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# VULNERABILITY OF $CO_2$ EXCHANGE IN TROPICAL PEAT ECOSYSTEMS: A CASE STUDY FROM SARAWAK, MALAYSIAN BORNEO

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## SUMMARY

Tower-based eddy covariance measurements of $CO_2$ concentration within and above the canopy were made to quantify the seasonal and inter-annual variations in the net ecosystem $CO_2$ exchange (NEE) of a tropical peat swamp forest in Sarawak, Malaysia (1º27'55"N, 111º9'20"E). NEE was estimated to be 631, 512, 184 and 358 g C $m^{-2}$ $y^{-1}$ for 2011, 2012, 2013 and 2014, i.e. the forest was a net source of $CO_2$ to the atmosphere during all four years of measurement. The inter-annual variation in NEE was largely driven by the variation in GPP of the tropical peat forest, which was strongly influenced by vapor pressure deficit (VPD).

***Keywords:*** *net ecosystem $CO_2$ exchange (NEE), tropical peat swamp forest, eddy covariance*

## INTRODUCTION

Southeast Asia's peat swamp forests are globally salient ecosystems, storing on the order of 77% of the world's tropical peat carbon and 11-14% of the world's peat carbon. Thus, tropical peatlands in Southeast Asia are a vital component of the global terrestrial carbon pool and quantifying the surface-atmosphere exchange of carbon dioxide in tropical peat forests is critical for understanding its sustainability.

The net ecosystem exchange of $CO_2$ (NEE) has rarely been measured in tropical peat forests to date, and existing measurements reveal net carbon losses to the atmosphere. The tropical peat forest ecosystem in Kalimantan, Indonesia was a slight sink of $CO_2$ or close to balance in the first half of the dry season, but emissions increased during beginning of the wet season (Hirano *et al*., 2007). In addition, the annual sum of NEE in an ENSO year was 220 and 289 g C $m^{-2}$ $y^{-1}$ higher than the two following consecutive years, mainly attributed to a reduction in PPFD caused by dense smoke emitted from large fires. The $CO_2$ emissions from a peat swamp forest floor in Kalimantan were highest during the dry season due to the lower water table and thicker oxic peat layer (Jauhiainen *et al.,* 2005). On the other hand, Melling *et al.* (2005) showed substantial variability in soil $CO_2$ efflux from three peat ecosystems of Sarawak in Malaysia; the annual soil $CO_2$ efflux at forest ecosystem differed from oil palm ecosystem by 33% and sago ecosystem by 63%.

Despite the noteworthy characteristic of tropical peat, relatively little is known on how vulnerable this carbon pool is to changes in the soil-vegetation-atmosphere continuum. To shed light on the paucity of this information, an eddy covariance tower erected in a protected peat swamp forest in Sarawak, Malaysia was instrumented to continuously measure the exchange of $CO_2$ between the forest ecosystem and atmosphere. The objective of the present paper is to quantify the seasonal and inter-annual variability of NEE, and to analyze the role and relative importance of environmental drivers in determining this variability.

## MATERIALS AND METHODS

*Site description*

The study was carried out in a tropical peat swamp forest in Maludam National Park in the Betong Division of Sarawak, Malaysia. The Park is the largest protected peat swamp forest in Sarawak, and is bordered on the north by Saribas River and on the south by Lupar River. The canopy has an average height of 25 m and emergent trees can exceed 30 m. A 40 m tower was erected in the southern part of the forest and was instrumented to continuously measure fluxes and meteorological variables (1º27'55"N, 111º9'20"E). Dominant over story vegetation includes *Shorea albida*, *Gonystylus bancanus* and *Stemonurus* spp (Anderson 1972).

