean absolute error
MOST	Monin-Obukhov Similarity Theory
MPOB	Malaysian Palm Oil Board
NEE	Net ecosystem exchange
NEM	Northeast Monsoon
NA	Non-available
NSL	Near surface layer
qc	Quality control
PAR	Photosynthetic Active Radiation
PET	Penman-Monteith evapotranspiration
PBL	Planetary boundary layer
PPFD	Photosynthetic photon flux density
RBL	Rural boundary layer
RFE	Relative flux error
RMSE	Root mean square error
RN	Relative non-stationary error
RNS	Vector wind relative non-stationary
RNu	Along wind relative non-stationary
RNv	Crosswind relative non-stationary
RS	Roughness sub-layer
RSE	Relative systematic flux error
R^2	Coefficient of determination
SBL	Stable boundary layer
SL	Surface layer
SVF	Sky view factor
STM	Spring Transitional Monsoon
SWC	Soil water contents
SWM	Southwest Monsoon
USDA	United States Department of Agriculture
VPD	Vapour Pressure Deficit
WS	Wind Speed

LIST OF SYMBOLS

δt	Time period (s)
δT	Change of air temperature at time period δt (°C)
δT_{soil}	Change in soil temperature at time period δt (°C)
dh	Depth of sensors (m)
dz	Difference in height between the sensors (m)
C'_{co_2}	CO_2 molar density fluctuation (µmol m^{-3})
$\overline{C_{co_2}}$	30 min average CO_2 molar density (µmol m^{-3})
C_{co_2}	Instantaneous CO_2 molar density (µmol m^{-3})
C_d	Specific heat capacity of dry mineral soil (J kg^{-1} °C^{-1})
C'_{H_2O}	Water vapour molar density fluctuation (µmol m^{-3})
$\overline{C_{H_2O}}$	30 min average water vapour molar density (µmol m^{-3})
C_{H_2O}	Instantaneous water vapour molar density (µmol m^{-3})
C_p	Specific heat capacity of actual air at time period δt (J kg^{-1} °C^{-1})
C_s	Specific heat capacity of moist soil (J kg^{-1} °C^{-1})
C_w	Specific heat capacity of water (J kg^{-1} °C^{-1})
G	Soil heat flux (W m^{-2})
H	Sensible heat flux (W m^{-2})
h	Height of the highest sensor (m)
λ	Latent heat of vaporisation of water (J µmol^{-1})
L	Obukhov length (m)
ρ	Actual air density at time period δt (kg m^{-3})
$\bar{\rho}$	30 min average vertical wind speed (kg m^{-3})
ρ_b	Soil bulk density (kg m^{-3})
ρ_w	Density of water (kg m^{-3})
Rn	Net radiation (W m^{-2})
S	Heat storage of biomass (W m^{-2})
T'	Temperature fluctuation (°C)
$\overline{T}$	30 min average temperature (°C)
T	Instantaneous temperature fluctuation (°C)
θ	Wind angle (°)
θ_v	Volumetric water content at time period δt (m^3 water m^{-3} soil)
u*	Friction velocity (m s^{-1})
w'	Vertical wind speed fluctuation (m s^{-1})

$\overline{w}$	30 min average vertical wind speed ($m\ s^{-1}$)
w	Instantaneous vertical wind speed ($m\ s^{-1}$)
ζ	Monin-Obukhov stability parameter (dimensionless)

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FLUKS KARBON DIOKSIDA, TENAGA DAN EVAPOTRANSPIRASI DARI KANOPI LADANG KELAPA SAWIT ATAS TANAH MINERAL

ABSTRAK

Kajian ini dijalankan untuk mengukur fluks karbon dioksida, fluks tenaga dan evapotranspirasi daripada ladang kelapa sawit yang di tanam atas tanah mineral di Keratong, Pahang. Tujuan pertama penyelidikan ini adalah untuk menilai tindak balas kanopi kelapa sawit (dari segi fluks karbon dioksida) kepada perubahan meteorologi dan musim, sementara itu tujuan kedua adalah untuk menilai prestasi model evapotranspirasi (model Penman-Monteith dan Bowen Ratio Energy Balance) untuk kanopi kelapa sawit. Tempoh pensampelan dijalankan sepanjang 25 bulan menggunakan purata data 30-min Eddy Covariance di Keratong, Pahang. Keputusan menunjukkan pokok kelapa sawit ialah tumbuhan C3 tropika yang sangat produktif yang mengasimilasi -4.3 μmol m^{-2} s^{-1} CO_2 (60 t ha^{-1} $yr^{-1)}$. Monsun Timur Laut dan Monsun Barat Daya dan variasi harian fluks karbon dioksida, fluks tenaga dan evapotranspirasi mempamerkan pola yang ketara. Pada skala monsun, variasi dalam radiasi bersih dan defisit tekanan wap menyebabkan peningkatan asimilasi karbon dioksida. Pengurangan tekanan wap merangsang pembukaan stomata pada tahap > 2000 Pa dan > 1000 Pa untuk Monsun Barat Daya dan Timur Laut, masing-masing. Analisis prestasi model evapotranspirasi menunjukkan bahawa model Penman-Monteith menganggar 2% lebih rendah daripada evapotranspirasi sebenar sementara model BREB menganggar 17% lebih tinggi daripada evapotranspirasi sebenar.

