LAND-ATMOSHPERE EXCHANGE OF CARBON AND ENERGY

AT A TROPICAL PEAT SWAMP FOREST IN

SARAWAK, MALAYSIA

by

Angela Tang Che Ing

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

Doctor of Philosophy

in

Ecology and Environmental Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

August 2017

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

TABLE OF CONTENTS CONTINUED

TABLE OF CONTENTS CONTINUED

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES CONTINUED

LIST OF FIGURES CONTINUED

ABSTRACT

Tropical peatlands comprise 11% of the global peat area of ca. 400 Mha and are estimated to store about 89 Gt of carbon (C). However, considerable uncertainties remain about their present role in global C cycle as interannual ecosystem-scale measurements of undisturbed tropical peat forests have not been measured to date. Hence, an eddy covariance tower was instrumented in a tropical peat forest in Sarawak, Malaysia over four years from 2011 to 2014. We found that the forest was a net source of CO_2 to the atmosphere during every year of measurement. The inter-annual variation in net ecosystem CO_2 exchange (NEE) was largely modulated by the variation in gross primary production (GPP), which was jointly controlled by vapor pressure deficit (VPD) and leaf area index (LAI) in addition to photosynthetically active photon flux density (PPFD). Greater reduction of GPP in 2011 and 2012, are likely attributed to the relative low atmospheric transmission due to massive peat fires in Indonesia.

Similarly, no analysis to our knowledge has measured whole-ecosystem methane (CH_4) flux from a tropical peat forested wetland to date despite their importance to global CH_4 budget. The two-month average of C-CH_4 flux measurements, on the order of 0.024 g C-CH_4 m^{-2} d^{-1}, suggests that tropical peat forests are not likely to be disproportionally important to global CH_4 flux. Results demonstrate a limited ability for simple models to capture the variability in the diurnal pattern of CH_4 efflux, but also consistent responses to soil moisture, water table height, and precipitation over daily to weekly time scales.

The sensible heat flux (H) and latent heat flux (LE) and their ratio (the Bowen ratio, Bo) at the study ecosystem were relatively invariant compared to other tropical rainforests. The average daily LE across the calendar year tended to be higher at MY-MLM (11 MJ m^{-2} day^{-1}) than most other tropical rainforest ecosystems in the FLUXNET2015 database. Results demonstrate important differences in the seasonal patterns in water and energy exchange in tropical rainforest ecosystems that need to be captured by models to understand how ongoing changes in tropical rainforest extent impact the global climate system.

CHAPTER ONE

INTRODUCTION

Tropical Peatlands and Their Global Importance

Peatlands cover less than three percent of the global land surface and contain around one-third of all terrestrial organic carbon (C) (Gorham, 1991; Turunen et al., 2002), making them the most significant C store of all terrestrial ecosystems. With their thick underlying peat deposits and high vegetation biomass, tropical peatlands may store more than 70 Gt C, or 20% of the global peat pool (Maltby and Immirzi, 1993), but in a total area of only 33-49 Mha (Immirzi et al., 1992). The extent to which tropical peat ecosystems function as sinks or sources of C remains obscure due to the paucity of empirical measurements, making it unclear how the C cycle in tropical peat forests responds to meteorological drivers that are rapidly changing in a changing climate.

Here, I study the surface-atmosphere exchange of carbon dioxide (CO_2) and methand (CH_4), as well as associated fluxes of water and energy, in a tropical peat rainforest in Sarawak, Malaysian Borneo. In Malaysia, peatlands constitute about 2.4 Mha, of which Sarawak has the largest peat areas with 1.6 Mha (Maltby and Immirzi, 1993), all within the most extensive area of tropical peatlands in Southeast Asia. Results are compared against ecosystem-scale measurements of other tropical rainforests to place the unique tropical peat rainforest study ecosystem in a global context.

Research Goals

This study analyses the present status of C, water, and energy exchange between the land surface and the atmosphere and the mechanisms driving these processes in a tropical peat swamp forest, Sarawak, Malaysian Borneo.

The study consists of four years measurements of eddy covariance CO_2 fluxes, energy fluxes and two months CH_4 fluxes and research was divided into three projects, each of them with specific aims:

1) The role of biophysical drivers in controlling the variability of net ecosystem CO_2 exchange in a tropical peat forest in Sarawak, Malaysian Borneo (Chapter 2)

   a) Determine the CO_2 source/sink status of the ecosystem.

   b) Describe the seasonal and interannual variability in NEE and its components (GPP and RE).

   c) Investigate the role of environmental factors in controlling the CO_2 exchange.

2) The exchange of water and energy between a tropical peat forest and the atmosphere: Seasonal trends and comparison against global tropical rainforests (Chapter 3)

   a) Describe the seasonal variability in sensible heat flux (*H*) and latent heat flux (*LE*).

   b) Quantify the evapotranspiration (ET) and energy balance closure between dry and wet season.

   c) Compare the seasonal variability of surface-atmosphere water and energy exchange across globally-distributed tropical rainforest ecosystems.

3) Eddy covariance measurements of methane flux at a tropical peat forest in Sarawak, Malaysian Borneo (Chapter 4)

   a) Determine the CH_4 source/sink status of the ecosystem.

   b) Investigate the mechanisms that control the CH_4 efflux at the ecosystem scale.

   c) Discuss CH_4 flux measurements in the context of similar measurements from other global ecosystems.

   Results are synthesized in a brief conclusions section that describes important future steps to be undertaken to further improve our understanding of the biogeochemistry and hydrology of tropical peat forests.

4

References

Gorham, E., 1991. Northern Peatlands : Role in the Carbon Cycle and Probable Responses to Climatic Warming. Ecol. Appl. 1, 182–195.

Immirzi, C.P., Maltby, E., Clymo, R.S., 1992. The global status of peatlands and their role in carbon cycling. A Report for Friends of the Earth by the Wetland Ecosystems Research Group, Department of Geography, University of Exeter. Friends of the Earth, London.

Maltby, E., Immirzi, P., 1993. Carbon Dynamics in Peatlands and other Wetland Soils Regional and Global Perspectives. Chemosphere 27, 999–1023.

Turunen, J., Tomppo, E., Tolonen, K., Reinikainen, A., 2002. Estimating carbon accumulation rates of undrained mires in Finland – application to boreal and subarctic regions.

CHAPTER TWO

THE ROLE OF BIOPHYSICAL DRIVERS IN CONTROLLING THE VARIABILITY OF NET ECOSYSTEM CO_2 EXCHANGE IN A TROPICAL PEAT FOREST IN SARAWAK, MALAYSIAN BORNEO

<u>Contribution of Author and Co-Authors</u>

Manuscript in Chapter 2

Author: Angela C. I. Tang

Contributions: Performed data processing and data analyses, generated figures and wrote manuscript in preparation for submission.

Co-Author: Paul C. Stoy

Contributions: Obtained funding, provided advice on data analyses, discussed results and edited the manuscript at all stages.

Co-Author: Kevin K. Musin

Contributions: Aided in collecting data and maintaining tower.

Co-Author: Edward B. Aeries

Contributions: Aided in collecting data and maintaining tower.

Co-Author: Joseph Wenceslaus

Contributions: Aided in collecting data and maintaining tower.

Co-Author: Mariko Shimizu

Contributions: Assisted with setting up tower instruments.

Co-Author: Ryuichi Hirata

Contributions: Assisted with setting up tower instruments, provided technical assistance and comments on manuscript.

Co-Author: Lulie Melling

Contributions: Obtained project funding and provided comments on manuscript.

7

Manuscript Information Page

Angela C. I. Tang, Paul C. Stoy, Kevin K. Musin, Edward B. Aeries, Joseph Wenceslaus, Mariko Shimizu, Ryuichi Hirata and Lulie Melling

Global Change Biology

Status of Manuscript:
__x_ Prepared for submission to a peer-reviewed journal
____ Officially submitted to a peer-review journal
____ Accepted by a peer-reviewed journal
____ Published in a peer-reviewed journal

Published by Wiley-Blackwell

THE ROLE OF BIOPHYSICAL DRIVERS IN CONTROLLING THE VARIABILITY OF NET ECOSYSTEM CO2 EXCHANGE IN A TROPICAL PEAT FOREST IN SARAWAK, MALAYSIAN BORNEO

Angela C. I. Tang[1,2], Paul C. Stoy[1], Kevin K. Musin[2], Edward B. Aeries[2], Joseph Wenceslaus[2], Mariko Shimizu[3], Ryuichi Hirata[4] and Lulie Melling[2]

1. Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, MT 59715, USA
2. Sarawak Tropical Peat Research Institute, Lot 6035, Kuching-Kota Samarahan Expressway, 94300 Kota Samarahan, Sarawak, Malaysia
3. Civil Engineering Research Institute for Cold Region, Sapporo 062-8602, Japan
4. Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba 305-8506, Japan

Abstract

We used the eddy covariance technique to measure the net exchange of CO_2 (NEE) between the atmosphere and an undisturbed tropical peat forest in Sarawak, Malaysia over four years from 2011 to 2014. The annual cumulative NEE was 632 ± 297, 509 ± 164, 183 ± 44, and 356 ± 98 g C m^{-2} y^{-1} for 2011, 2012, 2013 and 2014; that is, the forest was a net source of CO_2 to the atmosphere during every year of measurement, similar to a hydrologically disturbed tropical peat forest in central Kalimantan, Indonesian Borneo. Rates of NEE declined (i.e. the ecosystem became a sink for CO_2) during the rainy season relative to the dry season for 2011, but the converse held for the subsequent three years. The inter-annual variation in NEE was largely modulated by the variation in gross primary production (GPP), which was jointly controlled by vapor pressure deficit (VPD) and leaf area index (LAI) in addition to photosynthetically active photon flux density (PPFD). Temporal changes in ecosystem respiration (RE) were closely related to water table depth. Results suggest that potential future increases in VPD

may result in additional net CO_2 losses from this undisturbed tropical peat swamp forest

in the absence of plant acclimation to such changes in atmospheric dryness.

Introduction

Tropical peatlands are distributed over 33-49 Mha and comprise 9-12% of the

global peatland area (Maltby and Immirzi, 1993). Of this, about 60% of tropical peatlands

occur in Southeast Asia (25 Mha), largely in Indonesia (22 Mha) and Malaysia (2.5 Mha)

(Maltby and Immirzi, 1993). With their thick underlying peat deposits and high

vegetation biomass, tropical peatlands are among the most efficient terrestrial ecosystem

in sequestering carbon as they account for more than 70 Gt C, or 20% of the global peat

pool (Maltby and Immirzi, 1993). However, there remain considerable uncertainties

about their present role in global carbon cycle as interannual ecosystem-scale

measurements of undisturbed tropical peat forests have not been measured to date.

Previous studies in Southeast Asian peat forests have quantified the soil CO_2 flux

rates (Inubushi et al., 2003; Jauhiainen et al., 2005; Melling et al., 2005) with estimated

emissions of 952 to 2100 g C m^{-2} y^{-1}. Inubushi et al. (2003) and Melling et al. (2005)

found no distinct seasonal CO_2 variation while higher emission was observed during the

dry season in Jauhiainen et al. (2005). Despite their importance in global carbon cycle,

few data exist on the net CO_2 exchange at the tropical peat ecosystem scale on a

continuous basis. There are to our knowledge only five tropical peatland sites with

published NEE measurements. Among these five sites, three sites were located in Central

Kalimantan, Indonesia with altered hydrology including clearcutting (Hirano et al.,

2012), whereas the other two were the primary and secondary forest in Thailand that

employed a concentration gradient approach for CO_2 flux measurement (Suzuki et al., 1999). The net ecosystem CO_2 exchange (NEE) in tropical peatlands were found to vary substantially at seasonal and interannual time scales. The four-year mean annual NEE for a relatively intact peat forest with little drainage in Indonesia - including two El Niño years - was 174 ± 203 g C m^{-2} yr^{-1}, varying year-to-year from a carbon sink (-27 g C m^{-2} yr^{-1}) to a carbon source (443 g C m^{-2} yr^{-1}) (Hirano et al., 2012). Three years of NEE measurements at a peat forest disturbed by drainage exhibited seasonal variation, in which the forest was a small CO_2 sink or approximately C neutral in the early dry season, and emitted most CO_2 in late dry season or early rainy season (Hirano et al., 2007). In contrast, a large amount of C was accumulated over one year in both primary (-532 g C m^{-2} yr^{-1}) and secondary peat swamp forest (-522 g C m^{-2} yr^{-1}) in Thailand (Suzuki et al., 1999). The primary forest absorbed more carbon in the dry season than the rainy season whereas the converse was for the secondary forest (Suzuki et al., 1999).

Whether a tropical peat forest is a net sink or source of CO_2 depends on its response to climatic variables. Hirano et al. (2012) found that the CO_2 balance of three peat ecosystems was principally controlled by groundwater level (GWL), in which the NEE increased (i.e. the ecosystems became a stronger C source or weaker C sink) when GWL decreased on an annual basis, and suggesting that a lowering of 0.1 m of GWL increased the CO_2 efflux rates by 79 to 238 g C m^{-2} yr^{-1}. These observations contrast ecosystem-scale CO_2 flux observations from tropical ecosystems in the Amazon in which the seasonality (Malhi et al., 1998; Vourlitis et al., 2001; Goulden et al., 2004) and interannual variability (Hutyra et al., 2007) are more strongly related to rainfall.

In addition to CO_2 flux, auxiliary measurements of environment parameters provide insights into controls on NEE. A functional and mechanistic understanding of the response of ecosystem-scale CO_2 flux to hydrological and meteorological will improve models used to estimate the regional and global C budgets, and for predictions of potential responses of terrestrial ecosystem carbon cycling to global climate change (Pingintha et al., 2010) . Such results can also contribute to global CO_2 mitigation efforts. To our knowledge, this is the first multi-year dataset of eddy covariance measurement in an undrained tropical peat swamp forest. Hence, the aim of this paper is to improve the state of current knowledge of tropical peat forests with respect to its CO_2 sink or source strength, seasonal and interannual variability in NEE and its components (gross primary productivity and ecosystem respiration) and role of environmental factors in controlling the CO_2 exchange.

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. Maludam is the largest protected peat swamp forest in Sarawak, and is bordered on the north by the Saribas River and on the south by the Lupar River (Figure 2.1). The forest canopy in the vicinity of the eddy covariance tower has an average height of 25 m with emergent trees that exceed 30 m. Dominant overstory vegetation includes *Shorea albida*, *Gonystylus bancanus* and *Stemonurus* spp (Anderson, 1972). A 40 m eddy covariance tower was erected in the forest and was instrumented to continuously measure fluxes and meteorological variables

(1º27'55''N, 111º9'20''E) beginning in 2011. The terrain is relatively flat with an elevation

of 25 m above mean sea level. The peat thickness is *ca*. 8 m in the vicinity of the tower.

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), 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 Datalogger (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 at 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 incoming and

outgoing photosynthetic photon flux densities (PPFD). Air temperature (T_a) and relative

humidity were measured at 11 and 41 m using CS215 temperature and relative humidity

probes (Campbell Scientific). The tower was also equipped with a three-cup anemometer

and wind vane (01003-5 R.M. Young Co., Traverse, MI, USA) at 41 m to measure wind

speeds and wind directions in addition to the sonic anemometer. Rainfall was measured

by a TE525MM tipping-bucket rain gauge (Texas Electronics, Dallas, Texas, USA) 1 m

above the ground surface in an open area located *ca*. 5 m from the tower. 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). All meteorological variables were continuously recorded using CR3000 and CR1000 dataloggers 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 Flux Calculator (Ueyama et al., 2012), and included spike removal, double rotation (Wilczak et al., 2001), time-lag corrections, frequency response corrections (Massman, 2001; W. J. Massman, 2000) and density fluctuation corrections (Webb et al., 1980) to calculate the eddy covariance flux, F_c.

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

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

where P_a, R and T_a are respectively the ambient pressure (N m^{-2}), molar constant (N m mol^{-1} K^{-1}) and air temperature (K); h, $c(z)$, t and z represent the measurement height of F_c (m), CO_2 mixing ratio, time (s) and vertical distance from ground surface (m).

We used the atmospheric stability threshold after Novick et al. (2004), which requires near-neutral atmospheric stability for nighttime ($PPFD < 5$ μmol m^{-2} s^{-1}) data

acceptance. Atmospheric stability is defined as $\zeta = (z − d)/L$, where z is the measurement height of the sonic anemometer and L is the Obukhov length. In addition to the atmospheric stability filter, a $u*$ threshold value of 0.1 m s^{-1} was included to ensure that observations with insufficient turbulence were excluded from the analysis.

To fill the gaps in the half-hourly NEE, we used the Mitscherlich model (e.g. Aubinet et al., 2001; Reichstein et al., 2012):

$$NEE = -\left(b_M + g_M\right)\left(1 - \exp\left(\frac{-a_M PPFD}{b_M + g_M}\right)\right) + g_M \tag{2}$$

where α_M is the initial slope of the light response curve, β_M is the gross ecosystem productivity (GEP) at light saturation, and γ_M, the intercept parameter at $PPFD = 0$ µmol m^{-2} s^{-1}, represents RE. Parameters were fit using least squares regression for observations using seven-day moving windows. GPP was calculated as the difference between the estimated RE and the observed NEE: GPP = RE + NEE using the meteorological convention with negative values indicating ecosystem CO_2 uptake.

We applied the approach of Richardson et al. (2006) (see also Hollinger & Richardson, 2005) to estimate the random uncertainty of NEE. Random errors were inferred using the 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}. Sensitivity analyses demonstrated that there was little reason to alter the original values determined by Richardson et al. (2006) (data not shown). 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

previously calculated random errors following the recommendations of Motulsky &

Ransnas (1987). This procedure was iterated 100 times for each day such that 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 and uncertainty was estimated as the

monthly or annual sums of NEE, GPP, or RE multiplied by the percent random

uncertainty following Stoy et al. (2006) and Vick et al., (2016).

Diffuse Radiation

We estimated the diffuse radiation fraction K_d using the clearness index or

atmospheric transmissivity K_t, which is defined as the ratio of global solar radiation R_g to

the extra-terrestrial solar radiation R_o following Spitters et al., (1986).

Leaf area index (LAI)

Monthly leaf area index (LAI) was measured in situ using a LI-2200 plant canopy

analyzer (LI-COR) starting March 2013. Thus, we also estimated good quality MODIS

LAI values from 2011 to 2014. Simple linear interpolation was applied to fill gaps in

monthly MODIS LAI and monthly measured LAI.

