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RESEARCH PAPER

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Carbon dioxide and energy fluxes above an oil palm canopy in peninsular Malaysia

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Abstract

A study was conducted on carbon dioxide (CO_2) and energy fluxes (i.e. latent (L) and sensible heat (H)) above the canopy of mature oil palms planted on the inland mineral soil in Keratong, Pahang, Peninsular Malaysia. The measurement was conducted over an 18-month period from September 2013 to August 2014, using the eddy covariance method. There was a significant seasonal variation in the monthly averaged CO_2 fluxes over the measurement period. The monthly averaged CO_2 flux values ranged between -2 to -6 µmol m^{-2} s^{-1}, with an average value of about -3.5 µmol CO_2 m^{-2} s^{-1}. This could be due to the irregular cumulative monthly precipitation and net radiation during the observation period. Relatively low average monthly CO_2 flux (or high uptake of CO_2) also corresponds with the lowest monthly average LE and rainfall in months February 2013 and 2014. The negative CO_2 flux value shows that the mature oil palm ecosystem from an inland mineral soil area in Peninsular Malaysia was a sink for CO_2. Analysis of energy balance closure shows that the slope between latent and sensible heat fluxes and total incoming energy was about 0.69 with an r^2 value of 0.86. The slope value obtained in this study suggests that there was a surplus of available energy compared to the measured energy fluxes. Energy balance ratio was about 0.81 and comparable to other agricultural surfaces. This means that 81% of the available energy was accounted through the surface flux measurements.

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Introduction

In 2015, Malaysia has 5.6 million hectares of oil palm that produces 19.7 million metric tonnes of crude palm oil. The palm oil production is important for the economy of Malaysia, which is the world's second-largest producer of the commodity after Indonesia. Malaysia currently accounts for 39 % of world palm oil production and 44% of world exports. The total exports of oil palm products were about 25.37 million tonnes in 2015, with a total export revenue of about RM60.16 billion (MPOB, 2016).

Oil palm is a perennial crop with a closed canopy that also stores carbon, both above and below the ground. It has an important role in CO_2 balance and carbon sequestration. An oil palm plantation may accumulate 90-120 t ha^{-1} of biomass at the age of 25 years after planting (Sunaryathy *et al.*, 2015; Asari *et al.*, 2013; Khalid *et al.*, 1999). Henson (1999) showed that an oil palm plantation assimilates up to 36.5 tonnes of dry matter ha^{-1} year^{-1}, compared to 25.7 tonnes of dry matter ha^{-1} year^{-1} by natural tropical rainforest. Therefore, oil palm plantations are a significant carbon sink, almost similar to tropical rainforests in magnitude (Kosugi *et al.*, 2008; Clark, 2004; Yusuda *et al.*, 2003; Malhi and Grace, 2000; Soepadmo, 1993). Thus, the oil palm trees play an important role in the uptake of carbon dioxide (CO_2) and can contribute significantly towards mitigating the global rise in CO_2 levels (Lamade and Bouillet, 2005). Long-term measurements of the CO_2 uptake by oil palm plantations are needed to gain a better understanding of their CO_2 assimilation performance in Malaysia, since different conditions such as soil type, climatic factors, palm age and management practises, could influence their CO_2 sink capacity.

The eddy covariance method is the most widely-used, accurate, and direct method currently available for quantifying exchanges of CO_2, water vapour, and energy between the surface of the Earth and the atmosphere (Baldocchi, 2013; Burba, 2013; Foken, 2008). Emissions and fluxes are measured by instruments mounted on a stationary tower located in the specific ecosystem. This technique provides an accurate means to measure surface-to-atmosphere fluxes, gas exchange budgets, and emissions for a variety of ecosystems such as agricultural lands, primary and secondary forests.