CARBON DIOXIDE, ENERGY FLUXES AND EVAPOTRANSPIRATION OF THE OIL PALM CANOPY ON MINERAL SOIL

ABSTRACT

The research work focuses on the measurements of carbon dioxide flux, energy fluxes and evapotranspiration of the oil palm canopy for oil palm trees planted on mineral soil. The first aim of this research is to assess the responses of the oil palm canopy (in terms of carbon dioxide flux) to changes in meteorology and season while the second aim is to assess the performance of the evapotranspiration models (Penman-Monteith and Bowen Ratio Energy Balance) for the oil palm canopy. The sampling was conducted over a 25-month period using 30-min averaging time of eddy covariance method in Keratong, Pahang. Results show that the oil palm is very productive tropical C3 plant in which it assimilates -4.3 μmol m^{-2} s^{-1} (60 t ha^{-1} yr^{-1}) of carbon dioxide from the atmosphere. The monsoonal (the Northeast and Southwest monsoons) and the diurnal variations of carbon dioxide flux, energy flux and evapotranspiration exhibit notable patterns. On the monsoonal timescale, the variations in the net radiation and the vapour pressure deficit leads to the increase in carbon dioxide assimilations. The vapour pressure deficit threshold for the stomata was also observed to be >2000 Pa and >1000 Pa for the Southwest and Northeast monsoons, respectively. The evapotranspiration models' performance analyses show that the Penman-Monteith model tend to underestimate the actual evapotranspiration by 2% while the Bowen Ratio Energy Balance model overestimate actual evapotranspiration by 17%.

CHAPTER 1

INTRODUCTION

1.1 Research Background on Oil Palm

The oil palm plantations have expanded rapidly in recent decades and have had great ecological, economic, and social impacts on both the areas converted to oil palm plantations and their surroundings (Dislich et al., 2017). In Malaysia, the largest agricultural plantation sector is the oil palm (i.e., about 56% of total agricultural land), which accounted for 13% of the Peninsula Malaysia landmass (Mohammad Sabli et al., 2017). About 5.74 million hectares of land in Malaysia is under the oil palm cultivation in 2016 and increases by about 1.3% for the next year; producing 19.92 million tons of crude palm oil (CPO) which accounted for about 15% increment from the previous year. This is due to the significant recovery from the El-Nino event that respectively occurred in the year 2015 and 2016 (MPOB, 2017).

Palm oil has become the most consumed vegetable oil in the world (i.e., about 35% as of 2016) (Chong et al., 2017; MPOB, 2017) thereby contributing to the economic growth. The exporting palm oil enhancing from 2016 to 2017, however, the production dropped by about 13% from 2015 to 2016 due to El-Nino events even though the oil palm planted area has been increased by 1.7%. This situation on environmental sustainability have been a growing concern in recent years (Hergoualc'h and Verchot, 2011) when the wide land area of oil palm ecosystem should lead to an increase in carbon stock, thereby counteracting greenhouse gas (GHG) emissions responsible for global warming and climate change mitigation (Henson et al., 2012). Despite its economic benefits, environmental sustainability and climate change concerns have escalated. These concerns include environmental pollution, land use change, the burning of tropical rainforest, clearing of peatlands for plantations (Hergoualc'h and Verchot, 2011) and losses of biodiversity (Clough et al., 2016). In response to these concern, the Greenpeace's campaign of the public activist obligates the oil palm stakeholders and international NGO's to form the Roundtable on Sustainable Palm Oil (RSPO) to develop a certification standard (CSPO) for production of palm oil that meets a responsible ways (Orsato et al., 2013) to improve social, ecology and environmental performance. The pledges make giant companies (such as Nestle) as well as Netherland the first country to commit itself to use only sustainable palm oil.

On the other hand, the academic research of oil palm moves together with industry towards the sustainable oil palm by exploring the climatic and physiological aspect of oil palm ecosystems specifically on carbon dioxide emission. Therefore, enhancing photosynthesis on existing oil palm ecosystem increases carbon store in oil palm plantation. Oil palm C3 species exhibiting high leaf photosynthesis rates up to 20 μmol m^{-2} s^{-1} on adult trees under favourable conditions, but stomata are extremely sensitive to climate variability such as VPD and soil humidity (Legros et al., 2009). Oil palm trees are also very productive tropical C3 plants, that uses the Calvin cycle for fixing CO_2 in the air and produces three carbon molecules of 3-phosphoglyceride acid (3-PGA). This is the most common cycle utilized in the plant kingdom and comprise about 85% of all the plant species. The ecosystems are also characterized by tall canopy agricultural crop which increases leave area index (LAI) with palm age (Awal and Ishak, 2008). Hence, oil palm can substantially absorb CO_2 from the atmosphere. The height of the mature trees may grow up to 16 m and more. This is maximum height attainable before replanting due to economic lifespan.

Therefore, carbon storage under canopy is also important to quantify the whole net ecosystems exchange and carbon sink and source.