Results

Seasonal Patterns in Climatic Variables

Monthly averages of meteorological variables are shown in Figure 2.2. The

annual pattern of rainfall in Sarawak is characterized by a dry season, which typically

lasts from April to September, and a rainy season, which typically lasts from October to

March, with interannual variability during the measurement period as described in Figure 2.2a. Annual rainfall was 3290, 2941, 2688 and 2272 mm in 2011, 2012, 2013 and 2014, respectively. Rainfall during the October – March wet season accounted for 69%, 76%, 66% and 50% of the annual sum, respectively in 2011, 2012, 2013 and 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}, respectively). T_a increased sequentially over the four year study period with annual means of 26.6, 26.9, 27 and 27.1 °C in 2011, 2012, 2013 and 2014, respectively. May was the warmest month during 2011 and 2012, whereas the maximum monthly air temperature was recorded during June in 2013 and July in 2014. Daytime vapor pressure deficit (VPD) increased during the dry season and reached a maximum daytime average of 0.85, 0.98, 0.89 and 0.99 kPa respectively in July 2011, June 2012, June 2013, and July 2014 (Figure 2.2d). The observed soil moisture (Figure 2.2e) and water table depth (Figure 2.2f) exhibited substantial seasonal and interannual variations during the entire study period.

Seasonal and Annual Patterns in Surface-Atmosphere Carbon Dioxide Exchange

The annual course of cumulative NEE (Figure 2.3) exhibits different seasonality in ecosystem fluxes during the four-year observation period. In 2011, approximately 76 ± 31 g m^{-2} of carbon was taken up during the rainy season during the early portion of the calendar year and the early dry season before mid-June. In other words, the forest was a net carbon sink from January until the middle of the dry season in mid-June, after which the increasing RE (Figure 2.4) and declining GPP (Figure 2.5) coincided with a large

carbon loss event of > 600 g m^{-2} over a two-month period, as indicated with the I in Figure 2.3. GPP increased drastically from 50 ± 20 g C m^{-2} in August to 222 ± 64 g C m^{-2} in September 2011 (Figure 2.6), almost enough to offset the respiration rates, leading to a small carbon source for the month.

GPP remained high for the next rainy season and the early dry season of 2012, but began to decline in the middle of dry season, and the forest lost 241 ± 90 g C m^{-2} to the atmosphere in June, July, and August 2012. The seasonal trends of NEE in 2011 and 2012 were similar, except for the last quarter of 2012, where the respiration increased by 36% *versus* 2011, which resulted in large carbon loss despite an increased GPP during the October-December rainy season.

Contrary to 2011 and 2012, canopy carbon uptake in 2013 increased substantially during the middle of the dry season, totaling 751 ± 220 g C m^{-2} from June to August, whereas only 144 ± 25 g C m^{-2} and 391 ± 113 g C m^{-2} accumulated during this period in 2011 and 2012, respectively; consequently, the forest released less carbon during the dry season in 2013. A small sink of 29 ± 9 g C m^{-2} was observed in July of 2014; NEE in 2014 had a similar seasonal pattern but was less variable than that of 2013.

Inter-annual RE variation was not significantly different from 2011 to 2013 and took values of 2559 ± 745, 2772 ± 758, and 2637 ± 775 g C m^{-2} y^{-1}, respectively, but annual RE increased in 2014 to 3199 ± 937 g C m^{-2} y^{-1}, concomitant with an increase in annual GPP (Figs. 2.4 and 2.5). In 2012, RE was significantly greater during the rainy season than during the dry season ($p = 0.029$), but no statistically significant difference was found between wet and dry seasons during 2011, 2013 and 2014.

Annual GPP increased from year to year and took values of 1931 ± 483, 2263 ± 602, 2455 ± 735 and 2843 ± 842 g C m^{-2} y^{-1} for 2011, 2012, 2013 and 2014, respectively. GPP was greater during the rainy season of 2011 and 2012, but was slightly greater in the dry season for 2013 and 2014, which accounted for 35%, 41%, 55% and 53% of the annual sum for 2011-2014, respectively. GPP occurred at similar rates during the early part of each year but began to differ during the dry season (Figure 2.5). GPP peaked during the rainy season in 2011 (November) and 2012 (December), but during the dry season in 2013 (July) and 2014 (August). Minimum monthly GPP was observed during the middle of the dry season in July during 2011 and 2012, but during the rainy season in February and January during 2013 and 2014, respectively.

Seasonal and Interannual Differences in Canopy Characteristics

Figure 2.7 shows the seasonal pattern in albedo measured from 10:00 to 14:00 hours when incoming shortwave radiation was greater than 700 W m^{-2}. Albedo varied substantially between seasons with increases in the dry season (toward 0.09) and decreases in the wet season (often less than 0.08).

Effects of VPD on NEE

GPP was limited by higher VPD (~> 1 kPa), which caused an increase in NEE (Figure 2.8); noting that Figure 2.8 does not include a PPFD threshold such that it includes periods in which VPD is not limiting GPP. NEE generally decreased with PPFD at all levels of VPD (< 0.25 kPa, 0.25 - 0.5 kPa, 0.5 – 1 kPa, and > 1 kPa), demonstrating the critical role of light availability on GPP in this tropical ecosystem; on the other hand, NEE tended to decrease further under low VPD conditions regardless of PPFD (Figure

2.9), demonstrating its sensitivity to atmospheric demand for water. In 2011, under high atmospheric dryness with VPD greater than 1 kPa, NEE decreased linearly (i.e. ecosystem carbon uptake increased) as PPFD increased, until approximately 1100 µmol m^{-2} s^{-1}, where NEE started to increase from -5.5 µmol m^{-2} s^{-1} to -2.9 µmol m^{-2} s^{-1} at PPFD of 1580 µmol m^{-2} s^{-1}. A similar but smaller effect on NEE was also observed in 2012 when VPD was greater than 1 kPa. A mean positive slope of 0.0025 was observed for the NEE-VPD relationship at high PPFD of 1100-1800 µmol m^{-2} s^{-1}, whereas -0.0049, -0.008 and -0.0051 for 2012, 2013 and 2014, respectively.

Clearness Index and Diffuse Radiation Fraction

Using daytime data between 10 and 14 h, the three month (June-August) average for clearness index (K_t) in 2011 (0.571) were found to be significantly lower compared to 2013 (0.601) and 2014 (0.579) but no significant difference was found between 2011 and 2012 ($p>0.05$), while an inverse pattern depicted for the diffuse fraction (K_d) with the highest value in 2011 (0.520), followed by 2012 (0.509), 2014 (0.502) and 2013 (0.462) (Figure 11). On an average annual basis, K_t in 2011 (0.505) was significantly lower than 2012 (0.522), 2013 (0.537) and 2014 (0.516) while the K_d in 2011 (0.593) was significantly different from 2012 (0.568), 2013 (0.551) and 2014 (0.579).

GPP and NEE show similar changes with K_d (Figure 12), indicating that the effects of changes in K_d on respiration processes are minor compared to photosynthesis (Knohl and Baldocchi, 2008). The relationship between GPP (NEE) and K_d was nearly constant at low K_d and GPP (NEE) only became sensitive to change in K_d at high levels of K_d for 2012, 2013 and 2014. In 2011, however, we observe an initial rapid increase in

GPP and decrease in NEE with K_d but began to decline (increase) after the optimum at a diffuse fraction of 0.65.

Discussion

We focus our discussion on the mechanisms responsible for the seasonal and interannual variation in NEE, GPP, and RE described in the Results section.

Controls on Seasonal Variations in CO_2 Fluxes

Seasonal NEE, GPP, and RE were variable amongst years at the study site. For example, monthly average NEE was higher (i.e. the ecosystem was gaining less or losing more carbon) during the dry season than the wet season in 2011, but the converse held for the subsequent three years. Monthly average RE was higher during the rainy season than the dry season in 2012, but the converse was true for 2011, 2013 and 2014. Monthly average GPP was higher in the rainy season than the dry season in both 2011 and 2012, but the converse was true for the following two years.

We attribute the increase in respiration rates in the dry season of 2011, 2013 and 2014 to enhanced microbial decomposition under oxic condition because of the lowering of the water table (Figure 2.3f). Chambers et al. (2004) observed that inadequate oxygen supplies in saturated conditions restrict aerobic decomposition of organic matter in peat. In July-September of 2012, however, the site received the least amount of rainfall, which was 44-60% of the rainfall received during this period in other years, and GWL declined to 17-22 cm alongside low soil moisture content (0.09 to 0.2 m^3 m^{-3}). Over the next three months (October-December) of rainy season conditions, respiration was stimulated and

the monthly average respiration rates were highest in 2012 (Figure 2.5), following the

increases in rainfall inputs and soil moisture content despite a small decrease in

temperature (Figure 2.3c). The rewetting of dry soil induced a flush of respiration during

this period and thus the average respiration rate in the rainy season was 2.3 g C m^{-2} d^{-1}

greater than that of the dry season in 2012. A similar observation was found at an old-

growth tropical forest in Brazil (Goulden et al., 2004), where the rapid increase in

respiration following increased rainfall resulted from the relief of microbes from water

stress within the litter layer when the surface litter became quite dry in the dry season. It

is unclear if the microbial mechanism for increased soil respiration following rewetting,

the 'Birch effect' (e.g. Jarvis et al. (2007) is also at play in this tropical peat forest and

future studies should investigate microbial responses to peat rewetting. Otherwise, the

monthly average RE was similar but slightly greater in the dry season (0.37-0.58 g C m^{-2}

d^{-1}) and coincided with a small increase in T_a (Figure 2.3c). In other words, the seasonal

variation in respiration regulated by temperature, but became dominantly controlled by

the supply of water during substantial reduction in rainfall over a period 3-4 months,

causing GWL drawdown and decline in soil moisture, noting that the six-month dry

season accounted for 31%, 24%, 34% and 50% of the annual rainfall for 2011-2014

respectively.

Monthly average GPP was found to be considerably higher in the rainy season

than during the dry season in both 2011 ($p=0.014$) and 2012 ($p=0.004$), but the converse

was for the following two years. Apart from February of 2013, monthly GPP was lowest

in the dry season from June to August for both 2011 (30-64 g C m^{-2} month^{-1}) and 2012

(120-146 g C m^{-2} month^{-1}) among all months from 2011 to 2014. Figure 2.10b indicates that the maximum photosynthesis rates during DOY 165-234 (June 14 – August 22) of 2011 (20.6 µmol m^{-2} s^{-1}) and 2012 (21.2 µmol m^{-2} s^{-1}) were considerably low relative to 2013 (33.7 µmol m^{-2} s^{-1}) and 2014 (33.6 µmol m^{-2} s^{-1}), in which the VPD seemed to exert a major effect on canopy conductance, and thus the GPP was reduced by stomatal responses to VPD. Similarly, the maximum carbon uptake rate β on an annual basis in 2011 was lowest (30.5 µmol m^{-2} s^{-1}) (Figure 2.10a). The parameter β as a function of VPD decreased exponentially from the maximum value for VPD higher than a limiting value (VPD$_0$), which was set to be 1 kPa following leaf and ecosystem level syntheses (Körner, 1995; Lasslop et al., 2010; Oren et al., 1999; Reichstein et al., 2012). The decay rate, parameter k, which reflecting the steepness of the equation, however, was lowest during DOY 165-234 in 2011, followed by 2012, 2014 and 2013. When all days of each year were included, the photosynthetic rate declined fastest with VPD at 1.73 kPa in 2012, followed by 2011 at 1.54 kPa. The decrease in GPP due to VPD during the dry season was a major cause of the seasonal variation of GPP and thereby NEE during 2011 and 2012. Mean GPP was slightly higher during the dry season but did not vary significantly between seasons in 2013 (p=0.124) and 2014 (p=0.413).

Observed fluxes are also due in part to canopy structural changes in response to environmental conditions. The average MODIS LAI for June-August was 3.9, 4.3, 3.7 and 5 during 2011-2014, respectively, whereas in situ LAI was 5.3, 5.5, 5.4 and 6.3, for 2011, 2012, 2013 and 2014, respectively. In other words, both methods indicate an increase in LAI during 2014. Albedo tends to increase as leaf area index (LAI) decreases

(e.g. Beringer et al. (2005), further suggesting an increase in LAI over time; the average albedo for June-August of 2011 (0.089) and 2012 (0.090) was comparable but relatively high in comparison to 2013 (0.083) and 2014 (0.086). Decrease in LAI was likely due to the higher particle loads present in the atmosphere that might cause negative changes in leaf structure by directly covering the leaf surface and thus reduce the area of leaves.

Based on these results, we infer that the decrease in GPP during June-August of 2011 and 2012 as well as the seasonal variation in GPP for these two years was affected by VPD, radiation and LAI.

Controls on Interannual Variations in CO_2 Fluxes

Controls over interannual variability in CO_2 flux largely followed seasonal patterns. Cumulative RE between 2011, 2012 and 2013 was comparable. The RE was relatively high in 2014 in parallel with highest rainfall, highest T_a, and lowest GWL, even though the soil moisture was lowest in 2014 (Figure 2.3 and 2.5), noting considerable uncertainty about RE estimates (3199 ± 937 g C m^{-2} yr^{-1}) using our conservative uncertainty estimation approach.

The annual GPP on the other hand differed appreciably between years, that is, 1931, 2263, 2455 and 2843 g C m^{-2} yr^{-1}, for 2011, 2012, 2013 and 2014, respectively (p=0.0011) and corresponded to differences in VPD, PPFD and LAI although these interannual variations in these variables themselves were small, in which the mean annual range of VPD, PPFD and LAI for 2011 to 2014 differed by 3.8%, 2.3% and 13%, respectively. Site-level observations and MODIS agree that LAI increased during the measurement period (and albedo decreased), suggesting that canopy growth – perhaps

following a disturbance that occurred before the observation period – was in part responsible for the trend of increasing GPP. Interestingly, canopy sensitivity to VPD decreased (Figure 2.8b) over time, although it is unclear why. Tropical forests tend to be more isohydric than other terrestrial ecosystems (Fisher et al., 2006; Konings and Gentine, 2016), meaning that they reduce canopy conductance in response to increases VPD more strongly than other ecosystems on average. At the same time, tropical trees exhibit a range of isohydric to anisohydric hydraulic behavior (Klein, 2014) and it has been argued that anisohydric strategies may be preferred in tropical systems that have little risk of water stress (Kumagai and Porporato, 2012). What is less clear for the case of the present study is why GPP in 2011 was more sensitive to VPD at high levels of PPFD (Figure 2.9d). Tree species turnover of course was not observed during the study period, and a flux footprint analysis (data not shown) did not demonstrate significant differences in flux source area over the course of the study.

Reduction in GPP for 3 months from June to August in 2011 might in part attributed to the relative low atmospheric transmission which was mostly due to cloudiness or aerosols from massive fire in Indonesia that occurs during fire season from early June to late October (Yulianti and Hayasaka, 2013). At annual timescale, a potential increase in K_d resulted in an overall decline in carbon uptake when global radiation was decreasing (Knohl and Baldocchi, 2008). Hirano et al. (2012) also found that smoke in an El Niño year reduced annual net CO_2 uptake by 17% at a relatively intact peat forest with little drainage in Indonesia.

Comparison with other tropical forests

The 4-year mean annual NEE of 420 ± 194 g C m^{-2} yr^{-1} for this study site is higher than that of a relatively intact (but hydrologically disturbed) peat forest in Kalimantan, Indonesia, which was also a CO_2 source of 174 ± 203 g C m^{-2} yr^{-1} on average for 2004-2008, including El Niño (2004-2005 and 2006-2007) and La Niña years (2005-2006 and 200 7-2008) (Hirano et al., 2012) in which the annual net CO_2 uptake decreased by about 17% during the El Niño year (2006).

Conversely, a CO_2 uptake was observed from several Amazonian forests (-100 g C m^{-2} yr^{-1}, Grace et al., 1996; -591 g C m^{-2} yr^{-1}, Malhi et al., 1998; -390 g C m^{-2} yr^{-1}, Miller et al., 2004; 3-year average NEE: -246 g C m^{-2} yr^{-1}, Loescher et al., 2003). Carbon was also taken up at -79 to -147 g C m^{-2} yr^{-1} from 2003 to 2005 at a rainforest in Peninsular Malaysia (Kosugi et al., 2008a) with mineral soils, and also by a primary (532 g C m^{-2} yr^{-1}) and a secondary peat forest (522 g C m^{-2} yr^{-1}) in Thailand (Suzuki et al., 1999). The El Niño events, however, often turned the Amazonian forests into CO_2 source due to respiration losses from large amount of woody debris as a consequence of drought (130 g C m^{-2} yr^{-1}, Saleska et al., 2003; 4-year average NEE: 89 g C m^{-2} yr^{-1}, Hutyra et al., 2007). In brief, both peat forests in Borneo observed to date were net losses of CO_2 to the atmosphere on an annual basis, on average, regardless of meteorological in contrast to the typical behavior of tropical rainforests, which have the potential to turn into CO_2 sources under drought stress. Given that substantial peat deposits at both peat forest study sites indicate long-term carbon uptake on the time scales of soil development, it is unclear if multi-year net carbon losses to the atmosphere are a feature of peat forests, or if recent changes in ecosystem behavior – perhaps in response to

climate variability – have tipped these ecosystems to be net annual carbon sources over the long term. Future studies should seek to address the paradoxical result that tropical peat forests measurements indicate substantial CO_2 sources to the atmosphere on an annual basis.

Conclusion

In this study, we assessed eddy covariance-based CO_2 flux measurements and examined the controls on carbon exchange in an undisturbed peat forest at Maludam National Park in Sarawak, Malaysian Borneo was a carbon source each year from 2011 to 2014 in the absence of large natural disturbances. Meanwhile we also suspect that there might be underlying mechanisms causing a pulse in NEE of 2011. NEE was generally found to be highly sensitive to VPD controls over GPP during the dry season, similar to a hydrologically-disturbed forest site in Central Kalimantan, Indonesian Borneo.

Acknowledgements

References

Anderson, J.A.R., 1972. Synoptical Key for the Identification of the Trees of the Peat Swamp Forests of Sarawak. Forest Department, Sarawak.

Aubinet, M., Chermanne, B., Vandenhaute, M., Longdoz, B., Yernaux, M., Laitat, E., 2001. Long term carbon dioxide exchange above a mixed forest in the Belgian Ardennes. Agric. For. Meteorol. 108, 293–315.

Beringer, J., Chapin, F.S., Thompson, C.C., McGuire, A.D., 2005. Surface energy exchanges along a tundra-forest transition and feedbacks to climate. Agric. For. Meteorol. 131, 143–161.

