CO₂ balance on oil palm agrosystem in Sumatra, Indonesia

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Abstract. The high demand and advantage of palm oil as vegetable oil for food and cosmetic products, and more recently for biofuels have led to the development of area dedicated to this crop, especially in South East Asia, and to some extent in South America and in Africa. In South Asia, where the highest production is recorded in Indonesia, the development of oil palm plantations has often been done at the expense of forests, causing changes in the atmospheric carbon dioxide (CO₂) balance due to the land use changes and agricultural management practices. Several studies have emphasized the importance of quantifying the oil palm contribution to the global carbon budget. A Long-term spatial and temporal measurement during its 25-30 years of life-cycle is needed to provide an accurate CO₂ balance assessment. One of the advanced methods is to directly measure CO₂ fluxes across a relatively large area using a micrometeorological approach based on eddy covariance principles. This method can estimate time series of Net Ecosystem CO₂ Exchange (NEE), Gross Primary Production (GPP) and ecosystem respiration (Reco) which are useful to assess carbon balance over an oil palm plantation. For that purpose, a flux tower of 25 m height, fully equipped with micrometeorological instruments, has been installed in 2011 in the center of a 90-ha plot of mature palms planted in Riau Province (Sumatra, Indonesia). The average oil palm canopies height was 18 m with an annual average air temperature of 26°C, 80% air humidity and a 2,500 mm average annual precipitation. The atmospheric conditions, seasonal variations and air pollutants such as haze, heavily influenced the CO₂ flux measurement. During this 6 year of study, the mature oil palm agro-system acted as a carbon sink that assimilates CO₂ from the atmosphere between 36 to 40 t CO₂ ha⁻¹ y⁻¹ as NEE. This result was the balance between emission assimilation of 209 t CO₂ ha⁻¹ y⁻¹ (GPP) and release back to the atmosphere of between 138 and 173 t CO₂ ha⁻¹ y⁻¹ through respiration (Reco). These variations on the CO₂ fluxes were mainly caused by seasonal patterns with a significant contribution of wet and dry days.

1. Introduction
Southeast Asia is most expanding agriculture and practices in the last decade, the palm oil plantation is the most common plantation found from the main island of Papua New Guinea to Thailand [1]. The expansion of the palm oil plantation and as other crops have been directly and indirectly affecting biodiversity [2], the conversion of the crops and under-story vegetations leading to a global question of further impact to greenhouse gas emission to the environment [3]. Indonesia’s largest mainland Sumatra and Kalimantan involved developing palm oil plantation, the large-scale and intensive agro-system playing a significant role in the global carbon balance. However, the palm oil as the perennial crop with 25 to 30 years lifespan producing huge amount of biomass, some parts are recycled on site as the cultivation practices. The assessment of the net sequestration of the biomass due to palm oil stem growth...
is estimable from the balance of CO₂ uptake from the atmosphere and CO₂ released to the atmosphere, therefore estimating carbon sequestration of oil palm is a critical step to improve management practices.

The eddy covariance techniques along with micrometeorological measurement taking advantage of the improved technology of sonic anemometer and open path gas analyzer capable rapid measurement over 10 times per second enable detecting air parcel with low disturbance [4], monitoring environmental variation that governing vegetative growth and decomposition process over oil palm plantation. Flux measurements above the oil palm canopy using a micrometeorological method allow estimating the CO₂ exchange in the oil palm agro-system continuously through large spatial and temporal scales [5]. The daytime CO₂ exchange mostly is influenced by a photosynthetic variable such as concentration CO₂ in the air and light energy availability [6].

This study aims to obtain the value of the annual CO₂ uptake and emission rate through long-term continuous CO₂ flux measurement, on a representative mature oil palm plantation using the micrometeorological method and the response to the climatic condition.