There were some studies that was carried out to identified the oil palm plantation at tropical rainforest climate in the Southeast Asia (Henson, 1993; Yasuda et al., 2003; Harun et al., 2004; Henson and Harun, 2005; Lamade and Bouillet, 2005; Melling et al., 2005; Goodrick et al., 2016) to assess the exchanges of carbon and moisture by using the eddy covariance (EC) technique. But little work has been done on the oil palm plantations over the mineral soil. However, none of the afore mentioned studies was done on some seasonal scales that involve the monsoonal period within the Southeast Asia regions. There were two studies carried out in terms of Asian monsoon scale in Beijing, China and India, respectively by the Twine et al. (2000) and Patil et al. (2014). Consequent upon this, the carbon emission and absorption of the surface layer processes above oil palm plantations are still not well understood especially during monsoon seasons. Therefore, we access the fluxes exchange in the variation of the solar radiation and precipitation which changes during each of the monsoon seasons. The Southeast Asian countries include East India, South China, Myanmar, Thailand, Vietnam, Laos, Kampuchea, Malaysia, Singapore, Indonesia, Borneo, the Philippine islands, Portuguese Timor and western New Guinea (Loo et al., 2015) and these countries are influenced by the monsoon which is a ‘large-scale seasonal reversals of the wind regime’. Malaysia is located near to the equator and precisely in the tropical region. The region are exposed in the same manner by intense solar radiation throughout the year. As such, meteorological parameters such as ambient temperature, solar duration or radiation, and rainfall needs to be further discussed here.

The plantation is located within the tropical rainforest climate zone, which is hot and humid throughout the year. On the other part of the thesis is the study on water vapour of evapotranspiration (ET). The evapotranspiration is in two processes of water loss from land surface to atmosphere, evaporation and transpiration. Evaporation is the process where liquid water is converted to water vapour and removed from sources such as the soil particular as it relates to the mineral soil of oil palm ecosystem in this research work. Transpiration is a process of the vaporization of liquid water within a plant and later loss of water as vapour through leaf stomata (Zhang, 2017). Estimating evapotranspiration on oil palm crop is important for a hydrological aspect (Tani et al., 2003) as well as understanding the limitation of productivity due to water deficit in oil palm ecosystems (Dufrêne et al., 1992). The current study is also estimating potential evapotranspiration using Penman-Monteith model (PET) and Bowen Ratio Energy Balance (BREB) to see their performance with relation to climatic condition and comparing with actual evapotranspiration using direct measurement of Eddy Covariance method.

1.2 Problem Statement

The oil palm plantations are expanding annually in Malaysia due to the global increase in the demand for palm oil. This situation allows the transformation of lowland forest areas into oil palm plantations, and it was identified as the potential driver of climate change. Recently, deforestation accounts for 6 - 12% of the global anthropogenic CO_2 emissions to the atmosphere (Van Der Werf et al., 2009; Baccini et al., 2012) by the massive burning of tropical forests. However, the information on the state of carbon dioxide flux and water vapour (or evapotranspiration) above an oil palm plantation on mineral soil is scarce on variation temporal scales. Therefore, the precise monsoonal scale study on the emission of carbon dioxide in relation to meteorological parameters (such as air temperature, wind speed, relative humidity, solar radiation and vapour pressure deficit) above an oil palm plantation will be helpful to explore the response of carbon dioxide variations toward monsoon climate. On the other hand, the study on assimilation of carbon dioxide flux and water vapour also portraying the productivity of oil palm ecosystem through photosynthesis, but also the process of carbon-balance towards the sustainability oil palm ecosystem. Moreover, studies on oil palm in Malaysia were concentrated on the peat soil (Sakata et al., 2015) in which the capacity of carbon dioxide storage for the ecosystem is different compared with mineral soil and also there is the difference between the two distinct soil type on the soil water content for evapotranspiration processes. The information on the CO_2 fluxes from oil palm plantations on their sink or source capability on the ecosystem scale is unknown (Meijide et al., 2017) plus the driving factor that contributed to this situation.

1.3 Research Questions

This research work attempt to answer the following pertinent questions,

i. How the different meteorological variables distribute over the oil palm ecosystem based on the monsoon seasons?

ii. How does the temporal variations (e.g., the diurnal, monsoonal and annual) of the carbon dioxide flux emission in the oil palm plantation for the mineral soil correlate with the meteorological variables over the ecosystem?

iii. How does actual evapotranspiration vary with the potential evapotranspiration for the two models; 1.) The Penman- Monteith model and 2.) The Bowen

Ratio Energy Balance (BREB) model on the temporal scales of the diurnal, monsoonal and annual variations?

1.4 Research Objectives

The objectives of this research work are summarized as follows;

i. To investigate the impact of air temperature (Ta), wind speed (WS), wind direction (WD), atmospheric stability (ζ), net radiation (R_n), relative humidity (RH), rainfall/precipitation, vapour pressure deficit (VPD) and photosynthetical photon flux density (PPFD) on the mature oil palm plantation for mineral soil on the temporal scales of annual, diurnal and monsoonal.

ii. To access the variation of carbon dioxide emission in relation to meteorological variables at diurnal and inter-annual scale from 17 years old of the oil palm plantation using the eddy covariance method and investigate the physiological aspect of oil palm plantation using photosynthetically photon flux density (PPFD) and vapour pressure deficit (VPD) over monsoon seasons.

iii. To investigate the variation of the actual evapotranspiration (AET) in relation to potential evapotranspiration by using the Penman-Monteith (PET) model and the Bowen Ratio Energy Balance (BREB) model over the monsoon seasons.