Chambers, J.Q., Tribuzy, E.S., Toledo, L.C., Crispim, B.F., Higuchi, N., Santos, J.D., Araújo, A.C., Kruijt, B., Nobre, A.D., Trumbore, S.E., 2004. Respiration from a tropical forest ecosystem: partitioning of sources and low carbon use efficiency. Ecol. Appl. 14, 72–88.

Fisher, R.A., Williams, M., Do Vale, R.L., Da Costa, A.L., Meir, P., 2006. Evidence from Amazonian forests is consistent with isohydric control of leaf water potential. Plant. Cell Environ. 29, 151–165.

Goulden, M.L., Miller, S.D., Da Rocha, H.R., Menton, M.C., de Freitas, H.C., Silva Figueira, M.E., de Sousa, C.A.D., 2004. Diel and seasonal patterns of tropical forest CO_2 exchange. Ecol. Appl. 14, 42–54.

Grace, J., Malhi, Y., Lloyd, J., McIntyre, J., Miranda, A.C., Meir, P., Miranda, H.S., 1996. The use of eddy covariance to infer the net carbon dioxide uptake of Brazilian rain forest. Glob. Chang. Biol. 2, 209–217.

Hirano, T., Segah, H., Harada, T., Limin, S., June, T., Hirata, R., Osaki, M., 2007. Carbon dioxide balance of a tropical peat swamp forest in Kalimantan, Indonesia. Glob. Chang. Biol. 13, 412–425.

Hirano, T., Segah, H., Kusin, K., Limin, S., Takahashi, H., Osaki, M., 2012. Effects of disturbances on the carbon balance of tropical peat swamp forests. Glob. Chang. Biol. 18, 3410–3422.

Hollinger, D.Y., Richardson, A.D., 2005. Uncertainty in eddy covariance measurements and its application to physiological models. Tree Physiol. 25, 873–885.

Hutyra, L.R., Munger, J.W., Saleska, S.R., Gottlieb, E., Daube, B.C., Dunn, A.L., Amaral, D.F., de Camargo, P.B., Wofsy, S.C., 2007. Seasonal controls on the exchange of carbon and water in an Amazonian rain forest. J. Geophys. Res.

Biogeosciences 112, 1–16.

Inubushi, K., Furukawa, Y., Hadi, A., Purnomo, E., Tsuruta, H., 2003. Seasonal changes of CO_2, CH_4 and N_2O fluxes in relation to land-use change in tropical peatlands located in coastal area of South Kalimantan. Chemosphere 52, 603–608.

Jarvis, P., Rey, A., Petsikos, C., Wingate, L., Rayment, M., Pereira, J., Banza, J., David, J., Miglietta, F., Borghetti, M., Manca, G., Valentini, R., 2007. Drying and wetting of Mediterranean soils stimulates decomposition and carbon dioxide emission: the "Birch effect." Tree Physiol. 27, 929–940.

Jauhiainen, J., Takahashi, H., Heikkinene, J.E.P., Martikainen, P.J., Vasanders, H., 2005. Carbon fluxes from a tropical peat swamp forest floor. Glob. Chang. Biol. 11, 1788–1797.

Klein, T., 2014. The variability of stomatal sensitivity to leaf water potential across tree species indicates a continuum between isohydric and anisohydric behaviours. Funct. Ecol. 28, 1313–1320.

Knohl, A., Baldocchi, D.D., 2008. Effects of diffuse radiation on canopy gas exchange processes in a forest ecosystem. J. Geophys. Res. Biogeosciences 113, 1–17.

Konings, A.G., Gentine, P., 2017. Global variations in ecosystem-scale isohydricity. Glob. Chang. Biol. 23, 891-905.

Körner, C., 1995. Leaf diffusive conductances in the major vegetation types of the globe. Ecophysiol. Photosynth. 100, 463–490.

Kosugi, Y., Takanashi, S., Ohkubo, S., Matsuo, N., Tani, M., Mitani, T., Tsutsumi, D., Nik, A.R., 2008. CO_2 exchange of a tropical rainforest at Pasoh in Peninsular Malaysia. Agric. For. Meteorol. 148, 439–452.

Kumagai, T., Porporato, A., 2012. Strategies of a Bornean tropical rainforest water use as a function of rainfall regime: isohydric or anisohydric? Plant. Cell Environ. 35, 61–71.

Lasslop, G., Reichstein, M., Papale, D., Richardson, A., Arneth, A., Barr, A., Stoy, P., Wohlfahrt, G., 2010. Separation of net ecosystem exchange into assimilation and respiration using a light response curve approach: Critical issues and global evaluation. Glob. Chang. Biol. 16, 187–208.

Loescher, H.W., Oberbauer, S.F., Gholz, H.L., Clark, D.B., 2003. Environmental controls on net ecosystem-level carbon exchange and productivitty in a Central American tropical wet forest. Glob. Chang. Biol. 9, 396–412.

Malhi, Y., Nobre, A.D., Grace, J., Kruijt, B., Pereira, M.G.P., Culf, A., Scott, S., 1998. Carbon dioxide transfer over a Central Amazonia rain forest 103.

Maltby, E., Immirzi, P., 1993. Carbon Dynamics in Peatlands and other Wetland Soils Regional and Global Perspectives. Chemosphere 27, 999–1023.

Massman, W.J., 2000. A simple method for estimating frequency response corrections for eddy covariance systems. Agric. For. Meteorol. 104, 185–198.

Massman, W.J., 2001. Reply to comment by Rannik on "A simple method for estimatiog frequency responde corrections for eddy covariance systems." Agric. For. Meteorol. 107, 247–251.

Melling, L., Hatano, R., Goh, K.J., 2005. Soil CO_2 flux from three ecosystems in tropical peatland of Sarawak, Malaysia. Tellus, Ser. B Chem. Phys. Meteorol. 57, 1–11.

Miller, S.D., Goulden, M.L., Menton, M.C., Rocha, H.R., Freitas, H.C. De, Michela, A., Albert, C., Sousa, D. De, 2004. Biometric and Micrometeorological Measurements of Tropical Forest Carbon Balance. Ecol. Appl. 14, 114–126.

Motulsky, H.J., Ransnas, L.A., 1987. Fitting curves nonlinear regression : review a practical. FASEB J. 1, 365–374.

Novick, K.A., Stoy, P.C., Katul, G.G., Ellsworth, D.S., Siqueira, M.B.S., Juang, J., Oren, R., 2004. Carbon dioxide and water vapor exchange in a warm temperate grassland. Oecologia 138, 259–274.

Oren, R., Sperry, J.S., Katul, G.G., Pataki, D.E., Ewers, B.E., Phillips, N., Schäfer, K.V.R., 1999. Survey and synthesis of intra- and interspecific variation in stomatal sensitivity to vapour pressure deficit. Plant, Cell Environ. 22, 1515–1526.

Pingintha, N., Leclerc, M.Y., Beasley, J.P., Zhang, G., Senthong, C., Rowland, D., 2010. Hysteresis response of daytime net ecosystem CO_2 exchange during a drought. Biogeosciences 7, 1159–1170.

Reichstein, M., Stoy, P.C., Desai, A.R., Lasslop, G., Richardson, A.D., 2012. Partitioning of net fluxes. In: Eddy Covariance. Springer Netherlands, pp. 263–289.

Richardson, A.D., Hollinger, D.Y., Burba, G.C., Davis, K.J., Flanagan, L.B., Katul, G.G., Munger, J.W., Ricciuto, D.M., Stoy, P.C., Suyker, A.E., Verma, S.B., Wofsy, S.C., 2006. A multi-site analysis of random error in tower-based measurements of carbon and energy fluxes. Agric. For. Meteorol. 136, 1–18.

Saleska, S.R., Miller, S.D., Matross, D.M., Goulden, M.L., Wofsy, S.C., da Rocha, H.R., de Camargo, P.B., Crill, P., Daube, B.C., de Freitas, H.C., Hutyra, L., Keller, M., Kirchhoff, V., Menton, M., Munger, J.W., Pyle, E.H., Rice, A.H., Silva, H., 2003. Carbon in Amazon forests: unexpected seasonal fluxes and disturbance-induced losses. Science 302, 1554–1557.

Spitters, C.J.T., Toussaint, H.A.J.M., Goudriaan, J., 1986. Separating the diffuse and direct components of global radiation and its implications for modeling canopy photosynthesis. II. Calculation of canopy photosynthesis. Agric. For. Meteroloogy 38, 231–242.

Stoy, P.C., Katul, G.G., Siqueira, M.B.S., Juang, J., Novick, K.A., Uebelherr, J.M., Oren, R., 2006. An evaluation of models for partitioning eddy covariance-measured net ecosystem exchange into photosynthesis and respiration 141, 2–18.

Suzuki, S., Ishida, T., Nagano, T., Waijaroen, S., 1999. Influences of Deforestation on Carbon Balance in a Natural Tropical Peat Swamp Forest in Thailand. Environ. Control Biol. 37, 115–128.

Ueyama, M., Hirata, R., Mano, M., Hamotani, K., Harazono, Y., Hirano, T., Miyata, A., Takagi, K., Takahashi, Y., 2012. Influences of various calculation options on heat, water and carbon fluxes determined by open- and closed-path eddy covariance methods. Tellus B 64.

Vick, E.S.K., Stoy, P.C., Tang, A.C.I., Gerken, T., 2016. The surface-atmosphere exchange of carbon dioxide, water, and sensible heat across a dryland wheat-fallow rotation. Agric. Ecosyst. Environ. 232, 129–140.

Vourlitis, G.L., Filho, N.P., Hayashi, M.M.S., Nogueira, J.D.S., Caseiro, F.T., Jr, J.H.C., 2001. Seasonal variations in the net ecosystem CO_2 exchange of a mature Amazonian transitional tropical forest (cerradao). Funct. Ecol. 15, 388–395.

Wilczak, J.M., Oncley, S.P., Stage, S.A., 2001. Sonic anemometer tilt correction algorithms. Boundary-Layer Meteorol. 99, 127–150.

Yulianti, N., Hayasaka, H., 2013. Recent Active Fires under El Niño Conditions in Kalimantan, Indonesia. Am. J. Plant Sci. 4, 685–696.

Legends

Figure 2.1. Map of the study area in Maludam National Park, Sarawak, Malaysian Borneo.

Figure 2.2. Seasonal variations in monthly sums of (a) rainfall and (b) photosynthetic photon flux density (PPFD), and monthly means of (c) air temperature, (d) daytime vapor pressure deficit (VPD), (e) wind speed, (f) soil moisture and (g) water table depth (GWL) during the study period from 2011 to 2014.

Figure 2.3. The cumulative sum of net ecosystem CO_2 exchange (NEE) at the tropical peat swamp forest site in Maludam National Park, Sarawak, Malaysian Borneo for 2011, 2012, 2013 and 2014. The cumulative NEE measured during DOY 165-234 of 2011 was marked as I. Error bars represent one standard deviation from the cumulative sum.

Figure 2.4. The cumulative sum of ecosystem respiration (RE) for 2011, 2012, 2013 and 2014. Error bars represent one standard deviation from the cumulative sum.

Figure 2.5. The cumulative sum of gross primary production (GPP) for 2011, 2012, 2013 and 2014. Error bars represent one standard deviation from the cumulative sum.

Figure 2.6. Monthly time series of cumulative net ecosystem CO_2 exchange (NEE), ecosystem respiration (RE) and gross primary production (GPP) from 2011 to 2014.

Figure 2.7. Seasonal variations in monthly mean albedo for 2011, 2012, 2013 and 2014.

Figure 2.8. Effects of vapor pressure deficit (VPD) on (a) NEE and (b) GPP for 2011-2014.

Figure 2.9. Effects of photosynthetically photon flux density (PPFD) on NEE at different levels of vapor pressure deficit at (a) < 0.25 kPa, (b) 0.25 - 0.5 kPa, (c) 0.5 – 1 kPa and (d) > 1 kPa, for 2011-2014.

Figure 2.10. The function decreasing the parameter beta, β_M, the maximum carbon uptake as a function of VPD during DOY (a) 1-365 and (b) 165-234 for 2011, 2012, 2013 and 2014.

Figure 2.11. Monthly average (a) clearness index (K_t) and (b) diffuse fraction (K_d) for 2011, 2012, 2013 and 2014.

Figure 2.12. Changes in (a) canopy photosynthesis and (b) net ecosystem exchange with diffuse fraction. Values are half-hourly averages (± standard error) of daytime data between 10h and 14h on rainless days.

CHAPTER THREE

THE EXCHANGE OF WATER AND ENERGY BETWEEN A TROPICAL

PEAT FOREST AND THE ATMOSPHERE: SEASONAL TRENDS AND

COMPARISON AGAINST GLOBAL TROPICAL RAINFORESTS

Contribution of Author and Co-Authors

Manuscript in Chapter 3

Author: Angela C. I. Tang

Contributions: Performed data processing and data analyses, generated figures and wrote manuscript in preparation for submission.

Co-Author: Paul C. Stoy

Contributions: Obtained funding, provided advice on data analyses, discussed results and edited the manuscript at all stages.

Co-Author: Kevin K. Musin

Contributions: Aided in collecting data and maintaining tower.

Co-Author: Edward B. Aeries

Contributions: Aided in collecting data and maintaining tower.

Co-Author: Joseph Wenceslaus

Contributions: Aided in collecting data and maintaining tower.

Co-Author: Mariko Shimizu

Contributions: Assisted with setting up tower instruments.

Co-Author: Ryuichi Hirata

Contributions: Assisted with setting up tower instruments, provided technical assistance and comments on manuscript.

Co-Author: Lulie Melling

Contributions: Obtained project funding and provided comments on manuscript.

Manuscript Information Page

Angela C. I. Tang, Paul C. Stoy, Kevin K. Musin, Edward B. Aeries, Joseph Wenceslaus, Mariko Shimizu, Ryuichi Hirata and Lulie Melling

THE EXCHANGE OF WATER AND ENERGY BETWEEN A TROPICAL PEAT FOREST AND THE ATMOSPHERE: SEASONAL TRENDS AND COMPARISON AGAINST GLOBAL TROPICAL RAINFORESTS

Angela C. I. Tang[1,2], Paul C. Stoy[1], Kevin K. Musin[2], Edward B. Aeries[2], Joseph Wenceslaus[2], Mariko Shimizu[3], Ryuichi Hirata[4] and Lulie Melling[2]

1. Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, MT 59715, USA
2. Sarawak Tropical Peat Research Institute, Lot 6035, Kuching-Kota Samarahan Expressway, 94300 Kota Samarahan, Sarawak, Malaysia
3. Civil Engineering Research Institute for Cold Region, Sapporo 062-8602, Japan
4. Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba 305-8506, Japan

Abstract

Tropical rainforests control the exchange of water and energy between the land surface and the atmosphere near the equator and thus play an important role in the global climate system. Tropical rainforests are often thought of as energy limited, but water availability also determines the seasonal pattern of water and heat exchange to the atmosphere via the latent (LE) and sensible heat flux (H). Observations of LE and H have not been synthesized across global tropical rainforests to date, which can help place observations from individual tropical forests in a global context. Here, we use four years of eddy covariance measurements of LE and H in a tropical peat forest ecosystem to characterize their interannual variability and seasonality in response to wet and dry seasons. We hypothesize that the study ecosystem will exhibit less seasonal variability in LE and H than other tropical ecosystems as soil water is not expected to be limiting in a tropical forested wetland. We find that both fluxes and are relatively invariant across

seasons with *LE* values on the order of 11 MJ m^{-2} day and *H* on the order of 3 MJ m^{-2} day^{-1}. Their ratio (the Bowen ratio, *Bo*) across both wet season and dry season (0.25) was a function of net radiation (*R$_n$*). Annual evapotranspiration (ET) did not differ among years and averaged 1579 $\pm$ 47 mm year^{-1}. *LE* exceeded characteristic values from other tropical rainforest ecosystems in the FLUXNET 2015 database with the exception of GF-Guy near coastal French Guyana, which averaged 8-11 MJ m^{-2} day. *Bo* in tropical rainforests in the FLUXNET2015 database either exhibited two seasonal peaks (MY-PSO and PA-SPn), little seasonal trend during the measurement period (BR-Sa1 and BR-Sa3) or peaks later in the calendar year (Au-Rob, GF-Guy, GH-Ank, and the study ecosystem, MY-MLM). Results demonstrate important differences in the seasonal patterns in water and energy exchange in tropical rainforest ecosystems that need to be understood to quantify how ongoing changes in tropical rainforest extent will impact the global climate system.

Introduction

Tropical ecosystems play a critical role in the global climate system by regulating the amount of heat and water that enters the atmosphere near the equator to drive deep convection. Ongoing changes to tropical forest extent (Kim et al., 2015) have impacted regional and global climate (Avissar and Werth, 2005; Bala et al., 2007; Medvigy et al., 2011; Werth, 2002), emphasizing the importance of understanding how tropical rainforests exchange water and energy with the atmosphere and how differences among forests may determine these dynamics.

Tropical rainforests exhibit seasonal patterns of energy and water exchange in response to wet and dry season dynamics that may be considerable; many studies report a doubling of the Bowen ratio (Bo, the sensible heat flux H divided by the latent heat flux LE) or more during the dry season (Da Rocha et al., 2004; Gerken et al., 2017). These findings are consistent with the notion that tropical rainforest tree species tend to be isohydric, meaning that they strictly regulate canopy conductance in response to water deficits (Fisher et al., 2006; Konings and Gentine, 2016). At the same time, other studies using modeling approaches suggest that some tropical forests should exhibit anisohydric water regulation strategies (Kumagai and Porporato, 2012) and argue that different tree species exhibit a range of isohydric to anisohydric behavior (Klein, 2014), leaving it unclear if the conductance of diverse tropical forest canopies share similar responses to ongoing increases in the atmospheric vapor pressure deficit (D) (Novick et al., 2016; Sulman et al., 2016) and decreases in soil moisture (Jung et al., 2011). Carbon uptake across different tropical canopies varies considerably in response to increasing D (Fu et al., in review), but the response of H and LE to seasonal water availability across different tropical ecosystems has not been studied to date.

Here, we describe the seasonal variability in H and LE, and thereby Bo, as well as variables that characterize how ecosystems respond to net radiation (R_n), namely the evaporative fraction (EF), in a tropical peat rainforest ecosystem in Malaysian Borneo, hereafter abbreviated MY-MLM. We place these observations in the context of the seasonal variability of surface-atmosphere water and energy exchange across globally-distributed tropical rainforest ecosystems and hypothesize that the study ecosystem will

exhibit less seasonal variability in water and energy exchange than other tropical ecosystems as soil water is not expected to be limiting. We place particular emphasis on eddy covariance energy balance closure and uncertainty estimation, noting that whereas tropical rainforest ecosystems on average have higher energy balance closure than most other ecosystems (Gerken et al., 2017; Stoy et al., 2013), an analysis of energy balance closure cannot be excluded from a careful investigation of surface-atmosphere water and energy exchange using the eddy covariance technique.