2. Materials and methods

2.1. Measurement site and parameters

This study located at a homogenous oil palm plantation in Riau-Indonesia, the 25-m tower was constructed in the center of the site, 90 ha of almost flat terrain at 71 asl, planted at 1993 with deli x lane 136 palms per ha. The mean palm height was 18.4 m with mean diameter 55.3 cm at breast high. Under-storey vegetation dominated with Asystasia gangetica S.sp Micrantha, Neprolepis bissearata, and Asplenium longissimum. The soil classified as Typic Dystrudepts with the very deep-water table.

A set of CSAT3 3D Sonic Anemometer (Campbell Sci., USA) and LI-7500 Infra-red CO₂/H₂O gas analyzer (Li-Cor Biosciences, USA) alighted to 315 degrees from the North, heading the direction of the main wind. The measurement logged with CR3000 (Campbell Sci., USA) data logger with 10 Hz frequency. The gas analyzer was calibrated monthly period with High Purity N₂ gas, 402.8 ppm CO₂ tube, and dew point generator. The seamless measurement was started from 8th September 2011.

The meteorological measurement also installed at the same height, global and reflected radiation long and shortwave was measured with CNR-4 net radiometer (Kipp & Zonen, The Netherland). The air temperature (Tₐ), relative humidity (RH) sensed using HMP45 temperature humidity probe (Vaisala, Finland) was installed at 25-m height respectively, the vapor pressure deficit calculated using Tₐ and RH. Total Rainfall (Rₜ) was measured using tipping bucket TE525 (Texas Instrument, USA), Photosynthetic Photon Density (PPFD) was measured using SQ110 quantum sensor (Apogee Instrument, USA) also installed at a 25-m height.

Soil heat flux plate HFP01, soil moisture CS616, and soil temperature TCAV type E thermocouple averaging soil temperature sensor (Campbell Sci., USA) were installed at 5 cm and 10 cm under the soil surface. The setup was feed by 2x125 Watt hour off-grid solar cell and 3x100 Ampere hour valve regulated acid with the 12V parallel configuration as power storages.

2.2. Flux Calculation and post data processing

Eddy Pro version 5.1 software (Li-Cor Biosciences, USA) was used to calculate fluxes from 30-minute averaging data, the process through spike removal, plausible limit test, and skewness and kurtosis test [7]. Air density correction [8], planar fit rotation [9], frequency respond correction [10], bandpass correction factor transfer function calculate after [11]. The CO₂ flux was calculated by the covariance of gas fluxes density (ρₐ), vertical wind (w) and dry mole fraction of CO₂ as fluctuated from the mean value. The fluxes were tested QA/QC steady-state test after Foken [12] and on developed turbulence condition after Foken [13] which give the flag for each calculation result.

The NEE filtering was checked with overlap 4 days windowed 2.5-time moving average for spike removal, the plausible values were checked with assuming night-time fluxes were positive and daytime fluxes were negative. The NEE gap less than 4 continuous missing data were filled using linear interpolation. The larger dataset gap, mean diurnal variation were applied with differentiating daytime (PPFD > 10 µmol m⁻² s⁻¹) and night-time data, look-up table also apply if gap is still emerging, with
multiple input environmental data such as air and soil temperature, humidity, and PPFD to ensure look-up data is equal in environmental condition.

The ecosystem photosynthetic was estimated using light-respond curve with vapor pressure deficit (VPD) limitations after Lasslop [14] Eq. 1 and 2. The nighttime respiration temperature response Lloyd and Taylor model fitted to daytime temperature to calculate daytime ecosystem respiration (R ecosystem) with 4 days windows using Eq. 3 [15].

\[
\text{NEE} = - \frac{\alpha \beta \text{PPFD}}{\alpha \text{PPFD} + \beta} + \gamma \tag{1}
\]

\[
\beta = \frac{\beta_{\exp}(\text{VPD}-\text{VPD}_0)}{\beta_{\exp}(\text{VPD})} \begin{cases} \text{,VPD}>\text{VPD}_0 \\ \text{,VPD}<\text{VPD}_0 \end{cases} \tag{2}
\]