1.5 Scope of Research

The overall goal of this research is to further the understanding of energy and mass exchanges within the oil palm environments, with a particular focus on the carbon sequestration and evaporative processes. Acquiring the eddy covariance data for fluxes and the wind speed components, to study the effects of the climatic conditions particularly the monsoonal seasons. The scope of this study comprises of eight main parts as follows:

i. The meteorological parameters such as wind speed, wind directions, relative humidity, net radiation and air temperature are the major driver of climate variability in mesoscale system. These parameters are analysed to observe the behaviour of atmospheric trend above oil palm plantation at Keratong, Pahang, throughout temporal scales such as diurnal, monsoonal, inter-annual and annually. The division of for monsoon seasons are obtained most importantly for wet and dry seasons. These monsoonal characteristics are influenced by the variability of rainfall and perceived by using rain gauge (TR-525M) diurnally and inter-annually in this study. Furthermore, the correlation between the meteorological parameters are constructed by using Pearson's and t-test to validate the performance statistically. The significant between two parameters using various averaging data in order to define temporal atmospheric aspect especially during dry and wet monsoonal season.

ii. The second aim of this study is to investigate the carbon dioxide emission from oil palm canopy using eddy covariance technique based on temporal scale primarily on monsoon seasons. Measuring carbon dioxide flux using open-path CO_2 infrared gas analyser (LI-7550A) at height of 30 m were then undergoes the pre-processing for quality checks, gap-filled and finally data analysis. Using the previous work, the correlation of meteorological parameters and carbon dioxide flux are accessed to find the statistical and also correlation significant, therefore the driving factors toward behaviour of carbon dioxide emission can be identified.

iii. The final aim of this study is to access the evapotranspiration above canopy of oil palm plantation by direct measurement of eddy covariance technique using open-path H_2O gas analyser and to predict the potential evapotranspiration by Penman-Monteith (PET) and Bowen Ratio Energy Balance (BREB) models. The variability of actual evapotranspiration is also investigated in correlation between 30 min-average and daily-average of meteorological parameters. Therefore, the significant influence of climatic aspect can be obtained. Other than atmospheric aspect, the contributing factor of soil water content (SWC) to AET is also taking into account at inter-annual and daily-average studies. Both scales will access the entrance of water source into the oil palm system and how it distributed towards monthly scale. Thus, relationship between AET and water use efficiency are observed. Finally, the main temporal study of monsoon seasons are compared and correlated between actual evapotranspiration (AET) and both potential evapotranspiration. The performance of these two models are compared for the best estimation for which closest to actual evapotranspiration.

1.6 Structure of the Thesis

This thesis consists seven (7) chapters which includes Introduction, Literature Review, Methodology, Meteorology above Oil Palm Ecosystem, Trend of Energy and Carbon Dioxide, Evapotranspiration by Penman-Monteith and Bowen Ratio Energy Balance, and Conclusions. The Chapter 4, Chapter 5 and Chapter 6 are the results and discussion on the research objectives (refer 1.6). The descriptions of each chapters are as follows:

i. Chapter 1 introduces the general idea of the research and the micrometeorological aspects on oil palm, identifying the challenges of both the scientific and the local interest. At the end of the chapter, the objectives of the research project were well-defined.
ii. Chapter 2 discusses the literature review, identifying the theoretical factors that relates to the annual and monsoon condition that contributes to the variations in carbon and energy fluxes of the oil palm ecosystems in relation to geological factors required in the research with comparisons to the previous studies.
iii. Chapter 3 gives the site description and the experimental details. Discussions on the designs and implementation of the adopted procedures; including the instrumentation; the data analysis; and quality control; the gap-filling process; determine crop canopy; flux partitioning; statistical analysis and to finally identify the assumptions and limitations of the research work.
iv. Chapter 4 describes the meteorological conditions during the daytime and nighttime fluxes that are related to the local climates; meteorological variables such as the temperature, humidity, vapour pressure, radiation, rainfall, variations of the wind speed and wind directions, and the atmospheric stability. This chapter provides the results on the validity of eddy covariance technique by energy balance closure (EBC) together with the result of the data quality and optimizing heights analysis. These procedures are to ensure the reliability of data quality using the particular method in this

study. On the final note, the variables were used in constructing the energy balance closure for the study site.

v. Chapter 5 is an annual, monsoonal and diurnal observations of energy and carbon dioxide fluxes in oil palm. Obtaining correlation between CO_2 fluxes and energy fluxes and meteorological variables such as radiation, precipitation, vapour pressure deficit, air temperature over a mature oil palm plantation.

vi. Chapter 6 describes the evapotranspiration, comparison of the actual evapotranspiration and potential evapotranspiration through the direct measurements of eddy covariance and theoretical models of the Penman-Monteith (PET) and the Bowen Ratio Energy Balance (BREB). Finally, compare them on how they behave with monsoon and monthly analysis.

vii. Chapter 7 gives the conclusion, summary of the results that mostly answered the objectives of the study and the recommendations for future work that are closely related to the current study were made.

At the end of the thesis, the whole references cited in this study were also listed. Finally, the appendices for fundamental equations provided and the publications related to this PhD work were written on the last page of the thesis.

1.7 Research Contributions

It is important for the oil palm industry to make smart decisions based on the information from this study on the micrometeorological aspect. The information from this research will provide a better understanding of the interaction between the environmental, hydrological, physiological (oil palms), and climatologically controls of carbon, energy flux and water vapour flux between vegetation and the atmosphere.

It was found that the meteorology significantly correlates to productivity (i.e., photosynthesis) of the oil palm trees, as well as their relationship with monsoonal scale. On the other hand, the values of evapotranspiration (ET) provides the critical knowledge of water use efficiency (WUE) on the monsoonal scale which has been identified as water stress due to the drought events. These studies were also beneficial to the plantation management, such as to provide the better decisions on drainage and irrigation system according to time-based approach to oil palm plantation (i.e., soil water content, ET, water stress).

