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FIRE-DRIVEN BIOMASS AND PEAT CARBON LOSSES AND POST-FIRE SOIL CO_2 EMISSION IN A WEST KALIMANTAN PEATLAND FOREST

Astiani D[1, 2, *], Curran LM[3], Burhanuddin[1], Taherzadeh M[4], Mujiman[5, 6], Hatta M[1, 6], Pamungkas W[1] & Evi Gusmayanti[6, 7]

[1]*Faculty of Forestry, Universitas Tanjungpura, Jl Imam Bonjol Pontianak, 78124, Indonesia*
[2]*Consortium of Tropical Peat Sciences, Kalimantan Universities Consortium. C.q. Universitas Tanjungpura. Pontianak 78124, West Kalimantan, Indonesia*
[3]*Stanford Wood Institute for the Environment, Stanford University, 473 Via Ortega, Stanford,CA 94305, USA*
[4]*Graduate School of Resource Recovery University of Borås, SE-501 90, Borås, Sweden*
[5]*Forestry Agency of Kabupaten Landak, West Kalimantan Indonesia*
[6]*Lembaga Landscape Livelihood Indonesia Pontianak, Indonesia*
[7]*Faculty of Agriculture, Universitas Tanjungpura, Jalan A. Yani Pontianak, 78124, Indonesia*

**astiani.dwi@gmail.com*

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Indonesian peatland forest is considered a huge sink of tropical carbon and thereby make significant contribution to global terrestrial carbon storage. However, landcover and landuse changes in this ecosystem have incurred a synergistic exposure to drought and wildfires. Deforestation and forest degradation through combustion and decomposition of forest biomass and soil carbon have become global issues because of their greenhouse gas contribution to global climate change. Thus fire-driven carbon losses in these peatlands have increased the need to evaluate the impacts of fire at a landscape scale. In 6–10 week dry periods from January to April 2014 and in January 2015, wildfires burnt peatland forest in Kubu Raya, West Kalimantan province (Indonesian Borneo). An assessment was conducted to provide more reliable estimates of the effects of fire on aboveground and soil carbon losses and their dynamics in the coastal peatlands of the province. Carbon loss from combustion of both aboveground biomass and peat soil was substantial. Moreover, CO_2 emission from soil respiration at the burnt peat surface increased 46% over the first 9 months after the fire. This study clearly showed the magnitude of fire-driven carbon loss and the scale of CO_2 emission to the atmosphere arising from fire in tropical peatland forest.

Keywords: Aboveground carbon, peatland fire, soil CO_2 emission, peat carbon, tropical peatland

INTRODUCTION

The global peat carbon pool exceeds carbon in global vegetation and is equivalent to the current atmospheric carbon pools (Turetsky et al. 2002). Peatlands represent globally significant stores of soil carbon and are carbon dioxide (CO_2) sinks. They are also sources of atmospheric CO_2 and methane (CH_4), with dissolved organic carbon loss following peatland drainage (Astiani 2017b).

In undisturbed peatland forest, peat stocks generally continue sequestering carbon and are relatively protected from losses through anthropological fires (Astiani et al. 2017d, Muin & Astiani 2018). There is global concern that the increases in peat forest degradation, land-cover change and forest fires will increase carbon emission and reduce carbon sinks (Page et al. 2009). Global carbon sink should be preserved and augmented to reduce its contribution to carbon emission into the atmosphere (Watson et al. 2000).

Tropical carbon sinks store up to 3% of global carbon. Tropical peatland forests store a huge amount of carbon, predominantly in peat soil. Tropical peatland carbon storage has been estimated to be about 52 Tg C (Hoojier et al. 2006) and 27 Tg C in Indonesia (Shimada et al. 2016) . However, there is much concern that degradation of tropical peatlands is increasing atmospheric carbon emission and reducing peatland carbon stocks (Astiani et al. 2016). Landuse and land-cover changes to tropical peatlands, combined with intensive drainage development and climate change will lower water table (Astiani et al. 2017a) leading to peat dessication and increasing the risk, duration and frequency of peat fires. The combustion of the dessicated peat that was previously hydrologically undisturbed and had sequestered carbon results in soil carbon loss and the release of carbon emission into the atmosphere (Turetsky et al. 2002).

Peat soil can absorb substantial amounts of water. Where peat surface layers have dried out, subsurface peat remains moist due to its water-holding capacity. During periods of drought, soil surface layers dry fast and when peat is dried to less than 55% by weight, a wildfire may ignite the peat leading to a smoldering subsurface fire. While peatland wildfires emit significant amount of carbon, post-wildfire (smoldering fire) CO_2 emission can be considerable. Cummulative losses from fire disturbance must be understood to estimate the carbon budget of the peatland landscape and to increase awareness of the need for fire prevention. However, the magnitude of overall carbon loss in the event of a wildfire has not been quantified. The objective of the present study was to quantify and assess aboveground biomass and peat soil carbon losses, and post-fire CO_2 emission from wildfires in the field.