Recent studies with intact forest and other ecosystems have demonstrated that long-term, direct measurements of CO_2 flux using the eddy covariance method can define the magnitude of CO_2 fluxes and net ecosystem production ranging from hourly, seasonal, annual and inter-annual. Aoki *et al.* (1975) took intermittent measurements of CO_2 flux above the Pasoh tropical rain forest in Peninsular Malaysia. The estimated net CO_2 uptake rate by the forest was 27.27 μmol CO_2 m^{-2} s^{-1} when the incoming solar radiation was 907 W m^{-2}. Similarly, Yasuda *et al.* (2003) conducted a short-term observation of CO_2 flux above the same tropical forest at Pasoh and measured the CO_2 concentration profiles above and in the canopy. The CO_2 flux ranges between −22.72 to 11.36 μmol CO_2 m^{-2} s^{-1}. The daily values of the net ecosystem CO_2 exchange (NEE) ranged from −2.02 to −2.66 μmol CO_2 m^{-2} per day. The results suggest that the Pasoh tropical forest was a CO_2 sink during that period. The eddy covariance method was also used to observe CO_2 flux for three years over the Pasoh tropical rainforest in Peninsular Malaysia (Kosugi *et al.*, 2008). It was found that the average night time CO_2 flux and NEE were 3.6 and 4.7 μmol m^{-2} s^{-1}, respectively. The flux measurements provide a unique method for evaluating ecosystem models and for understanding the role of terrestrial ecosystems in the global carbon balance (Baldocchi *et al.*, 2001).

Eddy covariance measurements of CO_2 flux between an oil palm plantation ecosystem and the atmosphere provides an accurate approach to evaluating CO_2 uptake by the oil palm. Previously, this technique was used to study carbon assimilation, water use and energy balance at two different oil palm plantations in Peninsular Malaysia. The first study site was at a coastal area planted with nine-year-old oil palms (Henson, 1993).

Under the closed oil palm canopy conditions, it was found that diurnal changes in the CO_2 flux generally coincide closely with changes in radiation. The CO_2 flux (or CO_2 assimilation) was evidently reduced on days when maximum atmosp-heric vapour pressure deficit (VPD) approached or exceeded 2.0 MPa.

The second study site was in an inland area that had a regular dry season of three months or more annually and planted with three-year-old oil palms (Haniff *et al*., 2004; Henson and Haniff, 2005). Clear diurnal trends occurred in the concentration of CO_2 measured above this immature oil palm canopy. There was a regular overnight build-up of CO_2, supposed to represent efflux from the canopy and ground, as a consequence of plant and microbial respiration. This had been facilitated by the lower wind speeds common during the night.

There was a noticeable contrast in gas exchange and surface energy balance between the dry and wet periods or months. Daytime CO_2 flux to the ground (i.e. uptake by sinks) was significantly much higher during the wet, as compared with the dry period. The canopy CO_2 flux during the wet months was -4.31 µmol CO_2 m^{-2} s^{-1} and -0.96 µmol CO_2 m^{-2} s^{-1} during the dry months.

To date, continuous observation of CO_2 flux in oil palm plantations are very few and often only for short periods (Hensen, 1993; Haniff *et al*., 2004; Henson and Haniff, 2005). Therefore, a study to continuously measure CO_2, LE and H fluxes above a mature oil palm plantation on mineral soil was conducted at the MPOB research station in Keratong, Pahang.

Materials and methods

Site description

The study was conducted at the MPOB Research Station in Keratong, Pahang, and Peninsular Malaysia from September 2013 to February 2015. This inland oil palm study site is located at the coordinates: 2°47'20" N, 102°55'58" E (Fig. 1). A total area of 135 ha was planted in 1998, with commercial DxP palms at a planting density of 148 palms ha^{-1}. The soil is sandy clay of Rengam series (typic Paleudults, USDA Classification) and Holyrood series (typic Kandiudults, USDA Classification) with a gently undulating terrain.