CHAPTER 2

LITERATURE REVIEW

This chapter consists of literature based on the objectives of the study and critically discussed between the references in terms of four major parts; 1) The meteorological parameters in relations to oil palm plantation 2) The exchanges of carbon fluxes and water over the oil palm ecosystems 3) Actual potential evapotranspiration on the oil palm ecosystem and 4) Measuring flux using Eddy Covariance technique. These issues are introduced in earlier chapter.

2.1 The Meteorology and the Oil Palm Plantation

According to Malaysia's Meteorological Department, Malaysian weather system is characterized by two monsoon regimes, namely, the Southwest Monsoon from late May to September, and the Northeast Monsoon from November to March. The Northeast Monsoon brings heavy rainfall, particularly to the east coast states of Peninsular Malaysia and western part of Sarawak. On the other hand, Southwest Monsoon usually signifies a relatively drier weather than the Northeast Monsoon. The transition periods between the monsoons are referred to as the inter-monsoon period. The Monsoons are caused by the land-sea temperature differences due to the heating effect of the sun's radiations (Loo et al., 2015).

The location of Malaysia near to the Equator, and precisely in the rainforest tropical region, with both regions exposed to the same intense solar radiations throughout the year. As such, meteorological parameters such as the ambient temperature, solar duration or radiations, and precipitation needs to be further discussed. The average solar duration is usually about four to five hours per day during wetter months and nine to ten hours per day during the drier months. Solar radiations in the region is basically linked to the thickness of the clouds, which means that during the dry season, there are less clouds and solar radiations would be at its peak and vice versa. Since the observations were carried out in the dry season, the average solar duration is about nine to ten hours per day and the average of sunshine received in Peninsular Malaysia is 6 hours per day (Shavalipour et al., 2013).

Tropical monsoons affect the CO_2 exchanges of vegetated surfaces primarily due to the amount of precipitation and net solar radiation (Scott et al., 2009; Valsala et al., 2013; Patil et al., 2014). The latter factors are affected by the seasonal variations of water availability and the presence of clouds. The solar energy absorbed by the oil palm stimulates photosynthesis and stomata activity, which enhances the CO_2 assimilation. The sunlight intensities responsible for the photosynthetically active radiation (PAR) are the factors regulating the amount of carbon dioxide that would be removed from the atmosphere through photosynthesis. In spite of this, oil palm yield is also determined by the availability of active photosynthetically photon flux density (Woittiez et al., 2017), which is related directly to the net radiation. The response of the stomata activity to changing vapour pressure deficit caused by the water availability (Ocheltree et al., 2014), is also a significant regulating factor of the CO_2 exchange. Large vapour pressure deficits between the leaves and the atmosphere induce the plant to reduce stomatal conductance, leading to general reductions in productivity and CO_2 assimilation (Zhao and Running, 2010; Ocheltree et al., 2014). However, more data and analysis are needed to better the understanding of responses of the oil palm to the changing monsoons and the interactions of the predominant aforementioned factors.

Although some attempts have been made to determining the controls of the CO_2 exchanges of oil palm plantations (Lamade and Bouillet, 2005; Germer and Sauerborn, 2008), together with the mineral soil storage on the C storage (Smith et al., 2012), little work has been done to investigate the seasonal or monsoonal variations of the CO_2 fluxes due to lack of the data that spans the entire monsoonal cycle. Because of this, the CO_2 fluxes and the atmospheric processes that affect them are still not well reported. The responses of the CO_2 uptake, and the productivity of the oil palm plantation to the changing monsoons and its different controlling factors therein are still unknown (Fei et al., 2017).

2.2 The Exchanges of Carbon and Water over The Oil Palm Plantation

The oil palm (*Elaeis guineensis*) has been taken from its natural forest habitat in West Africa to become a large-scale commercial tree crop now centered in Southeast Asia. The utilization and economic benefits of the palm oil have risen dramatically in recent years, reflecting in an increased demand for vegetable oil. Malaysia has become a net exporter of palm oil by the year 2011 (Hassan et al., 2011). The growth in the oil-palm plantations has led to an increase in greenhouse gas (GHG) emissions from the agricultural sector (Henson, 2009). These agricultural activities have been able to contribute to the rapid economic growth of many developing countries in the Southeast Asia region like Malaysia, Indonesia, and Thailand. Over the years, the vast amount of virgin land have been converted to oil palm plantations, whereas in Malaysia, about 56% of the available agricultural land are dedicated to the cultivation of oil palm (Mohammad Sabli et al., 2017). The amount of carbon sequestered vary even though the same ecosystem has compared. This is because each ecosystem has different types of soil, climate and age. Other than that, the factor of clearing from forestry land has higher GHG emission, while non-forest has less ones (Pulhin et al., 2014). According to (Henson and Harun, 2005), oil palm cultivation (planting and harvesting), and the production in Malaysia emitted about 13 Mt of GHG per year, this is about 29% increase from that of the year 2000 (Henson, 2009). The main sources of GHG emissions were from land conversion (i.e., about 60%), while methane emission from palm oil mill effluent treatment via anaerobic digestion is about 13%, the fossil-fuel combustion is about 13% and fertilizer used is about 4% (Nor Azman Hassan et al., 2011). The rapid growth of tropical perennial crops over the last 40 years, have impacted the local environments (biodiversity, water and C balance, soil fertility, erosion, etc.), which require further studies to successfully adapt management strategies to sustainability. In spite of this, some other studies have shown that the oil palm plantation ecosystem actually increased the terrestrial carbon stocks in the form of plant biomass and detail comparisons have been made above the ground where biomass was found to be 5 times higher than those below the ground (Germer and Sauerborn, 2008). The authors reiterated that the tropical forest with mineral soil have been converted to oil palm plantation, hence, an estimated of about 5-180 Mg C ha^{-1} was a loss, thus, encouraging the increase in the concentration of greenhouse gases in the atmosphere.