Where \( \alpha \) is the initial slope of the light response curve (\( \mu \text{mol CO}_2 J^{-1} \)), \( \beta \) is the maximum CO\(_2\) uptake rate of the canopy light saturation (\( \mu \text{mol CO}_2 \text{ m}^{-2} \text{s}^{-1} \)), and \( \gamma \) is ecosystem respiration (\( \mu \text{mol CO}_2 \text{ m}^{-2} \text{s}^{-1} \)).

\[
\text{R}_{\text{eco}} = \text{R}_{\text{eco ref}} \cdot \text{Exp} \frac{1}{\text{T}_{\text{ref}}-\text{T}_0} - \frac{1}{\text{T}-\text{T}_0} \tag{3}
\]

Where \( \text{R}_{\text{eco ref}} \) is nighttime respiration base data (\( \mu \text{mol CO}_2 \text{ m}^{-2} \text{s}^{-1} \)), \( \text{T}_{\text{ref}} \) is reference temperature (°C), \( E_0 \) is the temperature sensitivity parameter, \( T_0 \) equal to -46.02°C as in the original model.

The daytime gross primary production estimated as a substitute of \( R_{\text{eco}} \) to NEE base on Desai [16] Eq. 4, the nighttime \( GPP \) assumed to zero.

\[
\text{Gpp} = \text{R}_{\text{eco}} - \text{NEE} \tag{4}
\]

3. Results and discussion
3.1. Environmental variable
The measured NEE values influenced by multiple droughts of the dry period with monthly precipitation lower than 100 mm [17] and wet season with high rain and cloudy days decrease the amount of PPFD reaching crop canopies. El Niño and La Niña variations caused drier and wetter than normal weather, the strong El Niño events at 2014 and 2015 and heavy peat fire in the neighboring region sent thick haze to the site influencing environment condition that drives NEE. The haze series reduce the amount of measured PPFD by 11% might be lowering plant physiological process and reduce CO\(_2\) uptake potential [19].

The air temperature oscillating between 23 °C to 34 °C, the dry season air temperature both maximum (Tmax) and minimum (Tmin) increased by 1.2 °C, the highest air temperature recorded in April 2016 reaching 35 °C and the lowest daily average air temperature recorded at 20 °C, the annual mean air temperature, however, it remains very close to constant. The wettest month recorded in October with 550 mm to November 2012 with 690 mm, follow the series of rain in the second semester of 2013, this phenomenon caused an increasing water content on the mineral soil reaching saturated maximum 50% (figure 1).

3.2. Seasonal variation
Regular wet and dry seasons show different in the daily sum of NEE, the wet season NEE tend to be more negative then shifted to less negative in the dry period. The dry season at the end of June to early of July 2013 follows with a thick haze on February 2014, in 2015 haze event occur from August to September. However, the haze was difficult to be determined using radiation base sensor due to cloud cover determination, haze event was visually observed. During this period the PPFD were declining followed by the less fluctuation daytime air temperature this condition suppressing both \( R_{\text{eco}} \) and NEE.
Figure 1. Seasonal variations of daily photosynthetic photon flux density (PPFD), daily mean air temperature ($T_a$), monthly rain total (Rt), soil water content (SWC) from January 2012 to December 2017. The black line is 15 days moving averages, bold grey shade indicating haze and light grey shades were indicating a dry period.

Figure 2. Seasonal variations of daily sum of NEE, $R_{eco}$, GPP. The black line is 15 days moving averages, bold grey shade indicating haze and light grey shades were indicating a dry period.

3.3. Annual CO$_2$ Flux
The palm oil in mineral soil showed annual NEE is negative ranging from lowest 38 to 40 t CO$_2$ ha$^{-1}$ y$^{-1}$ this result is almost consistent, highest CO$_2$ uptake was in 2017 which is 40 t CO$_2$ ha$^{-1}$ y$^{-1}$ and the lowest was on 2014 due to increasing $R_{eco}$ following the temperature increase. Both $R_{eco}$ and GPP is increasing during the measurement with different rate (table 1), The net carbon uptake of oil palm agro-system in Riau is higher than net carbon uptake by coconut (Cocos nucifera L.) in Vanuatu 17–30 t CO$_2$ ha$^{-1}$ yr$^{-1}$[20].