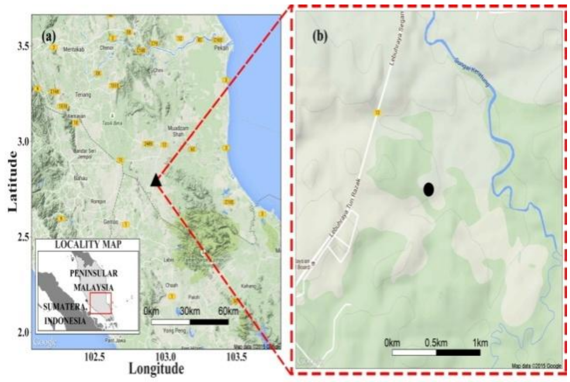

Fig. 1. Site location (marked by filled triangle) in (a) and location of the eddy covariance tower in Keratong (marked by filled circle, 2°47'20.10"N, 102°55' 57.89"E) in (b).

Eddy covariance flux tower setup

A 30 m tall aluminum scaffold tower with guy wires was established within a homogenous oil palm plantation (Fig. 2A). Palms were 15 years old at the start of the measurement period in 2013, with an average canopy height of 16 m. The CO_2 flux was measured at the top of the tower using the open-path infrared gas analyser system (IRGA), LI-7500A (LICOR, Lincoln, USA) and a three-dimensional (3D) sonic anemometer, CSAT-3 (Campbell Scientific Inc., Logan, USA). Both instruments were placed together on an extended 1-m aluminum pole at about 10 m above the oil palm canopy and oriented into the direction of the prevailing wind (i.e. Southwest) (Fig. 2B). Flux data was sampled at a frequency of 10 Hz and the average 1-second data was recorded into 30-minute files. The analyser interface LI-7550 (LICOR, Lincoln, USA) was connected to a Biomet datalogger (Xlite 9210, Sutron Corp., USA) for collecting supplementary meteorological data.

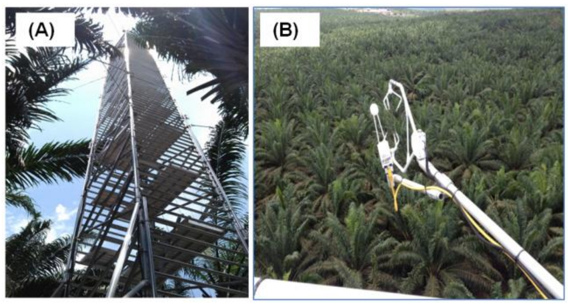

Fig. 2. (A) 30 m Eddy covariance tower installed in an oil palm plantation; (B) CO_2 and H_2O open path IRGA (LI-7500A) and 3D sonic anemometer (CSAT-3) mounted on the tower.

Meteorological data were collected by sensors installed at the top of the tower. Solar radiations were measured by pyranometer energy sensor LI-200SL (LICOR, Lincoln, USA), quantum sensor LI-190 (LICOR, Lincoln, USA) and net radiometer CNR4 (Kipp & Zonen, Netherlands). The quantum sensors were installed at 2 m, 10 m and 30.65 m above the ground for measuring photosynthetic photon flux density (PPFD).

Air temperature and relative humidity were measured by the HMP155G probes (Vaisala, Finland) installed at the same heights as the quantum sensors to acquire profile measurements. Rainfall was measured by a tipping bucket rain gauge TR-525USW (Texas Electronics, USA) installed on top of the tower at 30.65 m. Wind velocity and wind direction were measured by the Wind Monitor 05305 (RM Young, USA) installed on top of the tower.

Three self-calibrating soil heat flux plates HFP01SC (Huk-seflux, Netherlands) were buried 1 cm deep in the soil at 1-, 2- and 4-m distances from a palm close to the tower. Soil temperature sensor LI-7900-180 (LICOR, Lincoln, USA) and moisture probe EC5 (Decagon Devices, USA) were also installed at a soil depth of 5 cm near each location of the soil heat flux plate.

All instruments were powered by 12 VDC 150 Ah deep cycle batteries that were charged by a 220 VAC mains supply. The flux and supplementary data were continuously recorded by the Biomet data logger and downloaded at weekly intervals to a portable computer.

Flux data processing

The 10 Hz raw data from the sonic anemometer and CO_2 open path sensor was analyzed using the Eddy Pro software (version 5.1.1, LICOR, USA) to produce the half-hourly averages of CO_2 and energy fluxes. It also processes all-time series data from the Biomet data logger to produce mean values at the same averaging period of 30 min as the flux data.