However, previous studies have been reported on the exchanges of CO_2 over the oil palm plantation (Melling et al., 2005; Goodrick et al., 2016). These previous reports revealed that the oil palm plantation is a substantial carbon sink. Another study on Biofuel carbon debt was done by Fargione et al. (2008) in which they partitioned the below and above biomass carbon loss at different ecosystems. They found that the highest carbon debt in cropland Southeast Asia was at the peatlands which were ~ 610 Mg C ha^{-1}.

A previous study by Henson (1999), was carried out on the annual uptake of the carbon dioxide by mature oil palm on the coastal soil in Malaysia which was reported to have reached about 46.4 t ha^{-1} yr^{-1} with a net fixation of about 11 t ha^{-1} yr^{-1} based on the EC technique. In this study, soil respiration was estimated to be about 28.5 t ha^{-1} yr^{-1}, which was about half of that reported by the Melling et al. (2005), for peat soils under oil palm. A similar study was also done by Fowler et al. (2011), in the Borneo, by comparing the oil palm plantation and the rainforest ecosystem of the daytime CO_2 flux for the two canopies, e.g., about 1200 mg C m^{-2} h^{-1} for the oil palm, and about 700 mg C m^{-2} h^{-1} for the rainforest. In Indonesia, Lamade and Bouillet (2005), also reported the yearly rate of carbon sequestration by oil palm ecosystem which varied from about 250 to 940 C m^{-2} yr^{-1}. However, these results could not be generally applied to all plantations due to the varying plantation conditions as mentioned earlier, such as the type of soil (e.g., peat, mineral, etc.), the seasonal variations (e.g., monsoons, dry, wet, etc.), and the age (e.g., juvenile, mature, etc.), that could substantially affect the overall ecosystem CO_2 assimilation capability (Meijide et al., 2017). Furthermore, comparison of the oil palm plantation and tropical rainforest could be misleading, even though the carbon uptake of oil palm plantation is high (e.g., high growth rate of oil palm). This factor does not constitute a carbon sink, for example, about 50% of the net primary productivity (NPP), was exported via harvest, thus, it returns to the atmosphere offside of the oil palm ecosystem (Kotowska et al., 2015).

A study on a different crop by the Law et al. (2002), indicated that the net carbon dioxide uptake in the boreal and pine forest sites was greater during the cloudy periods compared to the sunny periods, which was also supported by other studies, e.g., (Randow et al., 2002). The authors noted that increase in the net carbon uptake was due to a decrease in the ecosystem respiration as a result of the lowered air and soil temperatures. The decrease in respiration (i.e., the release of carbon dioxide), under clear sky conditions, could be as a result of the reduction in the soil moisture contents, whereas another study (Ishizuka et al., 2002; Henson and Harun, 2005) also showed similar results in their report.

The different ecosystems environments produce different CO_2 sequestration capacities. As stated above, the oil palms have higher carbon sequestration rates due to their high productivity and growth rate. But this capacity can be inhibited by poor plantation management practices; the monsoons, and the soils with high organic contents. For example, high productivity is also an effect of the high fertilizer applications that caused a negative effects on the soil pH, nutrient losses, and the N_2O emissions (Clough et al., 2016). Soil with high organic contents (e.g., peat soil), would lower the net carbon sequestration capacity of the oil palm plantation ecosystem since the soil can emit large quantities of CO_2 from the respiration (Hergoualc'h and Verchot, 2011). Nonetheless, soil with low organic contents (e.g., mineral soil), is also subjected to the soil respiration and could tip the scale to emitting CO_2 under certain weather conditions. This is because soil respiration is affected by the seasons or monsoons, which would ultimately influence the overall sequestration capacity of the oil palm plantation.

In a good side of it, the oil palm offers several opportunities to mitigate the portion of the global greenhouse gas emissions that are directly dependent upon land use and land-management techniques (Suresh, 2013). It is photosynthesis that enables atmospheric CO_2 to enter the fronds when incident radiation is sufficient enough and when water supply conditions are more favourable (Lamade and Bouillet, 2005). Table 2.1 shows the various studies on carbon sequestration at different crops where the highest restoration of carbon was by Brazilian tropical rainforest during wet season and the lowest uptake was by soybean plantation with only 0.5 t ha^{-1} yr^{-1} of CO_2.

Table 2.1. Comparison between selected carbon sequestration capacities of different ecosystems.