MATERIALS AND METHODS

Study site

The study was conducted on drained, ombrogenous Fibrist to Hemist peat soil types at Kubu Raya district (0° 13' S and 109° 26' E, 4 m above sea level) in West Kalimantan province, Indonesia. Climatic data for 1960–2015 was obtained from the Supadio Airport weather station located about 3 km from the study site. Mean annual rainfall is 3238 mm (standard deviation = 489 mm). In normal years, monthly rainfall is ≥ 100 mm, while the dry season has two to three consecutive dry months (≤ 100 mm rainfall monthly). El Niño–Southern Oscillation (ENSO)-associated droughts occurred in this region in 2006, 2009, 2012 and 2015.

The 15-ha Kubu Raya study site was established for our research project in 2005 as a permanent research site. The study site is forested peatland surrounded by peat forests degraded by low impact logging that took place in 2002 and 2008. The local government established drainage canals for agricultural development. An annual census recorded peat depth and the growth and survival of all trees with diameter at breast height (DBH) > 5 cm. In early 2014, about 4 ha (20%) of the forested peatland covering the study site was burnt by several wildfires, resulting in the loss of almost all aboveground vegetation and varying depths of subsurface peat layers within the affected area(Figure 1).

Carbon loss assessments

Loss of aboveground biomass in each block of the permanent study site was estimated from previous tree census data. Mean basal area was 21.1 m^2 ha^{-1} while density for trees with DBH > 20 cm and 10–20 cm was 85 and 624 trees ha^{-1} respectively (Astiani 2014) Tree diameter and species were converted into standing biomass using allometric equation (Chave et al. 2005). Other forest biomass losses from smaller trees (DBH < 5 cm), coarse woody debris (both standing and fallen) and litter were estimated from previous annual censuses (Astiani 2014). All biomass was analysed for its carbon content then converted into CO_2 equivalent (CO_2-e) units.

Actual biomass loss from the fire was assessed manually in Febuary 2014, April 2014 and January 2015 soon after each peat fire event. The affected burnt area before and after the fire events are shown in Figure 1. Since burnt areas surrounded the permanent study site, we selected assessment plots that represented peatland forest affected by fire. We examined the depth of smoldering fires into subsurface layers. Ten plots were sampled using 25 quadrats (each 2 m × 2 m). Within each quadrat, peat loss was carefully and manually measured using volumetric estimation associated with cube, rectangle, cylinder or prism shapes, then cumulative volumes were obtained. Mean peat loss for each of the 10 plots was calculated by averaging cumulative volumes for the 25 quadrats. To estimate peat biomass loss, bulk density (g cm^{-3}) and percentage loss on ignition (% LOI) was determined via laboratory analysis of undisturbed peat samples.

Multi-year (2014–2015) soil CO_2 respiration and weekly measurements of water level were recorded using LiCor-8100 analyser which automatically delivered direct CO_2 respiration values for the peatland surface. The analyser was attached to 20-cm diameter soil collars inserted 10 and 2 cm below and above the soil surface respectively. The collars were then connected to a soil flux survey chamber. The analyser also measured soil surface relative humidity, CO_2 and H_2O concentrations. The system was attached to

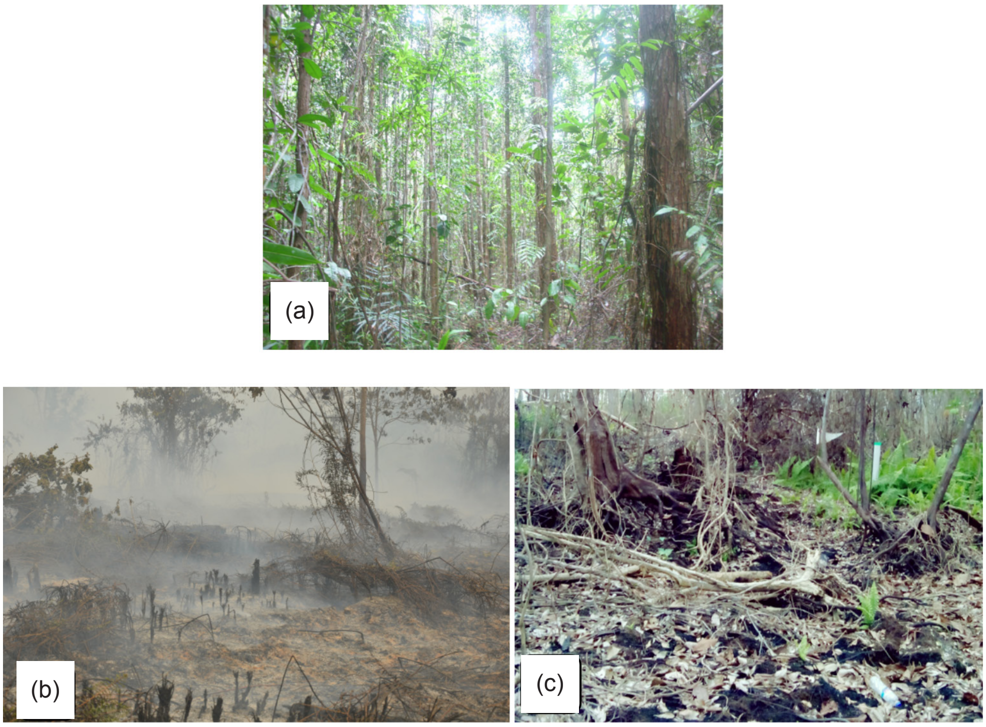

Figure 1 The Kubu Raya study site peatland forest: (a) before, (b) immediately after the wildfire in January 2014, and (c) two months after the wildfire