The data processing steps carried out started from data despiking, statistical screening, sonic anemometer axis rotating, block averaging, compensating for time lag and water vapour density, estimation of flux footprint and quality flagging.

A block averaging method was applied by averaging 30 min blocks of data to obtain the CO_2 flux (μmol m^{-2} s^{-1}), latent heat flux, LE (W m^{-2}) and sensible heat flux, H (W m^{-2}) values. In addition, quality flags (QC) were calculated for all the flux variables (i.e. CO_2, H and LE fluxes). Data points in the time series were flagged according to results from two tests, i.e., steady state test and the test on developed turbulent conditions (Foken *et al.*, 2004).

The two flags were then combined into a final flag based on the scheme after the Spoleto agreement in 2004 for Carbo Europe-IP (Mauder and Foken, 2004). The data were flagged according to different categories: QC0 denotes the best quality; QC1, good quality; and QC2, bad quality. All QC2 data points were removed from the final analysed dataset. The amount of flux data removed using this quality scheme was 31% for CO_2, 32% for LE and 30% for H. Subsequent data analyses were performed using R version 3.2.1 (R Core Team, 2015). Footprint estimation was done by evaluating the probability of the CO_2 concentrations that contribute to the CO_2 flux at the sensor location were emitted from the surface of the study site. It estimates the relative importance of passive scalar sources (i.e. CO_2 and water vapour fluxes) that add to the flux measurements at a given sensor height.

The estimations could be influenced by sensor height, atmospheric stability, and surface roughness (Kljun *et al.*, 2004). In this study, the footprint estimation method will use a simple footprint parameterization as described by Kljun *et al.* (2004) and Kormann and Meixner (2001).

Energy balance closure

The energy balance closure (EBC) can be used as a quality check of eddy covariance flux measurements. It can determine whether the sensible heat flux (H) and latent heat flux (LE) measured by an eddy covariance system are adequate to explain all of the 'available energy', indicated by net radiation (R_n) and soil heat flux (G), i.e. R_n – G – H – LE = closure error.

Energy balance closure is based on the fundamental theory of the first law of thermodynamics, where the sum of the measured latent heat flux (LE) and sensible heat flux (H) is required to be equal to all other energy sources and sinks (Wilson *et al.* 2002). Closure of the energy balance can be calculated using the following equation:

$$LE + H = R_n - G - S$$

Where, LE is latent heat flux (W m^{-2}), H is sensible heat flux (W m^{-2}), R_n is net radiation (W m^{-2}), G is soil heat flux (W m^{-2}) and S is heat storage (W m^{-2}). LE and H are both measured directly by the eddy covariance system, while R_n and G are measured using slower response sensors recorded by the Biomet data logger. Heat storage in terms of latent heat and sensible heat were calculated from the measurements taken by the air temperature and relative humidity sensors installed at different heights on the tower.

The energy balance closure can be evaluated by determining the slope and intercepts of a regression line calculated by using the ordinary least squares method between the sum of LE and H (i.e. LE + H) and the available energy (i.e. R_n – G – S) for half-hourly data throughout the measurement period. Similarly, it can be checked by the energy balance ratio (EBR), which is the ratio of the summation of (LE + H) and the summation of (R_n – G – S) as described by Wilson *et al.* (2002).

Results and discussion

Meteorological data

Table 1 shows the daily average net radiation, air temperature, relative humidity, soil water content and soil temperature measured at the study site over a period of 18 months (September 2013 to February 2015). The daily average for net radiation was 135.0 W m^{-2} , air temperature 26.6˚C, relative humidity 85.3%, soil water content 0.177 (m^3 water m^{-3} soil) and soil temperature 26.1°C.

Table 1. Average meteorological parameters throughout the 18-month measurement period.