Ecosystem	**Location**	**Carbon sequestration capacity (t C ha^{-1} yr^{-1} sequestered)**	**Remarks**	**Source**
Coconut	Vanuatu, South Pacific	38.95	Tropical wet	Navarro et al. (2008)
Rubber	Kerala, India	33.5	4-year-old	Annamalainathan et al. (2011)
Poplar	Lochristi, Belgium	3.5	1-year-old	Zona et al. (2013)
Pasture	Oklahoma	4.3	Non-drought years	Meyers (2001)
Maize	North China Plain	4.4 108.5	Seedling Ripening	Ji et al. (2011)
Soybean	Iowa	0.5	4-year-observation	Hernandez-Ramirez et al. (2011)
Malaysian tropical rainforest	Pasoh, Malaysia	31.1	3-year-observation	Kosugi et al. (2008)
Malaysian tropical rainforest	Pasoh, Malaysia	32.6	3-day-observation	Yasuda et al. (2003)
Brazilian tropical rainforest	Central Amazon, Brazil	135.7 200.6	Dry season Wet season	Randow et al. (2002)

2.2.1 Evapotranspiration on the Oil Palm Ecosystem

The measurement of crop water availability is a vital part of the agricultural systems specifically for the oil palm, because of its fruit yields of the oil palm could be effected by the water stress. The measured evapotranspiration flux (ET), could also be validated through a complete energy balance analysis (Roupsard et al., 2006).

About 99% of water used in agriculture is lost by crops as ET (Rana and Katerji, 2000). However, it is well documented for peatland and organic soil, unlikely as MPOB Keratong site which having a mineral soil. Therefore, it is crucial to understand the water loss by a plantation on oil palm's surface, under vapour form, by evaporation from mineral soil and transpiration from oil palms.

A recent study on the estimation of evapotranspiration was reported (Sigalingging et al., 2018) on an oil palm crop with the same species of *Elaeis guineensis,* with an average daily ET at 1.85 to 2 mm day^{-1}. They reported that the aging palms would increase the daily rate of evapotranspiration as SWC increases. A comparable study on the ET (Roupsard et al., 2006) on the seasonal scale was also done under the tropical palm canopy at a humid climate with evapotranspiration valued at about 952 mm year^{-1}. The study indicated that the seasonal variability was more pronounced, driven by radiation and vapour pressure deficit (VPD), and the canopy conductance of the coconut palms, that appeared to be strongly controlled by the VPD.

There were also numerous models to estimate ET depending on the measuring principle such as hydrology, plant physiology and micrometeorology approaches (Shaomin and Xu, 2018). The hydrology approach, such as by using the lysimeter, is limited to maintenance and areal extent especially when the surrounding crops are not uniform. Sap flow and ventilated chamber are widely used for the plant physiology approach and also gave satisfying results for the tall canopy, however, they cannot obtain continuous data as destructive sampling limits the high flow flux rate. Recently, a direct measurement using micro-climate data widely used around the world by in a different crop, it covers partitioning of ET combining with meteorological variables and physiological approach, therefore its robustness was proven by many authors (Carr, 2011; Corley and Tinker, 2015). A study on the comparison of 15 models (Rosenberry et al., 2007) by taking BREB as a standard were observed and the most favourable values were from the Priestley–Taylor, deBruin–Keijman, and PET models. All of them require net radiation, air temperature, heat storage, and vapour pressure, making them relatively data intensive. These micro-climate approach was also agreed by other oil palm study (Saugier and Katerji, 1991; Dufrêne et al., 1992; Henson, 1993).

2.2.1(a) Potential Evapotranspiration

The first quote by Penman (1948) was "*Three kinds of the surface are important in the return of rain to the atmosphere. For extended areas of land, they are, in order of importance: vegetation, on which plant leaves act as transpiring surfaces; bare or fallow soil, from which water evaporates at, or just below, the soil-air interface; and open water, from which evaporation takes place directly*" in the origin of forming equation to estimate evapotranspiration over water surface. This estimation of ET using weather data but then some other researchers (Thompson, 1979; Stewart, 1983) indicated that the Penman version could be enhanced by few factors as follow; 1) hourly weather data 2) atmospheric stability and 3) internal plant resistance. The last factor has come to debate when the Penman formulation is only applicable to the water surface and lack of physiological aspect which missing soil resistance, root resistance, xylem resistance, mesophyll resistance, stomata resistance and cuticle resistance. These features are described as the internal resistance of the plant. 18 years later, Monteith (1965) was the first to combine the physical and physiological aspect of evapotranspiration from a crop canopy. Today, the most widely applied combination equations-based ET model is the Penman-Monteith (PM) equation, which is driven by meteorological data, and defined as aerodynamic resistance and canopy resistance. Total ET flux is controlled by potential evapotranspiration (PET) which is defined as maximum ecosystem ET under no-water-stress conditions. The other method to estimate evapotranspiration is Bowen Ratio Energy Balance (BREB). BREB is a widely used technique for measuring surface water and heat exchange (Shaun, 2004), and BREB estimates sensible and latent heat flux from a surface based on measurements of air temperature and humidity gradients, net radiation, and soil heat flux (Tanner, 1960; Fritschen and Simpson, 1989; Ting-Ting et al., 2008). This method based on the assumption that the turbulent exchange coefficients for heat and water vapour are equal, conditions which are not always met. The comparing studies on estimation of model were made on tropical oil palm region (June et al., 2018).