Materials and Methods

Study Ecosystem and Micrometeorological Measurements

The primary study ecosystem, MY-MLM, is a tropical peat forest ecosystem in Maludam National Park in the Betong Division of Sarawak, Malaysia described in more detail in Tang et al. (in review). Dominant vegetation in the overstory includes *Shorea albida*, *Gonystylus bancanus* and *Stemonurus* spp (Anderson, 1972) with an average canopy height of 25 m and emergent trees that exceed 30 m. Peat thickness is 8 m in the vicinity of the eddy covariance tower at 1º27'55''N, 111º9'20''E. Micrometeorological variables important for understanding surface-atmosphere water and energy flux were made at half hourly intervals. These include rainfall (P), wind speed (WS), air temperature (T_{air}), relative humidity (RH, and thereby *D*), volumetric soil water content (SWC), soil temperature (T_{soil}), incident photosynthetically active (PPFD), net (R_n) and global radiation (R_g), and water table height (WT) as described in more detail in Tang et al. (in review).

Eddy Covariance Measurements

H and LE were measured at MY-MLM using the eddy covariance technique from 2011 to 2014 in the roughness sublayer at 41 m. The eddy covariance system was comprised 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). 10 Hz observations were stored on a CR3000 Datalogger (Campbell Scientific) and half-hourly flux measurements were calculated using EddyPro (LiCor) with WPL correction (Webb et al., 1980), double rotation to align the sonic anemometer with the mean flow (Wilczak et al., 2001), and time-lag and frequency response corrections (W. J. Massman, 2000) as described in more detail in Tang et al. (in review).

Gap Filling and Uncertainty Analysis

Missing H and LE were gap filled by fitting a daily linear regression between the fluxes and R_n that included a slope and an intercept parameter. We applied the approach of Richardson et al. (2006) (see also Hollinger & Richardson, 2005) to estimate the random uncertainty of H and LE. Random errors were inferred using the 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}, T_{air} differed by less than 3°C, and WS 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 previously calculated random errors following the recommendations of Motulsky & Ransnas (1987). This procedure was iterated 100 times for each day such that 100 gap filling models were fit

for each day using least squares regressions. Missing H and LE data were filled using the mean of the 100 models, which were also used to quantify uncertainty due to gapfiling. The squared sum of random and gapfilling uncertainty was computed to calculate the total uncertainty.

FLUXNET2015

Observations of H, LE, and R_n from tropical forest ecosystems in the FLUXNET2015 database are compared against observations from MY-MLM to address the experimental hypothesis by quantifying differences in seasonal patterns in surface-atmosphere energy exchange. The FLUXNET2015 database harmonizes, standardizes, and gap-fills half-hourly or hourly observations of H and LE submitted by Principal Investigators from regional flux networks using standard methods (Papale et al., 2006; Pastorello et al., 2017; Reichstein et al., 2005). The seven eddy covariance sites come from all continents on which tropical rainforests exist: Africa, Asia, Australia, North America, and South America, as described in Table 3.1 and Figure 3.1.

Results

Water and Energy Fluxes from MY-MLM

LE at MY-MLM decreased from the wet season (with characteristic values on the order of 11 MJ m^{-2} day^{-1}), to the dry season (with characteristic values on the order of 10 MJ m^{-2} day^{-1}) (Figure 3.2a) and largely followed seasonal patterns in R_n, which varied from 13-14 MJ m^{-2} day^{-1} on average. H exhibited less seasonal variability with average daily sums on the order of 3 MJ m^{-2} day^{-1}. LE, expressed in units of mm $time^{-1}$ as

evapotranspiration (ET), did not differ among the study years and averaged *ca.* 1579 ± 47

mm year^{-1} (Figure 3.3).

The evaporative fraction (EF) and *Bo* exhibited little interannual differences (data

not shown) nor differences during the daytime regardless of dry or rainy season (Figure

3.4). The EF was characteristically near 0.73 (Figure 3.4a) and the *Bo* near 0.25 during

daytime, and the *Bo* was more negative (and the EF more positive) during nighttime

periods of the dry season across all years (Figure 3.4b). The *Bo* increased in response to

R_n across both wet and dry seasons, indicating that additional energy is disproportionally

partitioned to *H* as R_n increases (Figure 3.5). Whereas ET and thereby *LE* by conversion

using the latent heat of vaporization did not exhibit annual differences as noted (Figure

3.3), there was a tendency for shortwave albedo to decrease during the later years of

measurement (2013-2014) to *ca.* 8% during mid-day from *ca.* 8.5% earlier during the

measurement period (Figure 3.6).

Energy Balance Closure at MY-MLM

Energy balance closure (calculated as the relationship between the daily sum of *H*

plus *LE versus* R_n) increased from 64% during the rainy season to 78% during the dry

season (Figure 3.7) and averaged 70% across the entire measurement period, somewhat

less than globally-distributed eddy covariance sites from the FLUXNET LaThuille

database ($84 \pm 20\%$, Stoy et al., 2013) and tropical sites from the LaThuille database

($94\% \pm 16\%$).

Water and Energy Fluxes from Global Tropical Rainforest Ecosystems

The magnitude of average daily *LE* across the calendar year tended to be higher at MY-MLM (11 MJ m^{-2} day^{-1}) than most other tropical rainforest ecosystems in the FLUXNET2015 database with the exception of GF-Guy near the coast in French Guyana (Figure 8a). Mean daily *LE* across the calendar year exhibited complicated patters across the different study ecosystems, with average daily fluxes differing by four times (*ca*. 2 MJ m^{-2} day^{-1}) from dry to wet season at GH-Ank in Ghana to a seasonaly invariant 8 ± 1 MJ m^{-2} day^{-1} at a tropical rainforest on Peninsular Malaysia (MY-PSO).

H at MY-MLM was less variable than most other study ecosystems despite large differences in wet and dry season precipitation that differed for example from more than 550 mm month^{-1} in December 2013 to less than 50 mm month^{-1} in July 2013 (Tang et al. in review). Daily average *H* reached as high as *ca* 8 MJ m^{-2} day at a tropical rainforest in Australia (AU-Rob), where it also reached net daily negative values, similar to GF-Guy (Figure 8b). As a consequence of the seasonal patterns in *LE* and *H*, the seasonal pattern of *Bo* can be characterized into sites that have two calendar year peaks (MY-PSO and PA-SPn), sites with little seasonal pattern in *Bo* (BR-Sa1 and BR-Sa3), and sites that characteristically low *Bo* values less than 0.25 early in the calendar year and larger values later (Au-Rob, GF-Guy, GH-Ank, and the study ecosystem, MY-MLM) (Figure 3.8c).

Discussion

Water and Energy Fluxes from MY-MLM: Energy Balance Closure and
Seasonal Patterns

Annual rainfall decreased during the measurement period (3290, 2941, 2688 and

2272 mm for 2011, 2012, 2013 and 2014, respectively (Tang et al., in review)), but

annual ET was comparable between years; 1568, 1616, 1516 and 1614 mm for 2011,

2012, 2013 and 2014, respectively (Figure 3.3). These observations suggest that ET was

insensitive to variability in P, and also that water available for groundwater recharge of

surface flow decreased across the measurement period from *ca*. 1700 mm in 2011 to *ca*.

660 mm in 2014. These observations are consistent with the notion that ET is a conserved

quantity compared to other terms in the water balance in energy-limited ecosystems

(Oishi et al., 2010).

Daytime EF and *Bo* were insensitive to dry or wet season (Figure 3.4), but, more

H was transmitted from the atmosphere to the surface, and less *LE* was released to the

atmosphere during the dry season at night, resulting in a relative negative *Bo* and high

EF. These observations are consistent with a more rapid nighttime cooling during the dry

season when WT heights were characteristically beneath the soil surface (Tang et al., in

review). In other words, the largest differences between the dry and wet season in *LE* and

H occurred at night and are consistent with the influence of standing water on ecosystem

energy fluxes rather than the influence of this water on daytime energy partitioning.

The non-closure of surface energy balance is common in eddy covariance

measurements (Stoy et al., 2013; Wilson, 2002) and is often attributed to a number of

causes such as inadequacy of instrument system, mismatch in footprint between R_n and

eddy fluxes, neglected energy sinks, advective flux divergence, low and high frequency

loss of turbulent fluxes at individual sites (Foken, 2008; Wilson, 2002). We note that the

present analysis of energy balance closure excludes unmeasured soil and ecosystem heat

fluxes, which are minor terms in the energy balance at diurnal time scales analyzed here

(Leuning et al., 2012). Because energy balance closure was lower during the wet season

when the water table characteristically exceeded the soil surface (Tang et al., in review),

observations here are consistent with the notion that the advective exchange of heat due

to flowing water is a nontrivial term in the energy balance, as has been found in other

wetland ecosystems (Barr et al., 2013). Energy balance closure values from the present

analysis are similar to wetland ecosystems in the LaThuille FLUXNET database (0.76),

which had the lowest average energy balance closure of any ecosystem (Stoy et al.,

2013). Results of this study and others suggest that additional instrumentation is needed

to capture advective energy flux in ecosystems characterized by flowing water.

Comparison of ET with Other Tropical Ecosystems

The mean annual ET at this study site (1579 mm yr^{-1}) was similar to a relatively

intact (but hydrologically disturbed) peat forest in Kalimantan, Indonesia (1636 mm yr^{-1},

Hirano et al., 2015) and a rainforest at Lambir Hills National Park in Sarawak, Malaysia

(1545 mm yr^{-1}, Kumagai et al., 2005), but higher than a rainforest in Peninsular Malaysia

(1287 mm yr^{-1}, Kosugi et al., 2012), central Amazonian forests (1123 mm yr^{-1}, Malhi et

al., 2002; 1123 mm yr^{-1}, Hutyra et al., 2007), and an afforested site (1114 mm yr^{-1}) and a

pasture site (1034 mm yr^{-1}) in Panama (Wolf et al., 2011). These observations are

consistent with experimental hypothesis that *LE* (and by conversion ET) would be higher

at MY-MLM than other tropical rainforest sites due to the consistent availability of water in a tropical peat forest wetland ecosystem, as also demonstrated by the insensitivity of daytime EF and *Bo* to wet and dry season. That being said, it is unclear how much soil moisture and plant function constrains *LE* at the other tropical rainforest study ecosystems, especially given that soil moisture is infrequently measured across tropical eddy covariance sites (Fu et al. in review) and may not capture water available in deeply-rooted ecosystems (Canadell et al., 1996; Jackson et al., 1996) near the tropical/subtropical boundary, namely AU-Rob, exhibited daily average *Bo* approaching 1.5, and Amazonian *terre firme* rainforests exhibited sharp increases in *Bo* to *ca.* 0.7 during conditions of high R_n (exceeding 900 W m^{-2}) (Gerken et al., 2017), suggesting that reduction in *LE* in response to dry conditions is an important feature of global tropical forests. *Bo* rarely exceeded 0.3 at the study ecosystem, even during the dry season, suggesting that water is consistently available for ET.

Conclusion

The experimental hypothesis that *H* and *LE* would be less variable at MY-MLM than other tropical rainforest ecosystems could not be falsified using observations, and results demonstrate considerable seasonal variability in surface-atmosphere water and energy fluxes across eddy covariance tropical rainforest study sites. ET was relatively constant despite decreasing rainfall over the four-year study period. Results demonstrate important differences in the seasonal patterns in water and energy exchange in tropical rainforest ecosystems, for which soil moisture is infrequently measured, yet that exhibit

large differences in the response of canopy processes to D (Fu et al., in review). Observations suggest considerable differences in hydrologic processes among tropical rainforest ecosystems that need to be understood to quantify how ongoing changes in tropical rainforest extent will impact the global climate system.

Acknowledgments

58

References

Anderson, J.A.R., 1972. Synoptical Key for the Identification of the Trees of the Peat Swamp Forests of Sarawak. Forest Department, Sarawak.

Avissar, R., Werth, D., 2005. Global hydroclimatological teleconnections resulting from tropical deforestation. J. Hydrometeorol. 6, 134–145.

Bala, G., Caldeira, K., Wickett, M., Phillips, T.J., Lobell, D.B., Delire, C., Mirin, A., 2007. Combined climate and carbon-cycle effects of large-scale deforestation. Proc. Natl. Acad. Sci. USA 104, 6550–6555.

Barr, J.G., Fuentes, J.D., Delonge, M.S., O'Halloran, T.L., Barr, D., Zieman, J.C., 2013. Summertime influences of tidal energy advection on the surface energy balance in a mangrove forest. Biogeosciences 10, 501–511.

Canadell, J., Jackson, R., Ehleringer, J., Mooney, H.A., Sala, O.E., Schulze, E.-D., 1996. Maximum rooting depth of vegetation types at the global scale. Oecologia 108, 583–595.

Da Rocha, H.R., Goulden, M.L., Miller, S.D., Menton, M.C., Pinto, L.D.V.O., de Freitas, H.C., de Silva Figueira, A.M., 2004. Seasonality of wtaer and heat fluxes over a tropical forest in eastern Amazonia. Ecol. Appl. 14, 22–32.

Fisher, R.A., Williams, M., Do Vale, R.L., Da Costa, A.L., Meir, P., 2006. Evidence from Amazonian forests is consistent with isohydric control of leaf water potential. Plant. Cell Environ. 29, 151–165.

Foken, T., 2008. The energy balance closure problem: An overview. Ecol. Appl. 18, 1351–1367.

Gerken, T., Ruddell, B.L., Fuentes, J.D., Araújo, A., Brunsell, N.A., Maia, J., Manzi, A., Mercer, J., dos Santos, R.N., von Randow, C., Stoy, P.C., 2017. Investigating the mechanisms responsible for the lack of surface energy balance closure in a central Amazonian tropical rainforest. Agric. For. Meteorol.

Hirano, T., Kusin, K., Limin, S., Osaki, M., 2015. Evapotranspiration of tropical peat swamp forests. Glob. Chang. Biol. 21, 1914–1927.

Hollinger, D.Y., Richardson, A.D., 2005. Uncertainty in eddy covariance measurements and its application to physiological models. Tree Physiol. 25, 873–885.

Hutyra, L.R., Munger, J.W., Saleska, S.R., Gottlieb, E., Daube, B.C., Dunn, A.L., Amaral, D.F., de Camargo, P.B., Wofsy, S.C., 2007. Seasonal controls on the exchange of carbon and water in an Amazonian rain forest. J. Geophys. Res. Biogeosciences 112, 1–16.

Jackson, R.B., Canadell, J., Ehleringer, J.R., Mooney, H. a., Sala, O.E., Schulze, E.D., 1996. A global analysis of root distributions for terrestrial biomes. Oecologia 108, 389–411.

Jung, M., Reichstein, M., Margolis, H.A., Cescatti, A., Richardson, A.D., Arain, M.A., Arneth, A., Bernhofer, C., Bonal, D., Chen, J., Gianelle, D., Gobron, N., Kiely, G., Kutsch, W., Lasslop, G., Law, B.E., Lindroth, A., Merbold, L., Montagnani, L., Moors, E.J., Papale, D., Sottocornola, M., Vaccari, F., Williams, C., 2011. Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations. J. Geophys. Res. Biogeosciences 116, G00J07.

Kim, D.-H., Sexton, J.O., Townshend, J.R., 2015. Accelerated deforestation in the humid tropics from the 1990s to the 2000s. Geophys. Res. Lett. 42, 3495–3501.

Klein, T., 2014. The variability of stomatal sensitivity to leaf water potential across tree species indicates a continuum between isohydric and anisohydric behaviours. Funct. Ecol. 28, 1313–1320.

Konings, A.G., Gentine, P., 2017. Global variations in ecosystem-scale isohydricity. Glob. Chang. Biol. 23, 891-905.

Kosugi, Y., Takanashi, S., Tani, M., Ohkubo, S., Matsuo, N., Itoh, M., Noguchi, S., Nik, A.R., 2012. Effect of inter-annual climate variability on evapotranspiration and canopy CO 2 exchange of a tropical rainforest in Peninsular Malaysia. J. For. Res. 17, 227–240.

Kumagai, T., Porporato, A., 2012. Strategies of a Bornean tropical rainforest water use as a function of rainfall regime: isohydric or anisohydric? Plant. Cell Environ. 35, 61–71.

Kumagai, T., Saitoh, T.M., Sato, Y., Takahashi, H., Manfroi, O.J., Morooka, T., Kuraji, K., Suzuki, M., Yasunari, T., Komatsu, H., 2005. Annual water balance and seasonality of evapotranspiration in a Bornean tropical rainforest. Agric. For. Meteorol. 128, 81–92.

Leuning, R., van Gorsel, E., Massman, W.J., Isaac, P.R., 2012. Reflections on the surface energy imbalance problem. Agric. For. Meteorol. 156, 65–74.

Malhi, Y., Pegoraro, E., Nobre, A.D., Pereira, M.G.P., Grace, J., Culf, A.D., Clement, R., 2002. Energy and water dynamics of a central Amazonian rain forest 107, 1–17.

Massman, W.J., 2000. A simple method for estimating frequency response corrections for eddy covariance systems. Agric. For. Meteorol. 104, 185–198.

Medvigy, D., Walko, R.L., Avissar, R., 2011. Effects of deforestation on spatiotemporal distributions of precipitation in South America. J. Clim. 24, 2147–2163.

Motulsky, H.J., Ransnas, L.A., 1987. Fitting curves nonlinear regression : review a practical. FASEB J. 1, 365–374.

Novick, K.A., Ficklin, D.L., Stoy, P.C., Williams, C.A., Bohrer, G., Oishi, A.C., Papuga, S.A., Blanken, P.D., Noormets, A., Sulman, B.N., Scott, R.L., Wang, L., Phillips, R.P., 2016. The increasing importance of atmospheric demand for ecosystem water and carbon fluxes. Nat. Clim. Chang. 6, 1023–1027.

Oishi, A.C., Oren, R., Novick, K.A., Palmroth, S., Katul, G.G., 2010. Interannual invariability of forest evapotranspiration and its consequence to water flow downstream. Ecosystems 13, 421–436.

Papale, D., Reichstein, M., Aubinet, M., Canfora, E., Bernhofer, C., Kutsch, W., Longdoz, B., Rambal, S., 2006. Towards a standardized processing of Net Ecosystem Exchange measured with eddy covariance technique : algorithms and uncertainty estimation 571–583.