Parameters	Minimum	Maximum	Mean
Net Radiation (W m^{-2})	–72.1	887.7	135.0
Air Temperature at 30.65 m (˚C)	19.5	36.8	26.6
Relative Humidity (%); averaged value of measurement at 2 m, 5 m, 10 m, 15 m and 30.65 m	40.2	99.5	85.3
Volumetric Soil Water Content (m^3 water m^{-3} soil), average of three sensors	0.000	0.487	0.177
Soil Temperature (˚C), average of three sensors	23.0	29.9	26.1

Average monthly rainfall was 90.6 mm with a total rainfall of 1,631 mm for the 18-month period (Fig. 3). There was one month without rain in February 2014 and a maximum monthly rainfall of 274 mm in December 2013.

The wind rose indicates that prevalent wind direction was from the Southwest and Northeast (Fig. 4) with an average wind speed of 1.9 m s^{-1} and maximum wind speed of 6.6 m s^{-1}.

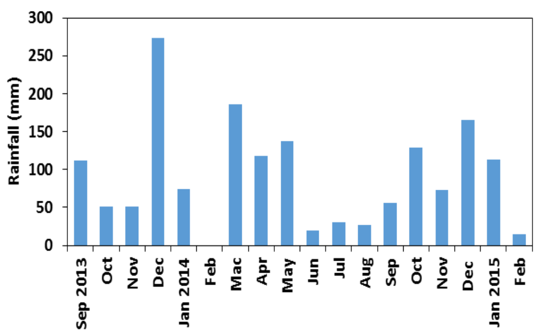

Fig. 3. Monthly rainfall distribution (mm) from September 2013 to February 2015 at the EC study site in Keratong, Pahang, Malaysia.

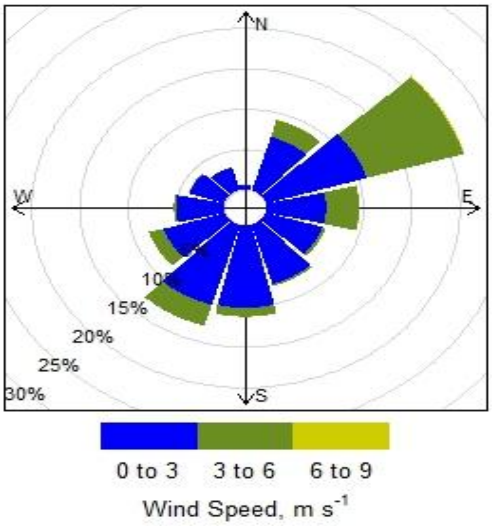

Fig. 4. The wind rose for an 18-month period from September 2013 to February 2015 at the EC study site in Keratong, Pahang.

CO_2 fluxes

The time series of the corrected half-hourly averaged CO_2, LE and H fluxes over the sampling period of 18 months are shown in Fig. 5.

The dataset was not "gap-filled" since this is a process-based study (Foken *et al.*, 2004). The range of fluxes obtained was typical of other similar agricultural surfaces.

LE value was three times greater than H due to the higher moisture content of the oil palm plantation surface and the hot and humid climate of the tropical region.

The CO_2 and energy fluxes above an oil palm plantation were clearly influenced by meteorological trends (Henson and Haniff, 2005; Haniff *et al.*, 2004).

Fig. 6 shows the variation of monthly averaged CO_2 flux over a period of 18 months (September 2013 to February 2015). There was a significant seasonal variation in monthly averaged CO_2 flux values. The monthly averaged CO_2 flux values ranged between -2 to -6 µmol m^{-2} s^{-1}, with an average value of about -3.5 µmol CO_2 m^{-2} s^{-1}. This could be due to the irregular cumulative monthly precipitation and net radiation during the observation period.