2.3 The Eddy Covariance Method

Eddy-covariance (EC) method emerged as a key method for measuring the trace gas and energy exchange between the whole ecosystems and the atmosphere (Baldocchi, 2003). Eddy covariance is also a direct measurement of the vertical turbulent fluxes of energy, water, and carbon dioxide over various terrestrial ecosystems such as on forests (Misson et al., 2007; Gonzalez et al., 2013; Melaas et al., 2013; Thomas et al., 2013; Hayek et al., 2018), oil palm (Roupsard et al., 2006; Hassan et al., 2011; Singh et al., 2013; Suresh, 2013; Rodrigues et al., 2014; Rivera-Méndez et al., 2017), in the coconut (Navarro et al., 2008), maize (Masseroni et al., 2014) and across a range of land types and climatic conditions. The eddy covariance method is also extensively studied in relation to the carbon dioxide fluxes (Krupa and Kickert, 1989; Raich and Schlesinger, 1992; Ishizuka et al., 2002; Loescher et al., 2006; Ji et al., 2011; Ago et al., 2014); net exchange ecosystem (NEE) (Aubinet et al., 2001; Loescher et al., 2006; Ago et al., 2014) and evapotranspiration (Roupsard et al., 2006; Li et al., 2008; Shi et al., 2008; Yusop et al., 2008; Evrendilek, 2013; Adzemi Mat, 2014).

2.3.1 The Background

During 1895, Reynolds was the first to study the averaging of turbulence process, then described the turbulence energy equation. Then mixing length study were done primarily (Taylor Geoffrey and Shaw William, 1915) and followed by the buoyancy effects of Richardson during 1920. The turbulence study has grown and continued to the year of 1940 in Russia with isotropic turbulence, while, turbulence spectra was done by Karman and Howardt and Taylor on 1938 and 1938, respectively, and it was continued the investigation on energy of the turbulence spectra by Kolmogorov during 1941 (Foken, 2008).

The modern turbulence study by Obukhov in 1946, found that the scaling parameters that connects all near-surface turbulence processes and the Obukhov theory (Obukhov, 1971; Foken, 2006) was then became so significant because of its relevance in micrometeorology studies. Using what it is now known as the similarity theory. In year 1954, Monin and Obukhov created the basis for the modern stability-dependent determination of the exchange process on a surface layer (Calder, 1966).

At the same time, a direct method of approach to measuring the turbulence fluxes were developed, e.g., (Montgomery, 1948; Swinbank, 1951) which has become the eddy covariance (EC) method. These work has been newly summarized and re-viewed by many authors (Foken, 2006; Foken, 2008; Leclerc et al., 2014). The development of sonic anemometer was ascertained, for which the basic equations were also recovered. Today's design of sonic anemometer was improved by Kaimal and Businger (1963) and Mitsuta (1966). On a later note, the Australian experiment starts to be developed rapidly for inter-comparison turbulence sensors (Miyake et al., 1971; Garratt and Hicks, 1990).

Starting with the turbulence studies in the atmospheric boundary layer (ABL), and the transfer of heat and momentum, the theoretical and experimental foundation for subsequent work on the CO_2 exchange have been conducted, which is of interest to the ecological community (Baldocchi, 2003). Measurement of the CO_2 exchange started with the flux-gradient method during the 1950's and decades after the initial studies, the techniques has grown extensively over various types of crops particularly the shorter agricultural crops. After 20 years of the initial applications of the EC method, measurement of the CO_2 exchange was made possible by adjusting the anemometer's alignment (Desjardins and Lemon, 1974). However, Baldocchi (2003) reviewed that earlier study was prompted to critique of the limitation as the time response of the sensors were relatively slow on the order of 0.5 s, that make it suffered from large errors (~40%).

Presently, the eddy covariance method is being used in over 150 sites worldwide as part of the FLUXNET program (Baldocchi et al., 2001).The regional networks are; the North America (AmeriFlux); Brazil, Europe (CarboEuroflux), Asia (AsiaFlux), Australia (OzFlux) and Africa. Eddy covariance tower has been built in

Malaysia mostly in the forest areas. Up to the present time, a total of 11 towers have been identified specifically on different peat ecosystems. Most towers are located in the forest areas, e.g. Pasoh (Negeri Sembilan), and Lambir (Sarawak). The Tropical Peat Research Institute in Sarawak has 3 towers located at different peat ecosystems.

2.3.2 Measuring Techniques

The Eddy covariance (EC) technique was used as the main measurement technique in this dissertation. The EC method is one of the most accurate and direct measurements of gas fluxes which can provide a real-time data at high frequency (Burba and Anderson, 2010). It has been used by many researchers to determine the momentum, sensible heat, water vapour and atmospheric gas (e.g., CO_2) on surface layer processes (Aubinet et al., 2005; Henson and Harun, 2005; Foken, 2008; Zona et al., 2013; Zhang et al., 2015). As early as the 19th century, Sir Osborne Reynolds developed the underlying theory of the EC technique (Reynold, 1895). Even though some applications were made in the 1950s, the lack of adequate equipment postponed the establishment of the EC technique until the 1980s (Baldocchi, 2003). Since the early 1990s (Wofsy et al., 1993), it has been used for year-round long-term monitoring of above canopies at mid-latitude forest.

Emissions and fluxes are measured by instrumentation mounted on a stationary tower above the ecosystem under study. As described by study earlier (Burba, 2013), the horizontal wind consists of numerous eddies of various sizes, rotating at a wide range of frequencies flowing horizontally across a surface. Therefore, it consists of an accurate technique to measure surface-to-atmosphere fluxes, gas exchange budgets, and emissions for a variety of ecosystems such as agricultural lands, primary and secondary forests. However, it was found that the limitation of eddy co-