Pastorello, G., Papale, D., Chu, H., Trotta, C., Agarwal, D., Canfora, E., Baldocchi, D., Torn, M., 2017. A New Data Set to Keep a Sharper Eye on Land-Air Exchanges. Eos (Washington. DC).

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grünwald, T., Havránková, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J.-M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., Valentini, R., 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration : review and improved algorithm. Glob. Chang. Biol. 11, 1424–1439.

Richardson, A.D., Hollinger, D.Y., Burba, G.C., Davis, K.J., Flanagan, L.B., Katul, G.G., Munger, J.W., Ricciuto, D.M., Stoy, P.C., Suyker, A.E., Verma, S.B., Wofsy, S.C., 2006. A multi-site analysis of random error in tower-based measurements of carbon and energy fluxes. Agric. For. Meteorol. 136, 1–18.

Stoy, P.C., Mauder, M., Foken, T., Marcolla, B., Boegh, E., Ibrom, A., Arain, M.A., Arneth, A., Aurela, M., Bernhofer, C., Cescatti, A., Dellwik, E., Duce, P., Gianelle, D., van Gorsel, E., Kiely, G., Knohl, A., Margolis, H., Mccaughey, H., Merbold, L., Montagnani, L., Papale, D., Reichstein, M., Saunders, M., Serrano-Ortiz, P., Sottocornola, M., Spano, D., Vaccari, F., Varlagin, A., 2013. A data-driven analysis of energy balance closure across FLUXNET research sites: The role of landscape scale heterogeneity. Agric. For. Meteorol. 171–172, 137–152.

Sulman, B.N., Roman, D.T., Yi, K., Wang, L., Phillips, R.P., Novick, K.A., 2016. High atmospheric demand for water can limit forest carbon uptake and transpiration as severely as dry soil. Geophys. Res. Lett. 43, 9686–9695.

Webb, E. K., Pearman, G. I., & Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. Q. J. R. Meteorol. Soc. 106, 85–100.

Werth, D., 2002. The local and global effects of Amazon deforestation. J. Geophys. Res. 107.

Wilczak, J.M., Oncley, S.P., Stage, S.A., 2001. Sonic anemometer tilt correction algorithms. Boundary-Layer Meteorol. 99, 127–150.

Wilson, K., 2002. Energy balance closure at FLUXNET sites. Agric. For. Meteorol. 113, 223–243.

Wolf, S., Eugster, W., Majorek, S., Buchmann, N., 2011. Afforestation of tropical pasture only marginally affects ecosystem-scale evapotranspiration. Ecosystems 14, 1264–1275.

Table 3.1: Tropical rainforest eddy covariance sites in the FLUXNET2015 database explored in the present study.

Site ID	Name	Lat.	Long.	Observation period (years of measurement)	References
AU-Rob	Robson Creek	-17.1175	145.6301	2014-2014 (1)	Bradford et al. (2014)
BR-Sa1	Santarem-Km67-Primary Forest	-2.8567	-54.9589	2002-2011 (9)	Martens et al. (2004)
BR-Sa3	Santarem-Km83-Logged Forest	-3.0180	-54.9714	2000-2004 (5)	Goulden et al. (2006)
GF-Guy	Guyaflux	5.2777	-52.9288	2004-2014 (11)	Bonal et al. (2008)
GH-Ank	Ankasa	5.2685	-2.6942	2011-2014 (4)	Albinet et al. (2015)
MY-PSO	Pasoh Forest Reserve	2.9730	102.3062	2003-2009 (7)	Kosugi et al. (2008b)
PA-SPn	Sardinilla Plantation	9.3181	-79.6346	2007-2009 (3)	Wolf et al., (2011a, 2011b, 2011c)

Figure 3.1. Map of the Maludam, Malaysia tropical peat forest research site (MY-MLM) and tropical rainforest FLUXNET tower sites used in this study (see Table 3.1).

Figure 3.2: The seasonal pattern of net radiation (R_n), latent heat flux (*LE*), and sensible heat flux (*H*) at the MY-MLM tropical peat forest ecosystem in Sarawak, Malaysian Borneo. Dots represent mean daily values for the four-year measurement period and lines represent a Savitzky-Golay filter applied to the average flux sum for each day of the calendar year.

Figure 3.3: The cumulative sum of evapotranspiration (ET) in a tropical peat forest ecosystem in Sarawak, Malaysian Borneo with uncertainty estimates displayed as +/- 1 standard deviation from the annual sum. Annual ET sums are not significantly different from each other.

Figure 3.4: Mean diurnal evaporative fraction (EF, top) and Bowen ration (Bo, bottom) for the dry and rainy season in a tropical peat forest ecosystem in Sarawak, Malaysian Borneo.

Figure 3.5: The response of the Bowen ratio to net radiation (R_n) across the dry and rainy seasons in a tropical peat rainforest ecosystem in Sarawak, Malaysian Borneo.

Figure 3.6: Energy balance closure, calculated as the daily sum of sensible (*H*) and latent heat flux (*LE*) *versus* the daily sum of net radiation (*R$_n$*) across the dry and rainy seasons for a four year measurement period in a tropical peat rainforest ecosystem in Sarawak, Malaysian Borneo.

Figure 3.7: The seasonal patterns of (a) latent heat flux (LE), (b) sensible heat flux (H), and (c) the Bowen ratio, across the eight eddy covariance research sites investigated here (see Table 3.1). Lines represent a Savitzky-Golay filter applied to average daily fluxes and ratios across all measurement years for each ecosystem. Values for MY-MLM follow Figure 3.2.

CHAPTER FOUR

EDDY COVARIANCE MEASUREMENTS OF METHANE FLUX AT A TROPICAL

PEAT FOREST IN SARAWAK, MALAYSIAN BORNEO

<u>Contribution of Author and Co-Authors</u>

Manuscript in Chapter 4

Author: Angela C. I. Tang

Contributions: Performed data processing and data analyses, generated figures and wrote manuscript in preparation for submission.

Co-Author: Paul C. Stoy

Contributions: Obtained funding, provided advice on data analyses, discussed results and edited the manuscript at all stages.

Co-Author: Kevin K. Musin

Contributions: Aided in collecting data and maintaining tower.

Co-Author: Edward B. Aeries

Contributions: Aided in collecting data and maintaining tower.

Co-Author: Joseph Wenceslaus

Contributions: Aided in collecting data and maintaining tower.

Co-Author: Mariko Shimizu

Contributions: Assisted with setting up tower instruments.

Co-Author: Ryuichi Hirata

Contributions: Assisted with setting up tower instruments, provided technical assistance and comments on manuscript.

Co-Author: Lulie Melling

Contributions: Obtained project funding and provided comments on manuscript.

72

<u>Manuscript Information Page</u>

Angela C. I. Tang, Paul C. Stoy, Kevin K. Musin, Edward B. Aeries, Joseph Wenceslaus, Mariko Shimizu, Ryuichi Hirata and Lulie Melling

Status of Manuscript:
__x_ Prepared for submission to a peer-reviewed journal
____ Officially submitted to a peer-review journal
____ Accepted by a peer-reviewed journal
____ Published in a peer-reviewed journal

EDDY COVARIANCE MEASUREMENTS OF METHANE FLUX AT A TROPICAL PEAT FOREST IN SARAWAK, MALAYSIA BORNEO

Angela C. I. Tang[1,2], Paul C. Stoy[1], Kevin K. Musin[2], Edward B. Aeries[2], Joseph Wenceslaus[2], Mariko Shimizu[3], Ryuichi Hirata[4] and Lulie Melling[2]

1. Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, MT 59715, USA
2. Sarawak Tropical Peat Research Institute, Lot 6035, Kuching-Kota Samarahan Expressway, 94300 Kota Samarahan, Sarawak, Malaysia
3. Civil Engineering Research Institute for Cold Region, Sapporo 062-8602, Japan
4. Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba 305-8506, Japan

Abstract

Methane (CH_4) is the third most potent greenhouse gas and its reduction is seen as an effective method for meeting global temperature targets, but the global growth rate of atmospheric CH_4 concentration has risen to 10.3 ± 2.1 ppb yr^{-1} from 2014 to 2016 after a period of relative stagnation from 2000-2006. Recent research has pointed to tropical biogenic sources as a likely cause. To improve our understanding of tropical methane sources, we measured CH_4 flux between a tropical peat forest ecosystem in Malaysian Borneo and the atmosphere over a two month period during the wet season. Mean $C-CH_4$ flux measurements, on the order of 0.024 g $C-CH_4$ m^{-2} d^{-1}, are similar to eddy covariance measurements from tropical rice agroecosystems and boreal fen ecosystems, suggesting that tropical peat forests are not likely to be disproportionally important to global CH_4 flux if the study ecosystem is representative of other tropical peat forests. Parsimonious linear models described about 10% of the variability of half-hourly CH_4 flux measurements, which exhibit a few morning peaks that are likely due to the flush out of

nighttime stored CH_4. Results demonstrate a limited ability for simple models to capture the variability in the diurnal pattern of CH_4 efflux, but also consistent responses to soil moisture, water table height, and precipitation over daily to weekly time scales. Future research should measure annual CH_4 flux from multiple tropical ecosystems to better understand their role in the global CH_4 balance.

Introduction

The contribution of methane (CH_4) to global radiative forcing is only exceeded by water vapor (H_2O) and carbon dioxide (CO_2), and CH_4 absorbs 25 times heat in the atmosphere than an equivalent amount of CO_2 over the course of a century (Myhre et al., 2013). Due to its relatively high potency and short life span of about 10 years, reduction in CH_4 emissions is seen as an effective approach for mitigating climate change. Global atmospheric CH_4 concentrations (Shindell et al., 2012), however, are on the rise and its growth rate in the atmosphere increased from 0.5 ± 3.1 ppb yr^{-1} from 2000-2006 to 7.1 ± 2.6 ppb yr^{-1} from 2007 to 2013 with a further increase to 10.3 ± 2.1 ppb yr^{-1} from 2014 to 2016 (Dlugokencky, 2017) for reasons that are still poorly understood.

Previous studies have come to different conclusions regarding the drivers of the atmospheric CH_4 growth rate over the past decades (Aydin et al., 2011; Bousquet et al., 2011; Hausmann et al., 2016; Helmig et al., 2016; Kai et al., 2011; Levin et al., 2012; Nisbet et al., 2016; Pison et al., 2013; Rice et al., 2016; Schaefer et al., 2016; Schwietzke et al., 2016; Simpson et al., 2012; Turner et al., 2017), making it difficult for national or regional policy makers to effectively implement strategies to control emissions from

sources. A number of lines of evidence point to biogenic rather than fossil sources as the leading cause of the recent CH_4 growth rate (Schaefer et al., 2016), and emphasize the likely role tropical agricultural and natural wetland ecosystems (Saunois et al., 2016; Schwietzke et al., 2016).

Nearly 2/3 of the global methane emissions of ca. 550 Tg CH_4 yr^{-1} are thought to originate from tropical sources (Denman et al., 2007; Kirschke et al., 2013; Saunois et al., 2016), and nearly 1/3 from natural wetlands (Kirschke et al., 2013; Saunois et al., 2016). At the regional scale, Southeast Asia is estimated to emit 73 Tg CH_4 yr^{-1}, dominated by wetland emissions (~37%) and agriculture and waste emissions (~33%) (Saunois et al., 2016). Wetland emissions remain the largest uncertainty in the methane budget (Kirschke et al., 2013; Saunois et al., 2016), owing in part to lack of observations. No analysis to our knowledge has measured whole-ecosystem CH_4 flux from a tropical peat forested wetland to date despite the importance of tropical wetlands to global CH_4 efflux and recent studies demonstrating that the areal extent of tropical peat forests is greater than previously thought (Dargie et al., 2017).

Here, we measure the flux of CH_4 between a tropical peat forest in Sarawak, Malaysian Borneo and the atmosphere during the transition to the wet season using the eddy covariance technique. We choose the eddy covariance system to make whole-ecosystem CH_4 flux measurements given recent findings that CH_4 transport through tree stems may be an important pathway that cannot be accounted for using soil chamber methods (Pitz and Megonigal, 2017). (Eddy covariance can also measure aerobic CH_4 emissions from vegetated canopies via ultraviolet irradiation of pectin (Keppler et al.,

2006), noting that recent studies have demonstrated that this source is likely to be a minor

(McLeod et al., 2008), on the order of $0.2 - 1.0$ Tg CH_4 yr^{-1} (Bloom et al., 2010)). We

place particular emphasis on understanding the mechanisms that control CH_4 efflux at the

ecosystem scale, and discuss CH_4 flux measurements in the context of similar

measurements from other global ecosystems.

Materials and Methods

Study Ecosystem and Micrometeorological Measurements

The study ecosystem is a tropical peat forest ecosystem in Maludam National

Park in the Betong Division of Sarawak, Malaysia described in more detail in Tang et al.

(in review). Dominant vegetation in the overstory includes *Shorea albida*, *Gonystylus*

bancanus and *Stemonurus* spp (Anderson, 1972) with an average canopy height of 25 m

and emergent trees exceeding 30 m. The peat thickness is *ca*. 8 m in the vicinity of the

tower located at 1º27'55"N, 111º9'20"E. A standard suite of micrometeorological

measurements including rainfall (P), wind speed (WS), air temperature (T_{air}), relative

humidity (RH, and thereby the vapor pressure deficit, VPD), volumetric soil water

content (SWC), soil temperature (T_{soil}), incident photosynthetically active (PPFD), net

(R_n) and global radiation (R_g), and water table height (WT) were made and recorded at

half hourly intervals as described in Tang et al. (in review).

Eddy Covariance Measurements

Eddy covariance measurements were made from November-December 2013 at 40

m using an open-path Li-7700 infrared gas analyzer (LiCor, Lincoln, NE, USA) and

CSAT3 three-dimensional sonic anemometer (Campbell Scientific, Logan, UT, USA). Post-processing calculations were performed using EddyPro software (LiCor). Double rotation was performed to align the *x*-axis of the sonic anemometer with the mean flow, and the WPL correction (Webb et al., 1980) was applied to compensate the density fluctuation effect and spectroscopic effect on measured CH_4. Fluxes were corrected for frequency response losses (William. J. Massman, 2000) and the time lag between wind measurements and CH_4 concentration measurements was compensated for during each averaging period.

We select flux observations with a Li-7700 relative signal strength indicator (RSSI) greater than 10% following the recommendations of (McDermitt et al., 2011) (see also (Chu et al., 2014) and explore the sensitivity of this threshold in Appendix A given the frequency of dew formation events that reduce the RSSI in tropical forest ecosystems with characteristically high dew points. We used both friction velocity and atmospheric stability thresholds following Novick et al. (2004) to determine sufficient turbulent intensity for nighttime eddy covariance flux measurements as described in Tang et al. (in review). We present eddy covariance flux data from the top of the canopy as within-canopy CH_4 concentration measurements were not made to calculate a storage flux, which is negligible at diurnal time scales. We test the sensitivity of this assumption for whole ecosystem fluxes using the one point time derivative (Gu et al., 2012) in Appendix B.

Gap Filling of CH$_4$ Flux Data

Continuous time series of scalar fluxes are not possible with eddy covariance systems due to periods of insufficient turbulence and disturbances like rain events that impede sonic anemometers and open path infrared gas analyzers. To obtain continuous time series to create daily and monthly sums of CH$_4$ flux, we used the Marginal Distribution Sampling (MDS) gap filling algorithm (Reichstein et al., 2005) as implemented in the REddyProc package (Department for Biogeochemical Integration at the Max Planck Institute for Biogeochemistry, 2017). The routine adopts the look-up table approach where the missing value is replaced by the mean value under similar meteorological conditions, or mean diurnal course method if the value could not be filled using look-up table approach.

Data Analysis

To understand the relationships between micrometeorological drivers and CH$_4$ flux, we use least-squares regression and identified parsimonious linear models of CH$_4$ flux using maximum likelihood techniques via the *dredge* function of the 'MuMIn' package in R (Bartoń, 2016). The *dredge* algorithm creates all possible uni- and multivariate models of a dependent variable (in this case CH$_4$ flux) based on independent variables (in this case the micrometeorological variables described in 2.1 and in more detail in Tang et al. (in review)), and selects the model with the minimum value of the Akaike Information Criterion (AIC) - the model with the lowest value of the likelihood function penalized by number of model parameters - as the most parsimonious (Akaike, 1974).

Results

Micrometeorological Variability

Average monthly air temperature decreased and precipitation increased from November 2013 (26.5°C; 224 mm) to December 2013 (26.2°C; 562mm) and less global radiation (R_g) accumulated in December (454 MJ m^{-2}) than November (532 MJ m^{-2}) (Figure 4.1a,b). SWC increased to field capacity – with the exception of a weeklong period of decline in mid-November – as WT approached and then exceeded the soil surface in late November (Figure 4.1c). The study period thus encompasses the transition from unsaturated to saturated soil conditions with standing water present throughout December.

Wind-rose analyses show that wind mainly came from southeast in November and northwest in December (Figure 4.2a), suggesting a shift in dominant source area. As a consequence we include wind direction in the modeling analysis and perform the modeling analysis for each month to explore if different variables are responsible for CH_4 efflux across time (Figure 4.1d) and space (Figure 4.2b).

CH_4 Flux

Monthly mean CH_4 flux was higher in December (25.3 ± 0.6 nmol m^{-2} s^{-1}) than November (20.3 ± 0.8 nmol m^{-2} s^{-1}; $p < 0.05$), but the temporal variability of CH_4 flux was higher during November than December (Figure 4.1d). Further, both daytime and nighttime CH_4 flux were higher in December (30 ± 1 nmol m^{-2} s^{-1}; 20 ± 0.4 nmol m^{-2} s^{-1}) than November (27 ± 1 nmol m^{-2} s^{-1}; 13 ± 0.6 nmol m^{-2} s^{-1}). The half-hourly mean CH_4 flux exhibited a few peaks in emissions on the order of 45 to 50 nmol m^{-2} s^{-1} during the

morning hours, and began to decline after a peak around 10:00 (Local Standard Time).

Higher flux was observed during the day (07:00 – 18:30) (29 ± 1 nmol m^{-2} s^{-1}) than at

night (19:00 – 06:30) (17 ± 0.3 nmol m^{-2} s^{-1}) (Fig 4.3) and a two-dimensional kernel

density estimate demonstrates two regions of higher CH$_4$ efflux that correspond to the

shift in wind direction from southeast in November to northwest in December (Fig 4.2c).