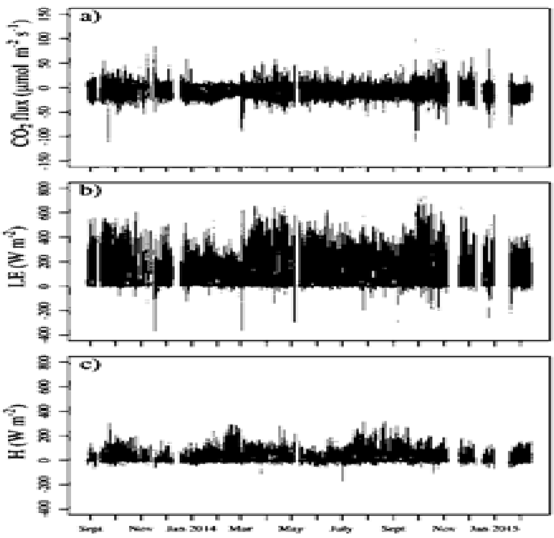

Fig. 5. Time series of 30-min averaged (a) CO_2 flux, (b) LE and (c) H from September 2013 to February 2015 above an oil palm plantation at Keratong, Pahang, Malaysia; gaps in data were caused by periodic instrument maintenance and troubleshooting.

Relatively low average monthly CO_2 flux (or high uptake of CO_2) also coincides with the lowest average LE and rainfall in months February 2013 and 2014.

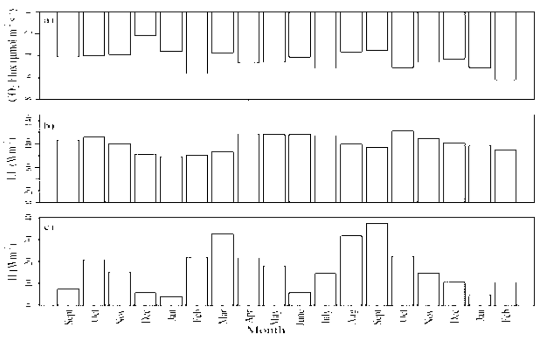

Fig. 6. Monthly means of (a) CO_2 flux and energy fluxes; (b) LE and (c) H above a matured oil palm plantation at Keratong, Pahang, Malaysia from September 2013 to February 2015.

Flux footprint analysis indicates that 90% of CO_2 sources originated from the oil palm plantation surface, ranging from 15 to 20,000 m with an average distance of 2,382 m (Fig. 7). Wind directions were predominantly from the Northeast, South, and Southwest directions, thus even at the longest 90% footprint distance, fluxes still originates from the oil palm plantation surface.

However, it should be noted that footprint locations can be overestimated or biased due to difficulty in modelling the contribution of flux sources under very stable conditions (Aubinet *et al.,* 2012).

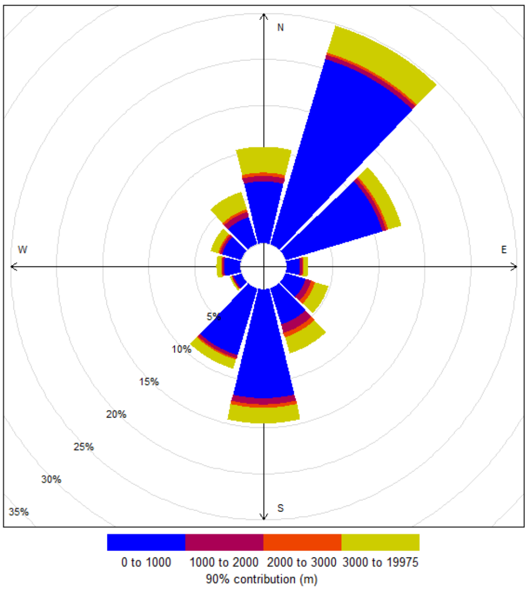

Fig. 7. Flux tower footprint of 90% of the CO_2 flux contribution (represented by X90%) over the 18-month period.

Energy balance closure

Evaluation of the energy balance closure (EBC) was done using the relevant measured and calculated energy flux parameters over the measurement period. Energy balance closure has been used to confirm and validate the estimated fluxes as representative of the actual emissions (e.g. CO_2 and energy fluxes) from the surface under study. Measured energy fluxes (LE + H) were plotted against available energy (R_n – G – S) as shown in Fig. 8. The slope of the regression line was 0.69 with an r^2 value of 0.86 and an intercept at 7.40 W m^{-2}. The Pearson correlation coefficient value (r) was 0.93, which indicates that there was a very strong positive correlation between the measured energy source and sinks with the measured surface fluxes. A complete EBC is indicated by a slope value of 1 and an intercept value of zero. However, the slope value obtained in this study suggests that there was a surplus of available energy compared to the measured energy fluxes. This agrees with the energy imbalance reported by Wilson *et al.* (2002) and Oliphant *et al.* (2004).