*Measurements of fluxes and micrometeorological variables*

NEE was measured continuously using the eddy covariance (*EC*) technique over four years from 2011 to 2014. The EC system consisted of a LI-7500A open-path $CO_2/H_2O$ analyzer (LI-COR Inc., Lincoln, NE, USA) coupled to a CSAT3 three-dimensional sonic anemometer (Campbell Scientific Inc., Logan, UT, USA), which measured the concentrations of $CO_2$ and water vapor, and the three components of wind speed. Signals from these sensors were recorded at a frequency of 10 Hz using a CR3000 Data logger (Campbell Scientific). A LI-820 closed-path $CO_2$ analyzer (LI-COR) was deployed to measure the vertical profile of $CO_2$ concentration at six levels within and above the canopy: 0.5, 1, 3, 11, 21 and 41 m. Net radiation was measured at 41 m using a CNR4 net radiometer (Kipp & Zonen, Delft, The Netherlands). Two LI-190SB quantum sensors (LI-COR) were likewise mounted at 41 m and pointed downward and upward to measure incident and absorbed photosynthetic photon flux densities (PPFD). Air temperature and relative humidity were measured at 11 and 41 m using CS215 temperature and relative humidity probe (Campbell Scientific). The tower was also equipped with a 3-cup anemometer and wind vane (01003-5 R.M. Young Co., Traverse, MI, USA) at 41 m to measure wind speeds and wind directions. Rainfall was collected by a TE525MM tipping-bucket rain gauge (Texas Electronics, Dallas, Texas, USA) 1 m above the ground surface in an open area. Soil temperature was measured with platinum resistance thermocouples at 5 and 10 cm below the ground surface. Volumetric soil water content was measured at a depth of 30 cm using CS616 time domain reflectometry (TDR) (Campbell Scientific, Logan, UT, USA). All meteorological variables were continuously recorded using CR3000 and CR1000 data loggers at a sampling frequency of 5 min and averaged over each 30 min period except groundwater level (*GWL*), which was monitored on a half-hourly basis using a water level logger (DL/N 70 STS Sensor Technik Sirnach AG, Sirmarch, Switzerland).

*Data processing, gap filling and uncertainty analysis*

Post-processing calculations were performed using the Flux Calculator software (Ueyama, 2012), and these include spike removal, double rotation (Wilczak *et al.,* 2001), time-lag corrections, frequency response corrections (Massman, 2000, 2001) and density fluctuation corrections (Webb *et al.,* 1980).

NEE was calculated as the sum of eddy flux ($F_c$) and the storage flux ($F_s$). The $F_s$ was inferred from vertical $CO_2$ concentration (*c*) profiles as (Aubinet *et al.,* 2001):

$$F_s = \frac{P_a}{RT_a}\int_0^h \frac{\partial c(z)}{\partial t}\, dz \tag{1}$$

where $P_a$ is the atmospheric pressure, $R$ is the molar gas constant and $T_a$ the air temperature ($K$).

A threshold of friction velocity ($u$*) was derived to discard underestimated nighttime flux data during stable periods when *PPFD* was less than 5 µmol m$^{-2}$ s$^{-1}$. We used the atmospheric stability threshold after Novick *et al.* (2004), which requires near-neutral atmospheric stability for nighttime data acceptance. The atmospheric stability defined as $\zeta = (z - d)/L$, where $z$ is the measurement height of the sonic anemometer and $L$ is the Obukhov length. In this study, the lower limit of 0.1 m s$^{-1}$ was accepted as the $u$* threshold as determined by a sensitivity analysis of annual NEE to the $u$* threshold.

To fill the gaps in the half-hourly NEE, we used the Mitscherlich model:

$$NEE = -(\beta_M + \gamma_M)\left(1 - \exp\left(\frac{-\alpha_M PPFD}{\beta_M + \gamma_M}\right)\right) + \gamma_M \tag{2}$$

where $\alpha_M$ is the initial slope of the light response curve, $\beta_M$ is the gross ecosystem productivity (GEP) at light saturation, and $\gamma_M$, the intercept parameter at zero light, represents the ecosystem respiration, RE. Parameters were fit using least squares regression for observations using seven-day moving windows. The gross primary productivity (GPP) is the difference between the estimated RE and the observed NEE: GPP = RE + NEE.