Models of Ecosystem-Scale CH$_4$ Flux

Observations demonstrated little reason to justify nonlinear relationships between

driver and response over the observed range of CH$_4$ flux and micrometeorological

variability (data not shown), hence we explore simple multiple linear models of daily

CH$_4$ flux selected by *dredge* to have the lowest AIC value. The most parsimonious model

for the entire measurement period included WD: 0.046– 0.000096WD but only explained

10% of the variance in half-hourly CH$_4$ flux measurements. Following studies that

included carbon dioxide flux as additional explanatory variables for CH$_4$ flux (e.g.

(Christensen et al., 1996)), we added eddy covariance-measured net ecosystem exchange

of CO$_2$ as well as eddy covariance-based estimates of gross primary productivity (GPP)

and ecosystem respiration (RE) following Tang et al. (in review) in the dredge procedure

to arrive at the same parsimonious linear model.

The *dredge* analyses fitted different models for November and December,

respectively. For November, the model -0.54 – 0.0034RH + 0.0096 T$_{air}$ explains

approximately 2.5% of the variability in CH$_4$ flux. About 3.4% of the variance in CH$_4$

flux can be explained by WD, WS and WT in December: 0.053 – 0.00012WD +

0.0098WS – 0.0013WT.

Discussion

Mean eddy covariance-measured CH_4 emissions on the order of 0.024 g C-CH_4 m^{-2} d^{-1} are of similar magnitude to eddy covariance measurements from rice agroecosystems in the Philippines and Taiwan (*ca.* 0.018 g C-CH_4 m^{-2} y^{-1}, Alberto et al., 2014; Tseng et al., 2010), and from boreal fens in Canada and Finland (*ca.* 0.019-0.026 g C-CH_4 m^{-2} d^{-1}, Long et al., 2010; Rinne et al., 2007, Table 4.1). Results therefore demonstrate little reason to believe that tropical peat forests are disproportionally important to the global CH_4 budget if the study ecosystem is representative of global tropical peat forests.

Table 4.1: Mean daily CH_4 flux measured using the eddy covariance method from different ecosystems in North America, Europe, and Asia.

Ecosystem	CH_4 emission (g C m^{-2} d^{-1})	References
Pine plantation, USA	0.0025	*Smeets et al.* [2009]
Soybean cropland, USA	0.0063	*Chu et al.* [2014]
Arctic tundra, Russia	0.0066	*Wille et al.* [2008]
Aapa mire, Finland	0.011	*Hargreaves et al.* [2001]
Aapa mire, Finland	0.013*	*Hartley et al.* [2015]
Rice fields, Philippines	0.018	*Alberto et al.* [2014]
Rice paddy, Taiwan	0.018	*Tseng et al.* [2010]
Boreal fen, Canada	0.019	*Long et al.* [2010]
Tropical peat forest, Malaysia	**0.024**	**This study**
Boreal fen, Finland	0.026	*Rinne et al.* [2007]
Aapa mire, Finland	0.033**	*Hartley et al.* [2015]
Subarctic peatland, Sweden	0.056	*Jackowicz-Korczyński et al.* [2010]
Alpine wetland, China	0.062	*Song et al.* [2015]
Freshwater marsh, USA	0.14	*Chu et al.* [2014]

*First campaign: 4-13 June
**Second campaign: 13-31 July

Modeling analyses revealed relatively poor fits to observations, suggesting that above-canopy micrometeorological variables and soil variables measured at a point do not capture whole-ecosystem methane efflux, which may be the result of multiple 'hot spot hot moment' dynamics distributed across the flux footprint (Wilson et al., 2009) and mixed by turbulence. The *dredge* analysis revealed that precipitation was an important model input in November and T_{air} and WT were important inputs in December suggesting a shift in controls over methane efflux from unsaturated to saturated conditions. Surprisingly, the best fit model included negative terms for all of these variables, highlighting that simple temperature sensitivity was not exhibited across the measurement period (for which the range of T_{air} was only 10.9°C), and also that high WT values may hinder CH_4 efflux by serving as a barrier to diffusion.

Combined, measurements demonstrate that CH_4 flux from a tropical peat forest was similar to other managed and natural wetland ecosystems, including those in different climate zones, but also that meteorological variability described CH_4 efflux poorly: whereas best fit models were highly significant ($p < 0.01$), they explained about 10% of observed variability.

Summary/Conclusions

Ecosystem-scale observations of CH_4 flux in an undisturbed tropical peat forest ecosystem in Malaysian Borneo during the wet season demonstrated a CH_4 source on the order of 0.024 g C m^{-2} d^{-1}, similar to eddy covariance measurements from rice agroecosystems in Southeast Asia and boreal fens in Finland and Canada (Table 4.1). Modeling results indicate that rainfall, wind direction and wind speed are important terms

for describing the variability of CH_4 flux for November, while global radiation, air temperature and water table for December, but tended to explain only a small part of its variability, on the order of 3.3 % and 4.4%, respectively. Results do not point to tropical peat forests as a dominant contributor to global atmospheric concentrations of CH_4 or their recent increase, and we suggest that whole-year CH_4 flux measurements across multiple tropical ecosystems will help understand their role in the global methane budget.

<u>Acknowledgements</u>

<u>Appendix A</u>

Eddy covariance measurements are sensitive to the thresholds used to adjudge if sensor response is adequate to measure the turbulent exchange of a scalar between the surface and atmosphere. In the case of the Li-7700, it is recommended that RSSI values greater than 10% be used to ensure that the instrument is not compromised by disturbances like dust or dew formation (McDermitt et al., 2011). We performed a sensitivity analysis on 10%, 15% and 20% RSSI threshold, and demonstrate that nighttime CH_4 flux was lowest with 20% threshold and highest with 15% threshold, whereas daytime CH_4 flux was highest with 10% threshold particularly in the morning (Figure A1). Mean daily CH_4 flux was 0.024, 0.022 and 0.02 g C m^{-2} d^{-1} for 10%, 15%

and 20% threshold, respectively, demonstrating minor sensitivity to the choice of RSSI value during the measurement period for mean CH_4 flux, but a dampening of the diurnal range and changes to nighttime CH_4 flux values, with modeling implications. Our results are subject to this uncertainty in the optimum value of RSSI to use for tropical ecosystems that are characteristically moist and for which dew events are exceedingly likely (Figure A1).

Appendix B

CH_4 concentration measurements were not made to estimate subcanopy storage (F_{STO}), which is trivial at diurnal time scales but can influence diurnal patterns. We applied the one point time derivative approach of (Gu et al., 2012) to estimate the contribution of subcanopy storage to CH_4 efflux. Results demonstrate that net F_s makes a negligible contribution to total CH_4 flux across the entire measurement period (Figure B1), but increases CH_4 flux estimates during early November (on the order of 5 nmol m^{-2} s^{-1}, *ca.* 20%) and decreases CH_4 flux estimates during after Nov. 20 on the order of 2 nmol m^{-2} s^{-1}. Results do not change CH_4 efflux estimates across the entire measurement period, but suggest that November CH_4 may be slightly underestimated and December CH_4 flux may be slightly overestimated. As a result, we suggest that F_{STO} measurements be made to improve estimates of CH_4 flux seasonality in forested ecosystems for which storage contributions are often non-trivial.

References

Akaike, H., 1974. A new look at the statistical model identification. IEEE Trans. Automat. Contr. 19, 716–723.

Alberto, M.C.R., Wassmann, R., Buresh, R.J., Quilty, J.R., Correa, T.Q., Sandro, J.M., Centeno, C.A.R., 2014. Measuring methane flux from irrigated rice fields by eddy covariance method using open-path gas analyzer. F. Crop. Res. 160, 12–21.

Anderson, J.A.R., 1972. Synoptical Key for the Identification of the Trees of the Peat Swamp Forests of Sarawak. Forest Department, Sarawak.

Aydin, M., Verhulst, K.R., Saltzman, E.S., Battle, M.O., Montzka, S.A., Blake, D.R., Tang, Q., Prather, M.J., 2011. Recent decreases in fossil-fuel emissions of ethane and methane derived from firn air. Nature 476, 198–201.

Bartoń, K., 2016. MuMIn: Multi-Model Inference. R package version 1.15.6, http://cran.r-project.org/package=MuMIn

Bloom, A.A., Lee-Taylor, J., Madronich, S., Messenger, D.J., Palmer, P.I., Reay, D.S., McLeod, A.R., 2010. Global methane emission estimates from ultraviolet irradiation of terrestrial plant foliage. New Phytol. 187, 417–425.

Bousquet, P., Ringeval, B., Pison, I., Dlugokencky, E.J., Brunke, E.G., Carouge, C., Chevallier, F., Fortems-Cheiney, A., Frankenberg, C., Hauglustaine, D.A., Krummel, P.B., Langenfelds, R.L., Ramonet, M., Schmidt, M., Steele, L.P., Szopa, S., Yver, C., Viovy, N., Ciais, P., 2011. Source attribution of the changes in atmospheric methane for 2006-2008. Atmos. Chem. Phys. 11, 3689–3700.

Christensen, T.R., Prentice, I.C., Kaplan, J., Haxeltine, A., Sitch, S., 1996. Methane flux from northern wetlands and tundra. Tellus B 48, 652–661.

Chu, H., Jiquan Chen, Johan F. Gottgens, Zutao Ouyang, Ranjeet John, Kevin Czajkowski, Richard Becker, 2014. Net ecosystem methane and carbon dioxide exchanges in a Lake Erie coastal marsh and a nearby cropland. J. Geophys. Res. Biogeosciences 119, 722–740.

Dargie, G.C., Lewis, S.L., Lawson, I.T., Mitchard, E.T.A., Page, S.E., Bocko, Y.E., Ifo, S.A., 2017. Age, extent and carbon storage of the central Congo Basin peatland complex. Nature 542, 86–90.

Denman, K.L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P.M., Dickinson, R.E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, U., Lohmann, S.R., da Silva Dias, P.L., Wofsy, S.C., Zhang, X., 2007. Couplings Between Changes in the Climate

System and Biogeochemistry. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin. In: Climate Change 2007: The Physical Science Basis. Cambridge University Press, Cambridge, United Kingdom and New York, USA.

Department for Biogeochemical Integration at the Max Planck Institute for Biogeochemistry, 2017. REddyProc: Data processing and plotting utilities of (half-)hourly eddy-covariance measurements, http://r-forge.r-project.org/projects/reddyproc/

Dlugokencky, E., 2017. NOAA/ESRL, http://www.esrl.noaa.gov/gmd/ccgg/trends_ch4/

Gu, L., Massman, W.J., Leuning, R., Pallardy, S.G., Meyers, T., Hanson, P.J., Riggs, J.S., Hosman, K.P., Yang, B., 2012. The fundamental equation of eddy covariance and its application in flux measurements. Agric. For. Meteorol. 152, 135–148.

Hausmann, P., Sussmann, R., Smale, D., 2016. Contribution of oil and natural gas production to renewed increase in atmospheric methane (2007-2014): Top-down estimate from ethane and methane column observations. Atmos. Chem. Phys. 16, 3227–3244.

Helmig, D., Rossabi, S., Hueber, J., Tans, P., Montzka, S.A., Masarie, K., Thoning, K., Plass-Duelmer, C., Claude, A., Carpenter, L.J., Lewis, A.C., Punjabi, S., Reimann, S., Vollmer, M.K., Steinbrecher, R., Hannigan, J.W., Emmons, L.K., Mahieu, E., Franco, B., Smale, D., Pozzer, A., 2016. Reversal of global atmospheric ethane and propane trends largely due to US oil and natural gas production. Nat. Geosci. 9, 490–495.

Kai, F.M., Tyler, S.C., Randerson, J.T., Blake, D.R., 2011. Reduced methane growth rate explained by decreased Northern Hemisphere microbial sources. Nature 476, 194–197.

Keppler, F., Hamilton, J.T., Bra, M., Rockmann, T., 2006. Methane emissions from terrestrial plants under aerobic conditions. Nature 439, 187–191.

Kirschke, S., Bousquet, P., Ciais, P., Saunois, M., Canadell, J.G., Dlugokencky, E.J., Bergamaschi, P., Bergmann, D., Blake, D.R., Bruhwiler, L., Cameron-Smith, P., Castaldi, S., Chevallier, F., Feng, L., Fraser, A., Heimann, M., Hodson, E.L., Houweling, S., Josse, B., Fraser, P.J., Krummel, P.B., Lamarque, J.-F., Langenfelds, R.L., Le Quéré, C., Naik, V., O'Doherty, S., Palmer, P.I., Pison, I., Plummer, D., Poulter, B., Prinn, R.G., Rigby, M., Ringeval, B., Santini, M., Schmidt, M., Shindell, D.T., Simpson, I.J., Spahni, R., Steele, L.P., Strode, S.A., Sudo, K., Szopa, S., van der Werf, G.R., Voulgarakis, A., van Weele, M., Weiss, R.F., Williams, J.E.,

Zeng, G., 2013. Three decades of global methane sources and sinks. Nat. Geosci. 6, 813–823.

Levin, I., Veidt, C., Vaughn, B.H., Brailsford, G., Bromley, T., Heinz, R., Lowe, D., Miller, J.B., Poß, C., White, J.W.C., 2012. No inter-hemispheric δ13CH4 trend observed. Nature 486, E3–E4.

Long, K.D., Flanagan, L.B., Cai, T., 2010. Diurnal and seasonal variation in methane emissions in a northern Canadian peatland measured by eddy covariance. Glob. Chang. Biol. 16, 2420–2435.

Massman, W.J., 2000. A simple method for estimating frequency response corrections for eddy covariance systems. Agric. For. Meteorol. 104, 185–198.

McDermitt, D., Burba, G., Xu, L., Anderson, T., Komissarov, A., Riensche, B., Schedlbauer, J., Starr, G., Zona, D., Oechel, W., Oberbauer, S., Hastings, S., 2011. A new low-power, open-path instrument for measuring methane flux by eddy covariance. Appl. Phys. B Lasers Opt. 102, 391–405.

McLeod, A.R., Fry, S.C., Loake, G.J., Messenger, D.J., Reay, D.S., Smith, K.A., Yun, B.W., 2008. Ultraviolet radiation drives methane emissions from terrestrial plant pectins. New Phytol. 180, 124–132.

Myhre, G., Shindell, D., Bréon, F.M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.F., Lee, D., Mendoza, B., Nakajima, T., 2013. Anthropogenic and Natural Radiative Forcing. Clim. Chang. 423, 658–740.

Nisbet, E.G., Dlugokencky, E.J., Manning, M.R., Lowry, D., Fisher, R.E., France, J.L., Michel, S.E., Miller, J.B., White, J.W.C., Vaughn, B., Bousquet, P., Pyle, J.A., Warwick, N.J., Cain, M., Brownlow, R., Zazzeri, G., Lanoisellé, M., Manning, A.C., Gloor, E., Worthy, D.E.J., Brunke, E.-G., Labuschagne, C., Wolff, E.W., Ganesan, A.L., 2016. Rising atmospheric methane: 2007-14 growth and isotopic shift. Global Biogeochem. Cycles 30, 1356–1370.

Novick, K.A., Stoy, P.C., Katul, G.G., Ellsworth, D.S., Siqueira, M.B.S., Juang, J., Oren, R., 2004. Carbon dioxide and water vapor exchange in a warm temperate grassland. Oecologia 138, 259–274.

Pison, I., Ringeval, B., Bousquet, P., Prigent, C., Papa, F., 2013. Stable atmospheric methane in the 2000s: Key-role of emissions from natural wetlands. Atmos. Chem. Phys. 13, 11609–11623.

Pitz, S., Megonigal, J.P., 2017. Temperate forest methane sink diminished by tree emissions. New Phytol. 214, 1432–1439.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grünwald, T., Havránková, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J.-M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., Valentini, R., 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration : review and improved algorithm. Glob. Chang. Biol. 11, 1424–1439.

Rice, A.L., Butenhoff, C.L., Teama, D.G., Röger, F.H., Khalil, M.A.K., Rasmussen, R.A., 2016. Atmospheric methane isotopic record favors fossil sources flat in 1980s and 1990s with recent increase. Proc. Natl. Acad. Sci. 113, 10791–10796.

Rinne, J., Riutta, T., Pihlatie, M., Aurela, M., Haapanala, S., Tuovinen, J.P., Tuittila, E.S., Vesala, T., 2007. Annual cycle of methane emission from a boreal fen measured by the eddy covariance technique. Tellus, Ser. B Chem. Phys. Meteorol. 59, 449–457.

Saunois, M., Jackson, R.B., Bousquet, P., Poulter, B., Canadell, J.G., 2016. The growing role of methane in anthropogenic climate change. Environ. Res. Lett. 11, 120207.

Schaefer, H., Fletcher, S.E.M., Veidt, C., Lassey, K.R., Brailsford, G.W., Bromley, T.M., Dlugokencky, E.J., Michel, S.E., Miller, J.B., Levin, I, Lowe, D.C., Martin, R.J., Vaughn, B.H., White, J.W.C., 2016. A 21st-century shift from fossil-fuel to biogenic methane emissions indicated by $^{13}CH_4$. Science. 352, 80–84.

Schwietzke, S., Sherwood, O.A., Bruhwiler, L.M.P., Miller, J.B., Etiope, G., Dlugokencky, E.J., Michel, S.E., Arling, V.A., Vaughn, B.H., White, J.W.C., Tans, P.P., 2016. Upward revision of global fossil fuel methane emissions based on isotope database. Nature 538, 88–91.

Shindell, D., Kuylenstierna, J.C.I., Vignati, E., van Dingenen, R., Amann, M., Klimont, Z., Anenberg, S.C., Muller, N., Janssens-Maenhout, G., Raes, F., Schwartz, J., Faluvegi, G., Pozzoli, L., Kupiainen, K., Hoglund-Isaksson, L., Emberson, L., Streets, D., Ramanathan, V., Hicks, K., Oanh, N.T.K., Milly, G., Williams, M., Demkine, V., Fowler, D., 2012. Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security. Science. 335, 183–189.

Simpson, I.J., Sulbaek Andersen, M.P., Meinardi, S., Bruhwiler, L., Blake, N.J., Helmig, D., Rowland, F.S., Blake, D.R., 2012. Long-term decline of global atmospheric ethane concentrations and implications for methane. Nature 488, 490–494.

Tseng, K.H., Tsai, J.L., Alagesan, A., Tsuang, B.J., Yao, M.H., Kuo, P.H., 2010. Determination of methane and carbon dioxide fluxes during the rice maturity period

in Taiwan by combining profile and eddy covariance measurements. Agric. For. Meteorol. 150, 852–859.