The mean daily value of NEE was also similar range compared to other measurements on tall canopy vegetation located at the tropical continent. A study from Pasoh Forest Reserve, Malaysia has shown net ecosystem CO$_2$ uptake by the tropical rain was around 8.95 g CO$_2$ m$^{-2}$ day$^{-1}$ [21]. This rate is much
higher than daily values of Amazonian tropical forests, which the NEE values were around 1.98–3.96 g CO₂ m² day⁻¹ [22]. However, those results were obtained from calculation of short-term measurement data that may ignore the temporal variability of NEE.

Table 1. Annual NEE, Reco, GPP during measurement

| Year | NEE tCO₂ ha⁻¹ yr⁻¹ | Reco GPP | Temp oC | RH % | PPFD μmol m⁻² s⁻¹ |
|------|-----------------|---------|--------|------|-----------------|
| Sum  | 138             | 176     | 25.8   | 81.8 | 622.8           |
| 2012 | -38             |         |        |      |                 |
| 2013 | -39             | 146     | 26.0   | 81.9 | 623.5           |
| 2014 | -38             | 173     | 26.3   | 83.5 | 661.8           |
| 2015 | -38             | 142     | 26.8   | 87.6 | 669.7           |
| 2016 | -40             | 164     | 27.4   | 84.6 | 689.8           |
| 2017 | -40             | 163     | 26.8   | 84.0 | 599.5           |

Peat fire and forest fire from neighboring region producing a haze that limiting visibility distance and so limiting solar radiation reaching the canopy, the low soil water content tend to correlate with haze event when soil biomass supports the low-temperature combustion. The peat fire also produces numerous GHG pollutant such as carbon dioxide, carbon monoxide, nitric oxide and nitrogen dioxide [23] and aerosol that less than 10 microns in diameter.

The haze series occur in dry season 2013, El Niño 2014, and strong El Niño 2015 with different thickness and duration, we tested haze series with simple one-way ANOVA before haze versus during haze data the result shows that haze is significantly influent the environmental parameter (P<0.01). The NEE was reduced by 19% and Reco by 13%. The soil water content is coincidently differed to the lower value due to haze apparent mostly caused by long drought.

Table 2. Haze effect on environmental parameter.

| Season | PPFD mmol d⁻¹ | VPD hPa | NEE g C ha⁻¹ d⁻¹ | Reco g C ha⁻¹ d⁻¹ | Temp °C | SWC m³ m⁻³ |
|--------|---------------|---------|-----------------|-----------------|--------|-------------|
| Dry w/o haze | 20.7±0.4         | 8.8     | -44.7±1.7      | 94.0±1.8        | 27.6   | ±0.1        | 13.3±1.5 |
| Dry w/ haze  | 18.3±0.4         | 10.9    | -35.9±1.7      | 81.9±1.9        | 27.2   | ±0.1        | 7.2±1.5  |
| Sig test    | ***             | ***     | ***            | ***             | ***    | ***         |

Note: Significant test using One-way ANOVA

4. Conclusion

The appearance of haze during El Niño significantly influenced agro-system as the aerosol obstructing PPFD to reach the palm canopy. It also affected the temperature and VPD that control the rate of photosynthesis. The prolonged dry season might contribute to low-temperature biomass combustion that causing haze.

The mature oil palm agro-system could be part or importance role of carbon sequester about 40 t CO₂ ha⁻¹ yr⁻¹ or equal to 10.5 t C ha⁻¹ yr⁻¹ as NEE, at the same time the release back to the ecosystem about 160 t CO₂ ha⁻¹ yr⁻¹ equal to 42 t C ha⁻¹ yr⁻¹ as respiration. Total CO₂ assimilate on the oil agro-system were about 200 t CO₂ ha⁻¹ yr⁻¹ as equal to 50 t C ha⁻¹ yr⁻¹. However, this assumption and measurement result using the EC method should be complemented by field measurement to provide substantial supportive data [18].

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