We applied the approach of Richardson *et al.* (2006) to estimate the random uncertainty of NEE. Random errors were inferred using paired daily-difference approach in which a measurement pair was selected only if the mean half-hourly PPFD for two successive days differed by less than 75 µmol m$^{-2}$ s$^{-1}$, air temperature differed by less than 3°C, and wind speed differed by less than 1 m s$^{-1}$. Random uncertainty was propagated through the gap filling routines by perturbing the input flux observations with a random value drawn from a normal distribution multiplied by the afore-calculated random errors. This procedure was iterated 100 times for each day, and 100 gap filling models were fit for each day using least squares regressions. Missing NEE data were filled using the mean of the 100 models.

## RESULTS AND DISCUSSIONS

The annual pattern of rainfall in Sarawak is characterized by two seasons: the dry season typically lasts from April to September and the wet season lasts from October to March (Figure 1). In brief, 2013 and 2014 were warmer and drier than 2011 and 2012. The mean annual air temperature above the canopy increased from 26.6 °C in 2011 to 27.09 °C in 2014. The annual cumulative PPFD was 4.7% greater in 2013 (6152 MJ $m^{-2}$ $y^{-1}$) than in 2011 (5877 MJ $m^{-2}$ $y^{-1}$), whereas comparable cumulative PPFD was observed in 2012 and 2014 (6015 and 6017 MJ $m^{-2}$ $y^{-1}$). The mean annual water table depth was lowest in 2014 (-11.3 cm), followed by -5.3 cm in 2011, -2.5 cm in 2012 and above ground at 3.2 cm in 2013.