Turner, A.J., Frankenberg, C., Wennberg, P.O., Jacob, D.J., 2017. Ambiguity in the causes for decadal trends in atmospheric methane and hydroxyl. Proc. Natl. Acad. Sci. 114, 201616020.

Webb, E.K., Pearman, G.I., Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. Q. J. R. Meteorol. Soc. 106, 85–100.

Wilson, D., Alm, J., Laine, J., Byrne, K.A., Farrell, E.P., Tuittila, E.S., 2009. Rewetting of cutaway peatlands: Are we re-creating hot spots of methane emissions? Restor.

Figure 4.1. Time series of daily (a) rainfall, (b) air temperature (T_{air}) and soil temperature (T_s), (c) wind speed, (d) water table (WT) depth and soil water content (SWC), and (e) methane (CH_4) flux.

Figure 4.2. (a) Wind rose indicating the predominant wind direction at the study site. (b) The relationship between wind direction and CH_4 flux as represented by a two-dimensional kernel density estimate ("heat map") for all half-hourly observations.

Figure 4.3: Diurnal pattern of CH_4 flux.

Figure A1: The diurnal variability of the CH_4 flux to relative signal strength indicator (RSSI) thresholds of the Li-Cor 7700 CH_4 analyzer.

Figure B1: Daily averaged ecosystem-atmosphere CH_4 efflux measurements from a tropical peat forest in Sarawak Malaysia using the eddy covariance system (F_{CH4} and subcanopy storage (F_{STO})) using the one point time derivative approach of Gu et al. [2002], which are summed to estimate the net ecosystem exchange of CH_4 (NEE).

CHAPTER FIVE

CONCLUSIONS

The present research comprised the first known ecosystem-scale measurements of CO_2, CH_4, water, and energy fluxes from an undisturbed tropical peat forest ecosystem. I highlight the major findings from Chapters 2-4 in this brief conclusion and discuss important future steps to take to further our understanding of the carbon metabolism and hydrology of tropical peat forests, especially in light of recent findings of previously undiscovered tropical peat forests in the Congo Basin (Dargie et al., 2017).

Chapter 2 demonstrated that the study ecosystem, a tropical peat swamp forest in Sarawak, Malaysian Borneo, constituted a substantial net CO_2 source during the measurement period from 2011 to 2014, similar to a hydrologically disturbed tropical peat forest in central Kalimantan, Indonesian Borneo. Specifically, the annual cumulative net ecosystem CO_2 exchange NEE was 632 ± 297, 509 ± 164, 183 ± 44, and 356 ± 98 g C m^{-2} y^{-1} for 2011, 2012, 2013 and 2014. The inter-annual variation in NEE was largely modulated by the variation in gross primary production (GPP), which was jointly controlled by vapor pressure deficit (VPD) and leaf area index (LAI) in addition to photosynthetically active photon flux density (PPFD). Temporal changes in ecosystem respiration (RE) were closely related to water table depth.

Results from Chapter 2 are perhaps alarming given that the study ecosystem must have served as a net C sink over time scales of centuries to millennia in order to accumulate the 8 m of peat found in the vicinity of the eddy covariance tower. Results highlight that the C balance tropical peat forest ecosystems may also be sensitive to

indirect anthropogenic disturbances given that the study ecosystem is a C source to the atmosphere. It was difficult to attribute the large C emission event in 2011 to a particular micrometeorological or hydrological driver, and it may be speculated that high atmospheric ozone concentrations arising from the abundant peat fires in Indonesia during the 2011 dry season may have played a role in reducing GPP. Ozone is rarely measured in conjunction with eddy covariance towers and future studies should explore its role in controlling GPP at the study site and in other tropical rainforest ecosystems that are subject to atmospheric pollution due to industrial and agricultural sources. To this end, measurements of direct and diffuse PPFD at the tower would enable future studies to isolate how radiation attenuation *versus* atmospheric chemistry provide constraints on the seasonal patterns of GPP at the study ecosystem and other tropical rainforests and peat forests in SE Asia.

The third chapter found that both sensible heat flux (*H*) and latent heat flux (*LE*) and their ratio (the Bowen ratio, *Bo*) were relatively invariant compared to other tropical rainforests with *LE* values on the order of 11 MJ m^{-2} day and *H* on the order of 3 MJ m^{-2} day^{-1}.Annual evapotranspiration (ET) did not differ among years and averaged 1579 ± 47 mm $year^{-1}$. The magnitude of average daily *LE* across the calendar year tended to be higher at MY-MLM (11 MJ m^{-2} day^{-1}) than most other tropical rainforest ecosystems in the FLUXNET2015 database.

Results demonstrate important differences in the seasonal patterns in water and energy exchange in tropical rainforest ecosystems that need to be captured by models to understand how ongoing changes in tropical rainforest extent impact the global climate

system. Findings illustrate the hydrologic diversity of tropical rainforest ecosystems in response to seasonal availability of moisture and energy to drive ET. They also provide a framework for analyzing eddy covariance measurements of water and energy flux in the future by placing results from a particular ecosystem (in this case a tropical peat forest) in the context of similar ecosystems (in this case other tropical rainforests) to emphasize similarities and differences among ecosystems to aid in finding universal patterns and important distinctions that can guide modeling studies in the future.

The fourth chapter found that the two-month average of C-CH$_4$ flux measurements, was on the order of 0.024 g C-CH$_4$ m^{-2} d^{-1} during the dry to wet season transition. A comparison against C-CH$_4$ measurements from other temperate ecosystems suggests that tropical peat forests are not likely to be disproportionally important to global CH$_4$ flux if the study ecosystem is representative of other tropical peat forests. Results demonstrate a limited ability for simple models to capture the variability in the diurnal pattern of CH$_4$ efflux, but also consistent responses to soil moisture, water table height, and precipitation over daily to weekly time scales.

A logical extension of the fourth chapter is to continue to make ecosystem-scale CH$_4$ measurements from the study ecosystem to quantify interannual patterns in CH$_4$ uptake and emission. Given that the present findings represent the first known ecosystem-scale CH$_4$ flux measurements from a tropical rainforest, future studies should also compare multiple ecosystems, both *terre firme* and seasonally flooded, to improve our understanding of the biospheric sources and sinks of this critical greenhouse gas.

References

Dargie, G.C., Lewis, S.L., Lawson, I.T., Mitchard, E.T.A., Page, S.E., Bocko, Y.E., Ifo, S.A., 2017. Age, extent and carbon storage of the central Congo Basin peatland complex. Nature 542, 86–90.

REFERENCES CITED

Akaike, H., 1974. A new look at the statistical model identification. IEEE Trans. Automat. Contr. 19, 716–723.

Alberto, M.C.R., Wassmann, R., Buresh, R.J., Quilty, J.R., Correa, T.Q., Sandro, J.M., Centeno, C.A.R., 2014. Measuring methane flux from irrigated rice fields by eddy covariance method using open-path gas analyzer. F. Crop. Res. 160, 12–21.

Anderson, J.A.R., 1972. Synoptical Key for the Identification of the Trees of the Peat Swamp Forests of Sarawak. Forest Department, Sarawak.

Aubinet, M., Chermanne, B., Vandenhaute, M., Longdoz, B., Yernaux, M., Laitat, E., 2001. Long term carbon dioxide exchange above a mixed forest in the Belgian Ardennes. Agric. For. Meteorol. 108, 293–315.

Avissar, R., Werth, D., 2005. Global hydroclimatological teleconnections resulting from tropical deforestation. J. Hydrometeorol. 6, 134–145.

Aydin, M., Verhulst, K.R., Saltzman, E.S., Battle, M.O., Montzka, S.A., Blake, D.R., Tang, Q., Prather, M.J., 2011. Recent decreases in fossil-fuel emissions of ethane and methane derived from firn air. Nature 476, 198–201.

Bala, G., Caldeira, K., Wickett, M., Phillips, T.J., Lobell, D.B., Delire, C., Mirin, A., 2007. Combined climate and carbon-cycle effects of large-scale deforestation. Proc. Natl. Acad. Sci. USA 104, 6550–6555.

Barr, J.G., Fuentes, J.D., Delonge, M.S., O'Halloran, T.L., Barr, D., Zieman, J.C., 2013. Summertime influences of tidal energy advection on the surface energy balance in a mangrove forest. Biogeosciences 10, 501–511.

Bartoń, K., 2016. MuMIn: Multi-Model Inference. R package version 1.15.6, http://cran.r-project.org/package=MuMIn

Beringer, J., Chapin, F.S., Thompson, C.C., McGuire, A.D., 2005. Surface energy exchanges along a tundra-forest transition and feedbacks to climate. Agric. For. Meteorol. 131, 143–161.

Bloom, A.A., Lee-Taylor, J., Madronich, S., Messenger, D.J., Palmer, P.I., Reay, D.S., McLeod, A.R., 2010. Global methane emission estimates from ultraviolet irradiation of terrestrial plant foliage. New Phytol. 187, 417–425.

Bousquet, P., Ringeval, B., Pison, I., Dlugokencky, E.J., Brunke, E.G., Carouge, C., Chevallier, F., Fortems-Cheiney, A., Frankenberg, C., Hauglustaine, D.A., Krummel, P.B., Langenfelds, R.L., Ramonet, M., Schmidt, M., Steele, L.P., Szopa, S., Yver, C., Viovy, N., Ciais, P., 2011. Source attribution of the changes in atmospheric methane for 2006-2008. Atmos. Chem. Phys. 11, 3689–3700.

Canadell, J., Jackson, R., Ehleringer, J., Mooney, H.A., Sala, O.E., Schulze, E.-D., 1996. Maximum rooting depth of vegetation types at the global scale. Oecologia 108, 583–595.

Chambers, J.Q., Tribuzy, E.S., Toledo, L.C., Crispim, B.F., Higuchi, N., Santos, J.D., Araújo, A.C., Kruijt, B., Nobre, A.D., Trumbore, S.E., 2004. Respiration from a tropical forest ecosystem: partitioning of sources and low carbon use efficiency. Ecol. Appl. 14, 72–88.

Christensen, T.R., Prentice, I.C., Kaplan, J., Haxeltine, A., Sitch, S., 1996. Methane flux from northern wetlands and tundra. Tellus B 48, 652–661.

Chu, H., Jiquan Chen, Johan F. Gottgens, Zutao Ouyang, Ranjeet John, Kevin Czajkowski, Richard Becker, 2014. Net ecosystem methane and carbon dioxide exchanges in a Lake Erie coastal marsh and a nearby cropland. J. Geophys. Res. Biogeosciences 119, 722–740.

Da Rocha, H.R., Goulden, M.L., Miller, S.D., Menton, M.C., Pinto, L.D.V.O., de Freitas, H.C., de Silva Figueira, A.M., 2004. Seasonality of wtaer and heat fluxes over a tropical forest in eastern Amazonia. Ecol. Appl. 14, 22–32.

Dargie, G.C., Lewis, S.L., Lawson, I.T., Mitchard, E.T.A., Page, S.E., Bocko, Y.E., Ifo, S.A., 2017. Age, extent and carbon storage of the central Congo Basin peatland complex. Nature 542, 86–90.

Denman, K.L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P.M., Dickinson, R.E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, U., Lohmann, S.R., da Silva Dias, P.L., Wofsy, S.C., Zhang, X., 2007. Couplings Between Changes in the Climate System and Biogeochemistry. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin. In: Climate Change 2007: The Physical Science Basis. Cambridge University Press, Cambridge, United Kingdom and New York, USA.

Department for Biogeochemical Integration at the Max Planck Institute for Biogeochemistry, 2017. REddyProc: Data processing and plotting utilities of (half-)hourly eddy-covariance measurements, http://r-forge.r-project.org/projects/reddyproc/

Dlugokencky, E., 2017. NOAA/ESRL, http://www.esrl.noaa.gov/gmd/ccgg/trends_ch4/

Fisher, R.A., Williams, M., Do Vale, R.L., Da Costa, A.L., Meir, P., 2006. Evidence from Amazonian forests is consistent with isohydric control of leaf water potential. Plant. Cell Environ. 29, 151–165.

Fisher, R.A., Williams, M., Do Vale, R.L., Da Costa, A.L., Meir, P., 2006. Evidence from Amazonian forests is consistent with isohydric control of leaf water potential. Plant. Cell Environ. 29, 151–165.

Foken, T., 2008. The energy balance closure problem: An overview. Ecol. Appl. 18, 1351–1367.

Gerken, T., Ruddell, B.L., Fuentes, J.D., Araújo, A., Brunsell, N.A., Maia, J., Manzi, A., Mercer, J., dos Santos, R.N., von Randow, C., Stoy, P.C., 2017. Investigating the mechanisms responsible for the lack of surface energy balance closure in a central Amazonian tropical rainforest. Agric. For. Meteorol.

Gorham, E., 1991. Northern Peatlands : Role in the Carbon Cycle and Probable Responses to Climatic Warming. Ecol. Appl. 1, 182–195.

Goulden, M.L., Miller, S.D., Da Rocha, H.R., Menton, M.C., de Freitas, H.C., Silva Figueira, M.E., de Sousa, C.A.D., 2004. Diel and seasonal patterns of tropical forest CO2 exchange. Ecol. Appl. 14, 42–54.

Grace, J., Malhi, Y., Lloyd, J., McIntyre, J., Miranda, A.C., Meir, P., Miranda, H.S., 1996. The use of eddy covariance to infer the net carbon dioxide uptake of Brazilian rain forest. Glob. Chang. Biol. 2, 209–217.

Gu, L., Massman, W.J., Leuning, R., Pallardy, S.G., Meyers, T., Hanson, P.J., Riggs, J.S., Hosman, K.P., Yang, B., 2012. The fundamental equation of eddy covariance and its application in flux measurements. Agric. For. Meteorol. 152, 135–148.

Hausmann, P., Sussmann, R., Smale, D., 2016. Contribution of oil and natural gas production to renewed increase in atmospheric methane (2007-2014): Top-down estimate from ethane and methane column observations. Atmos. Chem. Phys. 16, 3227–3244.

Helmig, D., Rossabi, S., Hueber, J., Tans, P., Montzka, S.A., Masarie, K., Thoning, K., Plass-Duelmer, C., Claude, A., Carpenter, L.J., Lewis, A.C., Punjabi, S., Reimann, S., Vollmer, M.K., Steinbrecher, R., Hannigan, J.W., Emmons, L.K., Mahieu, E., Franco, B., Smale, D., Pozzer, A., 2016. Reversal of global atmospheric ethane and propane trends largely due to US oil and natural gas production. Nat. Geosci. 9, 490–495.

Hirano, T., Kusin, K., Limin, S., Osaki, M., 2015. Evapotranspiration of tropical peat swamp forests. Glob. Chang. Biol. 21, 1914–1927.

Hirano, T., Segah, H., Harada, T., Limin, S., June, T., Hirata, R., Osaki, M., 2007. Carbon dioxide balance of a tropical peat swamp forest in Kalimantan, Indonesia. Glob. Chang. Biol. 13, 412–425.

Hirano, T., Segah, H., Kusin, K., Limin, S., Takahashi, H., Osaki, M., 2012. Effects of disturbances on the carbon balance of tropical peat swamp forests. Glob. Chang. Biol. 18, 3410–3422.

Hollinger, D.Y., Richardson, A.D., 2005. Uncertainty in eddy covariance measurements and its application to physiological models. Tree Physiol. 25, 873–885.
Hollinger, D.Y., Richardson, A.D., 2005. Uncertainty in eddy covariance measurements and its application to physiological models. Tree Physiol. 25, 873–885.

Hutyra, L.R., Munger, J.W., Saleska, S.R., Gottlieb, E., Daube, B.C., Dunn, A.L., Amaral, D.F., de Camargo, P.B., Wofsy, S.C., 2007. Seasonal controls on the exchange of carbon and water in an Amazonian rain forest. J. Geophys. Res. Biogeosciences 112, 1–16.

Immirzi, C.P., Maltby, E., Clymo, R.S., 1992. The global status of peatlands and their role in carbon cycling. A Report for Friends of the Earth by the Wetland Ecosystems Research Group, Department of Geography, University of Exeter. Friends of the Earth, London.

Inubushi, K., Furukawa, Y., Hadi, A., Purnomo, E., Tsuruta, H., 2003. Seasonal changes of CO_2, CH_4 and N_2O fluxes in relation to land-use change in tropical peatlands located in coastal area of South Kalimantan. Chemosphere 52, 603–608.

Jackson, R.B., Canadell, J., Ehleringer, J.R., Mooney, H. a., Sala, O.E., Schulze, E.D., 1996. A global analysis of root distributions for terrestrial biomes. Oecologia 108, 389–411.

Jarvis, P., Rey, A., Petsikos, C., Wingate, L., Rayment, M., Pereira, J., Banza, J., David, J., Miglietta, F., Borghetti, M., Manca, G., Valentini, R., 2007. Drying and wetting of Mediterranean soils stimulates decomposition and carbon dioxide emission: the "Birch effect." Tree Physiol. 27, 929–940.

Jauhiainen, J., Takahashi, H., Heikkinene, J.E.P., Martikainen, P.J., Vasanders, H., 2005. Carbon fluxes from a tropical peat swamp forest floor. Glob. Chang. Biol. 11, 1788–1797.

Jung, M., Reichstein, M., Margolis, H.A., Cescatti, A., Richardson, A.D., Arain, M.A., Arneth, A., Bernhofer, C., Bonal, D., Chen, J., Gianelle, D., Gobron, N., Kiely, G., Kutsch, W., Lasslop, G., Law, B.E., Lindroth, A., Merbold, L., Montagnani, L., Moors, E.J., Papale, D., Sottocornola, M., Vaccari, F., Williams, C., 2011. Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations. J. Geophys. Res. Biogeosciences 116, G00J07.

Kai, F.M., Tyler, S.C., Randerson, J.T., Blake, D.R., 2011. Reduced methane growth rate explained by decreased Northern Hemisphere microbial sources. Nature 476, 194–197.

Keppler, F., Hamilton, J.T., Bra, M., Rockmann, T., 2006. Methane emissions from terrestrial plants under aerobic conditions. Nature 439, 187–191.

Kim, D.-H., Sexton, J.O., Townshend, J.R., 2015. Accelerated deforestation in the humid tropics from the 1990s to the 2000s. Geophys. Res. Lett. 42, 3495–3501.