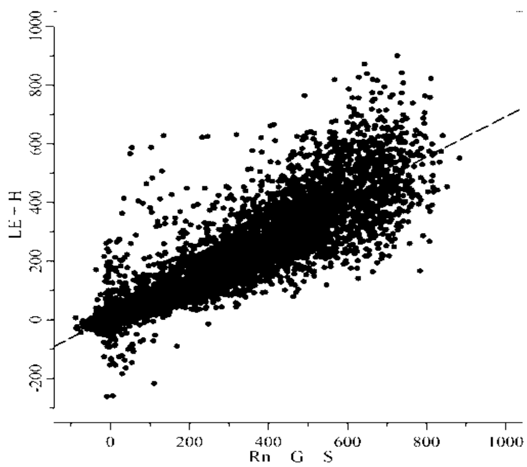

Fig. 8. Sum of latent heat flux and sensible heat flux (LE + H) against sum of net radiation, soil heat flux and heat storage (Rn – G – S); the dashed line indicates the ordinary least squares regression line with slope of 0.69, intercept of 7.17 W m^{-2} and r^2 value of 0.86.

The calculated EBR value was 0.81 for the 18-month period, where ideal closure is met when the EBR has a value of 1. This means that 81% of the available energy was accounted through the surface flux measurements. The EBR value in this study was almost similar to values previously reported. One of the main reasons for the energy imbalance is the underestimation of the surface fluxes relative to available energy by neglecting the advective transport of heat (Foken *et al.*, 2006). For example, during the preliminary data processing, sonic anemometer axis was rotated for tilt correction so that the mean vertical wind speed was zero. As a consequence, the flux measurements during events of vertical advection of heat (i.e. poor turbulent conditions or low friction velocity, u^*) were neglected. These events were commonly observed during night conditions and often cause surface flux measurements to be underestimated relative to the available energy.

Unclosed energy balance could result from instrument errors that occur during physical events such as precipitation. The close mounting between instruments or faulty calibration of the instruments can cause systematic biases in measurements that are difficult to detect (Wilson *et al.*, 2002; Oliphant *et al.*, 2004; Foken *et al.*, 2006).

Furthermore, the presence of neglected energy sinks could cause an overestimation of the available energy and subsequently, an unclosed energy balance. For example, due to the high prod-uctivity of oil palms, the conversion of photosynthetic active radiation (PAR) to chemically stored energy in its biomass can be a significant energy sink. However, the amount of energy absorbed by plants is difficult to measure accurately even when photosynthetic photon flux density (PPFD) is measured. This is because the calculation of the total amount of photosynthetic photons absorbed by plants and the energy contained within the photosynthetic photons are required. Similarly, the efficiency in converting PAR into chemical energy, the amount of energy utilized by the plants, the loss of energy to the surroundings and the amount of energy that is chemically stored within the plant biomass have to be identified.

Conclusion

This paper presents the first assessment of CO_2 flux measured over a mature palm oil plantation from an inland mineral soil area in Peninsular Malaysia, using the eddy covariance method, over a continuous period of 18 months. The monthly averaged CO_2 flux values over the 18-month period show a significant relationship with seasonal variation, such as rainfall and net radiation. The CO_2 flux values ranged between -2 to -6 μmol m^{-2} s^{-1}, with an average value of about -3.5 μmol CO_2 m^{-2} s^{-1}. The negative CO_2 flux value indicates that the mature oil palm ecosystem from an inland mineral soil area in Peninsular Malaysia was a sink for CO_2. Energy balance closure analysis had a slope value of 0.69 between latent and sensible heat fluxes and total incoming energy, and an energy balance ratio of 0.81, which was comparable to other agricultural surfaces. Further long-term research and measurements are needed to collect continuous and consistent eddy covariance datasets, which will help us to understand the oil palm ecosystem dynamics, environment and climate change.

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