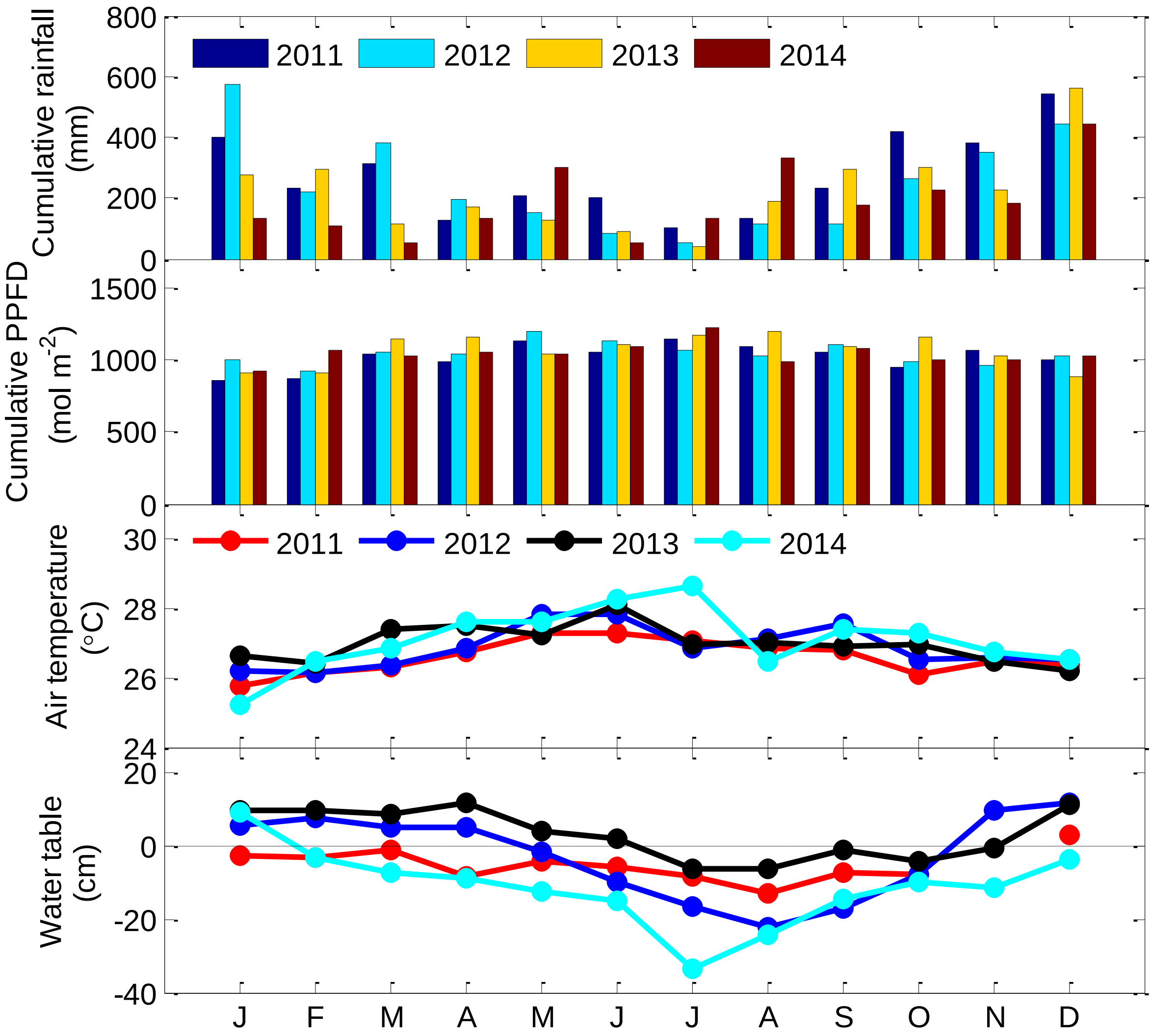


Figure 1: Seasonal variations in monthly sums of rainfall, monthly sums of photosynthetic photon flux densities (PPFD), monthly means of air temperature and water table from 2011 to 2014.

Rainfall was highest in 2011 (3890 mm) and NEE was negative (indicating a carbon sink) during the wet season until mid-June, after which the increasing vapor pressure deficit (VPD) and declining water table depth coincided with a large C loss event of >500 g C $m^{-2}$ over a three month period (Figure 2). Meanwhile, the monthly sum of PPFD in May increased by 14% compared to April 2011; the mean air temperature and daytime VPD increased respectively by 0.6°C and 0.15 kPa from April to May. Notwithstanding higher PPFD in the dry season, higher temperature induced an increase in VPD, which could limit GPP through stomatal closure. These environmental conditions together led to a lower net $CO_2$ uptake.