Kirschke, S., Bousquet, P., Ciais, P., Saunois, M., Canadell, J.G., Dlugokencky, E.J., Bergamaschi, P., Bergmann, D., Blake, D.R., Bruhwiler, L., Cameron-Smith, P., Castaldi, S., Chevallier, F., Feng, L., Fraser, A., Heimann, M., Hodson, E.L., Houweling, S., Josse, B., Fraser, P.J., Krummel, P.B., Lamarque, J.-F., Langenfelds, R.L., Le Quéré, C., Naik, V., O'Doherty, S., Palmer, P.I., Pison, I., Plummer, D., Poulter, B., Prinn, R.G., Rigby, M., Ringeval, B., Santini, M., Schmidt, M., Shindell, D.T., Simpson, I.J., Spahni, R., Steele, L.P., Strode, S.A., Sudo, K., Szopa, S., van der Werf, G.R., Voulgarakis, A., van Weele, M., Weiss, R.F., Williams, J.E., Zeng, G., 2013. Three decades of global methane sources and sinks. Nat. Geosci. 6, 813–823.

Klein, T., 2014. The variability of stomatal sensitivity to leaf water potential across tree species indicates a continuum between isohydric and anisohydric behaviours. Funct. Ecol. 28, 1313–1320.

Knohl, A., Baldocchi, D.D., 2008. Effects of diffuse radiation on canopy gas exchange processes in a forest ecosystem. J. Geophys. Res. Biogeosciences 113, 1–17.

Konings, A.G., Gentine, P., 2017. Global variations in ecosystem-scale isohydricity. Glob. Chang. Biol. 23, 891-905.

Körner, C., 1995. Leaf diffusive conductances in the major vegetation types of the globe. Ecophysiol. Photosynth. 100, 463–490.

Kosugi, Y., Takanashi, S., Ohkubo, S., Matsuo, N., Tani, M., Mitani, T., Tsutsumi, D., Nik, A.R., 2008. CO2 exchange of a tropical rainforest at Pasoh in Peninsular Malaysia. Agric. For. Meteorol. 148, 439–452.

Kosugi, Y., Takanashi, S., Tani, M., Ohkubo, S., Matsuo, N., Itoh, M., Noguchi, S., Nik, A.R., 2012. Effect of inter-annual climate variability on evapotranspiration and canopy CO 2 exchange of a tropical rainforest in Peninsular Malaysia. J. For. Res. 17, 227–240.

Kumagai, T., Porporato, A., 2012. Strategies of a Bornean tropical rainforest water use as a function of rainfall regime: isohydric or anisohydric? Plant. Cell Environ. 35, 61–71.

Kumagai, T., Saitoh, T.M., Sato, Y., Takahashi, H., Manfroi, O.J., Morooka, T., Kuraji, K., Suzuki, M., Yasunari, T., Komatsu, H., 2005. Annual water balance and seasonality of evapotranspiration in a Bornean tropical rainforest. Agric. For. Meteorol. 128, 81–92.

Lasslop, G., Reichstein, M., Papale, D., Richardson, A., Arneth, A., Barr, A., Stoy, P., Wohlfahrt, G., 2010. Separation of net ecosystem exchange into assimilation and respiration using a light response curve approach: Critical issues and global evaluation. Glob. Chang. Biol. 16, 187–208.

Leuning, R., van Gorsel, E., Massman, W.J., Isaac, P.R., 2012. Reflections on the surface energy imbalance problem. Agric. For. Meteorol. 156, 65–74.

Levin, I., Veidt, C., Vaughn, B.H., Brailsford, G., Bromley, T., Heinz, R., Lowe, D., Miller, J.B., Poß, C., White, J.W.C., 2012. No inter-hemispheric $\delta 13CH4$ trend observed. Nature 486, E3–E4.

Loescher, H.W., Oberbauer, S.F., Gholz, H.L., Clark, D.B., 2003. Environmental controls on net ecosystem-level carbon exchange and productivitty in a Central American tropical wet forest. Glob. Chang. Biol. 9, 396–412.

Long, K.D., Flanagan, L.B., Cai, T., 2010. Diurnal and seasonal variation in methane emissions in a northern Canadian peatland measured by eddy covariance. Glob. Chang. Biol. 16, 2420–2435.

Malhi, Y., Nobre, A.D., Grace, J., Kruijt, B., Pereira, M.G.P., Culf, A., Scott, S., 1998. Carbon dioxide transfer over a Central Amazonia rain forest 103.

Malhi, Y., Pegoraro, E., Nobre, A.D., Pereira, M.G.P., Grace, J., Culf, A.D., Clement, R., 2002. Energy and water dynamics of a central Amazonian rain forest 107, 1–17.

Maltby, E., Immirzi, P., 1993. Carbon Dynamics in Peatlands and other Wetland Soils Regional and Global Perspectives. Chemosphere 27, 999–1023.

Massman, W.J., 2000. A simple method for estimating frequency response corrections for eddy covariance systems. Agric. For. Meteorol. 104, 185–198.

Massman, W.J., 2000. A simple method for estimating frequency response corrections for eddy covariance systems. Agric. For. Meteorol. 104, 185–198.

Massman, W.J., 2000. A simple method for estimating frequency response corrections for eddy covariance systems. Agric. For. Meteorol. 104, 185–198.

Massman, W.J., 2001. Reply to comment by Rannik on "A simple method for estimatiog frequency responde corrections for eddy covariance systems." Agric. For. Meteorol. 107, 247–251.

McDermitt, D., Burba, G., Xu, L., Anderson, T., Komissarov, A., Riensche, B., Schedlbauer, J., Starr, G., Zona, D., Oechel, W., Oberbauer, S., Hastings, S., 2011. A new low-power, open-path instrument for measuring methane flux by eddy covariance. Appl. Phys. B Lasers Opt. 102, 391–405.

McLeod, A.R., Fry, S.C., Loake, G.J., Messenger, D.J., Reay, D.S., Smith, K.A., Yun, B.W., 2008. Ultraviolet radiation drives methane emissions from terrestrial plant pectins. New Phytol. 180, 124–132.

Medvigy, D., Walko, R.L., Avissar, R., 2011. Effects of deforestation on spatiotemporal distributions of precipitation in South America. J. Clim. 24, 2147–2163.

Melling, L., Hatano, R., Goh, K.J., 2005. Soil CO2 flux from three ecosystems in tropical peatland of Sarawak, Malaysia. Tellus, Ser. B Chem. Phys. Meteorol. 57, 1–11.

Miller, S.D., Goulden, M.L., Menton, M.C., Rocha, H.R., Freitas, H.C. De, Michela, A., Albert, C., Sousa, D. De, 2004. Biometric and Micrometeorological Measurements of Tropical Forest Carbon Balance. Ecol. Appl. 14, 114–126.

Motulsky, H.J., Ransnas, L.A., 1987. Fitting curves nonlinear regression : review a practical. FASEB J. 1, 365–374.

Myhre, G., Shindell, D., Bréon, F.M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.F., Lee, D., Mendoza, B., Nakajima, T., 2013. Anthropogenic and Natural Radiative Forcing. Clim. Chang. 423, 658–740.

Nisbet, E.G., Dlugokencky, E.J., Manning, M.R., Lowry, D., Fisher, R.E., France, J.L., Michel, S.E., Miller, J.B., White, J.W.C., Vaughn, B., Bousquet, P., Pyle, J.A., Warwick, N.J., Cain, M., Brownlow, R., Zazzeri, G., Lanoisellé, M., Manning, A.C., Gloor, E., Worthy, D.E.J., Brunke, E.-G., Labuschagne, C., Wolff, E.W., Ganesan, A.L., 2016. Rising atmospheric methane: 2007-14 growth and isotopic shift. Global Biogeochem. Cycles 30, 1356–1370.

Novick, K.A., Ficklin, D.L., Stoy, P.C., Williams, C.A., Bohrer, G., Oishi, A.C., Papuga, S.A., Blanken, P.D., Noormets, A., Sulman, B.N., Scott, R.L., Wang, L., Phillips, R.P., 2016. The increasing importance of atmospheric demand for ecosystem water and carbon fluxes. Nat. Clim. Chang. 6, 1023–1027.

Novick, K.A., Stoy, P.C., Katul, G.G., Ellsworth, D.S., Siqueira, M.B.S., Juang, J., Oren, R., 2004. Carbon dioxide and water vapor exchange in a warm temperate grassland. Oecologia 138, 259–274.

Oishi, A.C., Oren, R., Novick, K.A., Palmroth, S., Katul, G.G., 2010. Interannual invariability of forest evapotranspiration and its consequence to water flow downstream. Ecosystems 13, 421–436.

Oren, R., Sperry, J.S., Katul, G.G., Pataki, D.E., Ewers, B.E., Phillips, N., Schäfer, K.V.R., 1999. Survey and synthesis of intra- and interspecific variation in stomatal sensitivity to vapour pressure deficit. Plant, Cell Environ. 22, 1515–1526.

Papale, D., Reichstein, M., Aubinet, M., Canfora, E., Bernhofer, C., Kutsch, W., Longdoz, B., Rambal, S., 2006. Towards a standardized processing of Net Ecosystem Exchange measured with eddy covariance technique : algorithms and uncertainty estimation 571–583.

Pastorello, G., Papale, D., Chu, H., Trotta, C., Agarwal, D., Canfora, E., Baldocchi, D., Torn, M., 2017. A New Data Set to Keep a Sharper Eye on Land-Air Exchanges. Eos (Washington. DC).

Pingintha, N., Leclerc, M.Y., Beasley, J.P., Zhang, G., Senthong, C., Rowland, D., 2010. Hysteresis response of daytime net ecosystem CO_2 exchange during a drought. Biogeosciences 7, 1159–1170.

Pison, I., Ringeval, B., Bousquet, P., Prigent, C., Papa, F., 2013. Stable atmospheric methane in the 2000s: Key-role of emissions from natural wetlands. Atmos. Chem. Phys. 13, 11609–11623.

Pitz, S., Megonigal, J.P., 2017. Temperate forest methane sink diminished by tree emissions. New Phytol. 214, 1432–1439.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grünwald, T., Havránková, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J.-M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., Valentini, R., 2005. On the separation of net ecosystem

exchange into assimilation and ecosystem respiration : review and improved algorithm. Glob. Chang. Biol. 11, 1424–1439.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grünwald, T., Havránková, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J.-M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., Valentini, R., 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration : review and improved algorithm. Glob. Chang. Biol. 11, 1424–1439.

Reichstein, M., Stoy, P.C., Desai, A.R., Lasslop, G., Richardson, A.D., 2012. Partitioning of net fluxes. In: Eddy Covariance. Springer Netherlands, pp. 263–289.

Rice, A.L., Butenhoff, C.L., Teama, D.G., Röger, F.H., Khalil, M.A.K., Rasmussen, R.A., 2016. Atmospheric methane isotopic record favors fossil sources flat in 1980s and 1990s with recent increase. Proc. Natl. Acad. Sci. 113, 10791–10796.

Richardson, A.D., Hollinger, D.Y., Burba, G.C., Davis, K.J., Flanagan, L.B., Katul, G.G., Munger, J.W., Ricciuto, D.M., Stoy, P.C., Suyker, A.E., Verma, S.B., Wofsy, S.C., 2006. A multi-site analysis of random error in tower-based measurements of carbon and energy fluxes. Agric. For. Meteorol. 136, 1–18.

Richardson, A.D., Hollinger, D.Y., Burba, G.C., Davis, K.J., Flanagan, L.B., Katul, G.G., Munger, J.W., Ricciuto, D.M., Stoy, P.C., Suyker, A.E., Verma, S.B., Wofsy, S.C., 2006. A multi-site analysis of random error in tower-based measurements of carbon and energy fluxes. Agric. For. Meteorol. 136, 1–18.

Rinne, J., Riutta, T., Pihlatie, M., Aurela, M., Haapanala, S., Tuovinen, J.P., Tuittila, E.S., Vesala, T., 2007. Annual cycle of methane emission from a boreal fen measured by the eddy covariance technique. Tellus, Ser. B Chem. Phys. Meteorol. 59, 449–457.

Saleska, S.R., Miller, S.D., Matross, D.M., Goulden, M.L., Wofsy, S.C., da Rocha, H.R., de Camargo, P.B., Crill, P., Daube, B.C., de Freitas, H.C., Hutyra, L., Keller, M., Kirchhoff, V., Menton, M., Munger, J.W., Pyle, E.H., Rice, A.H., Silva, H., 2003. Carbon in Amazon forests: unexpected seasonal fluxes and disturbance-induced losses. Science 302, 1554–1557.

Saunois, M., Jackson, R.B., Bousquet, P., Poulter, B., Canadell, J.G., 2016. The growing role of methane in anthropogenic climate change. Environ. Res. Lett. 11, 120207.

Schaefer, H., Fletcher, S.E.M., Veidt, C., Lassey, K.R., Brailsford, G.W., Bromley, T.M., Dlugokencky, E.J., Michel, S.E., Miller, J.B., Levin, I., Lowe, D.C., Martin, R.J.,

Vaughn, B.H., White, J.W.C., 2016. A 21st-century shift from fossil-fuel to biogenic methane emissions indicated by 13CH4. Science. 352, 80–84.

Schwietzke, S., Sherwood, O.A., Bruhwiler, L.M.P., Miller, J.B., Etiope, G., Dlugokencky, E.J., Michel, S.E., Arling, V.A., Vaughn, B.H., White, J.W.C., Tans, P.P., 2016. Upward revision of global fossil fuel methane emissions based on isotope database. Nature 538, 88–91.

Shindell, D., Kuylenstierna, J.C.I., Vignati, E., van Dingenen, R., Amann, M., Klimont, Z., Anenberg, S.C., Muller, N., Janssens-Maenhout, G., Raes, F., Schwartz, J., Faluvegi, G., Pozzoli, L., Kupiainen, K., Hoglund-Isaksson, L., Emberson, L., Streets, D., Ramanathan, V., Hicks, K., Oanh, N.T.K., Milly, G., Williams, M., Demkine, V., Fowler, D., 2012. Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security. Science. 335, 183–189.

Simpson, I.J., Sulbaek Andersen, M.P., Meinardi, S., Bruhwiler, L., Blake, N.J., Helmig, D., Rowland, F.S., Blake, D.R., 2012. Long-term decline of global atmospheric ethane concentrations and implications for methane. Nature 488, 490–494.

Spitters, C.J.T., Toussaint, H.A.J.M., Goudriaan, J., 1986. Separating the diffuse and direct components of global radiation and its implications for modeling canopy photosynthesis. II. Calculation of canopy photosynthesis. Agric. For. Meteroloogy 38, 231–242.

Stoy, P.C., Katul, G.G., Siqueira, M.B.S., Juang, J., Novick, K.A., Uebelherr, J.M., Oren, R., 2006. An evaluation of models for partitioning eddy covariance-measured net ecosystem exchange into photosynthesis and respiration 141, 2–18.

Stoy, P.C., Mauder, M., Foken, T., Marcolla, B., Boegh, E., Ibrom, A., Arain, M.A., Arneth, A., Aurela, M., Bernhofer, C., Cescatti, A., Dellwik, E., Duce, P., Gianelle, D., van Gorsel, E., Kiely, G., Knohl, A., Margolis, H., Mccaughey, H., Merbold, L., Montagnani, L., Papale, D., Reichstein, M., Saunders, M., Serrano-Ortiz, P., Sottocornola, M., Spano, D., Vaccari, F., Varlagin, A., 2013. A data-driven analysis of energy balance closure across FLUXNET research sites: The role of landscape scale heterogeneity. Agric. For. Meteorol. 171–172, 137–152.

Sulman, B.N., Roman, D.T., Yi, K., Wang, L., Phillips, R.P., Novick, K.A., 2016. High atmospheric demand for water can limit forest carbon uptake and transpiration as severely as dry soil. Geophys. Res. Lett. 43, 9686–9695.

Suzuki, S., Ishida, T., Nagano, T., Waijaroen, S., 1999. Influences of Deforestation on Carbon Balance in a Natural Tropical Peat Swamp Forest in Thailand. Environ. Control Biol. 37, 115–128.

Tseng, K.H., Tsai, J.L., Alagesan, A., Tsuang, B.J., Yao, M.H., Kuo, P.H., 2010. Determination of methane and carbon dioxide fluxes during the rice maturity period in Taiwan by combining profile and eddy covariance measurements. Agric. For. Meteorol. 150, 852–859.

Turner, A.J., Frankenberg, C., Wennberg, P.O., Jacob, D.J., 2017. Ambiguity in the causes for decadal trends in atmospheric methane and hydroxyl. Proc. Natl. Acad. Sci. 114, 201616020.

Turunen, J., Tomppo, E., Tolonen, K., Reinikainen, A., 2002. Estimating carbon accumulation rates of undrained mires in Finland – application to boreal and subarctic regions.

Ueyama, M., Hirata, R., Mano, M., Hamotani, K., Harazono, Y., Hirano, T., Miyata, A., Takagi, K., Takahashi, Y., 2012. Influences of various calculation options on heat, water and carbon fluxes determined by open- and closed-path eddy covariance methods. Tellus B 64.

Vick, E.S.K., Stoy, P.C., Tang, A.C.I., Gerken, T., 2016. The surface-atmosphere exchange of carbon dioxide, water, and sensible heat across a dryland wheat-fallow rotation. Agric. Ecosyst. Environ. 232, 129–140.

Vourlitis, G.L., Filho, N.P., Hayashi, M.M.S., Nogueira, J.D.S., Caseiro, F.T., Jr, J.H.C., 2001. Seasonal variations in the net ecosystem CO_2 exchange of a mature Amazonian transitional tropical forest (cerradao). Funct. Ecol. 15, 388–395.

Webb, E. K., Pearman, G. I., & Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. Q. J. R. Meteorol. Soc. 106, 85–100.

Werth, D., 2002. The local and global effects of Amazon deforestation. J. Geophys. Res. 107.

Wilczak, J.M., Oncley, S.P., Stage, S.A., 2001. Sonic anemometer tilt correction algorithms. Boundary-Layer Meteorol. 99, 127–150.

Wilson, D., Alm, J., Laine, J., Byrne, K.A., Farrell, E.P., Tuittila, E.S., 2009. Rewetting of cutaway peatlands: Are we re-creating hot spots of methane emissions? Restor. Ecol. 17, 796–806.

Wilson, K., 2002. Energy balance closure at FLUXNET sites. Agric. For. Meteorol. 113, 223–243.

Wolf, S., Eugster, W., Majorek, S., Buchmann, N., 2011. Afforestation of tropical pasture only marginally affects ecosystem-scale evapotranspiration. Ecosystems 14, 1264–1275.

Yulianti, N., Hayasaka, H., 2013. Recent Active Fires under El Niño Conditions in Kalimantan, Indonesia. Am. J. Plant Sci. 4, 685–696.