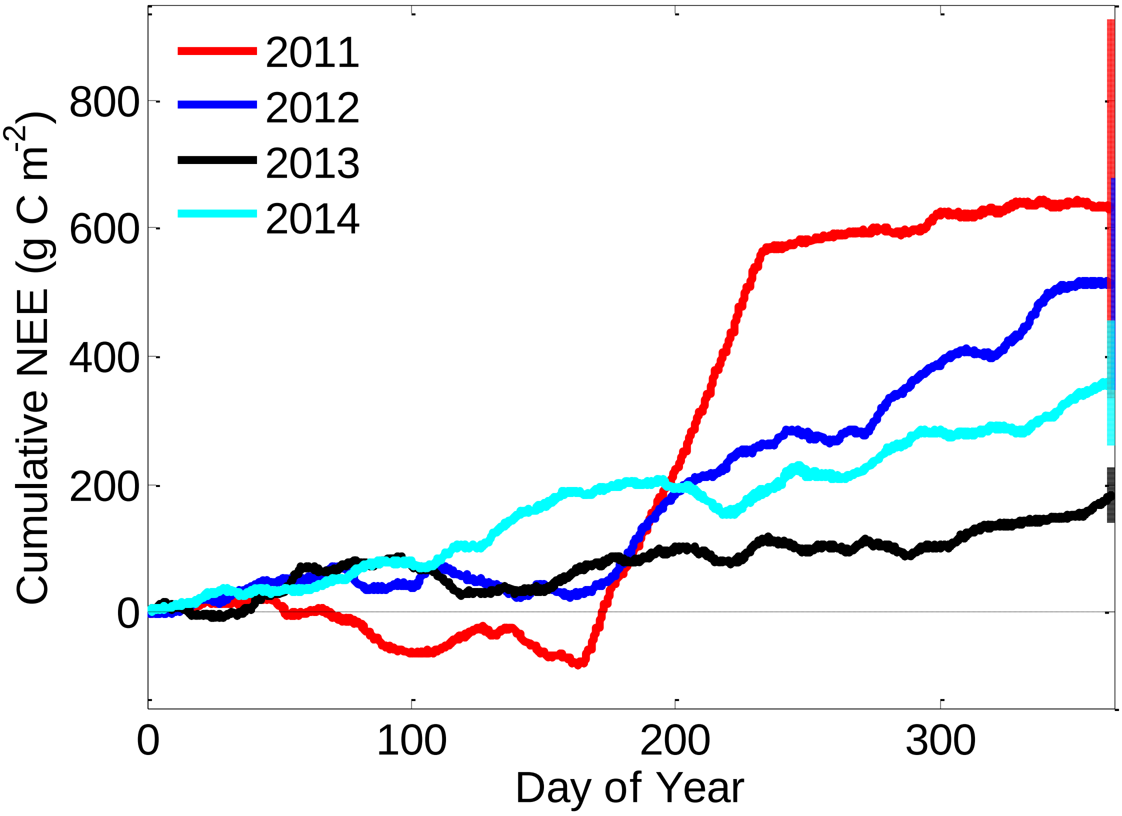


Figure 2: The cumulative sum of NEE for 2011, 2012, 2013 and 2014. Uncertainty bars represent one standard deviation from the sum of one-year study period.

Rainfall in 2012 and 2013 was close to the long-term average (2798 mm) and the cumulative NEE in these two years were similar until early July. The rates of C loss then increased and coincided with decrease in radiation, PPFD, and water table depth and increase in wind speed, noting that the mean daytime VPD increased from 0.66 kPa in April to 0.9 kPa and 0.98 kPa in May and June, respectively. This further suggests that VPD demonstrated lagged effects on $CO_2$ uptake and the impacts of water stress on GPP that warrant further investigation. 2014 experienced the lowest rainfall (2272 mm) but rates of C loss similar to the average of the other three years.

Table 1: Annual NEE, RE and GPP for 4 years between 2011 and 2014

| Year | NEE ($g\ C\ m^{-2}\ y^{-1}$) | RE ($g\ C\ m^{-2}\ y^{-1}$) | GPP ($g\ C\ m^{-2}\ y^{-1}$) |
|---|---|---|---|
| 2011 | 631 | 2550 | 1919 |
| 2012 | 512 | 2789 | 2277 |
| 2013 | 184 | 2684 | 2500 |
| 2014 | 358 | 3216 | 2858 |
| Mean | 421 ± 194 | 2810 ± 288 | 2389 ± 394 |

The cumulative sum of NEE during the study period is shown in Table 1. Annual NEE varied from 184 g C $m^{-2}$ $y^{-1}$ to 631 g C $m^{-2}$ $y^{-1}$, with a four-year average of 421 ± 194 g C $m^{-2}$ $y^{-1}$. Annual GPP increased linearly from 2550 g C $m^{-2}$ $y^{-1}$ in 2011 to 3216 g C $m^{-2}$ $y^{-1}$ in 2014, whereas inter-annual RE variation was not evident except for annual RE in 2014 which increased with annual GPP. At the annual timescale, GPP was clearly more important in modulating inter-annual variance in NEE particularly during the dry season. These findings demonstrate the critical role of plant-water relations, even in the tropical peat forests of Borneo which are amongst the wettest in the world, for regulating the exchange of carbon dioxide between the land surface and the atmosphere.

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