an auxiliary sensor interface terminal to assess soil surface temperature and water content at 10-cm peat depth. Twenty four points of collars were set up for measurement and data were taken weekly, averaging daily emission for 15 months. Annual peatland CO_2 emission was estimated from those measurements.

Data analysis

Aboveground biomass loss was calculated by summing up all carbon sources (i.e. trees with DBH > 5 cm, course wood debris and litter) that were lost in fire events. The carbon source data were analysed and presented in unit of tonne ha^{-1}. Peat carbon loss was calculated as peat volume × bulk density × % LOI, and carbon content. Mean carbon loss was calculated across the 25 quadrats and converted to carbon loss unit of tonne ha^{-1}. Post-fire CO_2 emission were separated from root respiration, which was derived from soil CO_2 respiration measurement (49%) by Malhi et al. (2012). To calculate cummulative carbon loss from 2014 and 2015 fire events, all partial soil carbon mean values were transformed into CO_2-e using default values of C = 50% biomass, 1 g C = 3664 g CO_2-e, summed and partially presented with their minimum and maximum probability of losses. Soil CO_2 emission data was converted from µmol s^{-1} m^2 into Mg CO_2 ha^{-1} year^{-1}. Data are given as means and standard errors.

Aboveground biomass loss

Based on our pre-assessment data for standing biomass, estimated aboveground losses varied with a mean of 139.0 ± 4.9 Mg/ha. Trees with DBH > 20 cm experienced the highest losses (37.5–159.1 Mg ha^{-1}) while trees in the 10–20 and 5–10 cm DBH classes lost 6.9–71.5 and 11.5–53.3 Mg ha^{-1} biomass respectively. The estimated mean losses for course wood debris and litter were 1.05 ± 0.13 and 6.59 ± 0.51 Mg ha^{-1} respectively. Total aboveground biomass loss was estimated at 146.64 Mg ha^{-1}. The study site as a whole reported 108 tree species (31 families) killed by fires, not including other plant species such as orchids and other epiphytes, mushrooms, ferns and lianas.

Peat soil loss from fire

The two-month post-fire assessment revealed substantial peat biomass loss (Table 1). Mean carbon loss was 135.2 ± 24.4 Mg ha^{-1}. Carbon loss varied widely among the 10 plots. Peat layer loss was measured to depths ranging from 7–62 cm in

Table 1 Mean peat depth layer loss, water table level, biomass loss (± SE) from plots burnt by wildfires two months post-fires

Site	Depth of peat layer loss (cm)	Water table depth (cm)	Biomass loss (C Mg ha^{-1})
1	11.9 ± 0.9	76 ± 0.8	15.4 ± 0.3
2	17.1 ± 0.9	76 ± 1.1	60.8 ± 5.3
3	23.6 ± 1.4	97 ± 0.6	236.8 ± 6.5
4	24.1 ± 2.2	113 ± 2.4	278.8 ± 10.7
5	14.1 ± 0.9	92 ± 3.2	155.6 ± 2.6
6	19.4 ± 2.2	87 ± 1.9	146.4 ± 14.8
7	12.5 ± 0.5	78 ± 2.4	99.6 ± 1.6
8	13.3 ± 1.0	80 ± 1.8	109.5 ± 3.6
9	10.5 ± 0.7	78 ± 2.7	116 ± 2.9
10	11.6 ± 0.6	78 ± 0.9	133 ± 2.7

SE = standard error

the quadrat scale within plots measurement, with overall mean depth of 15.8 ± 0.5 cm. The burnt peat layer depth was smaller than that recorded for a large forest fire in central Kalimantan in 1997 (Boehm et al. 2001).

The water table at the plots ranged from 76–113 cm. The long drought from December 2013 to February 2014 and lowered water table due to drainage development, increased the fire hazard level resulting in large wildfires upon ignition. Either or both conditions could ignite and enhance peat fires (Takahashi et al. 2001).

Peat type may have influenced peat biomass losses. Saprist peat is more difficult to ignite than peat types at other decomposition levels, i.e. Hemist and Fibrist, because Saprist peat holds more water. The speed at which fire spreads is dictated by peat water content, wind speed and direction, and fire intensity at the ignition source (Usup et al. 2004). In our study, drought caused lower subsurface water level and when fire happened, larger biomass was burnt and lost. Usually this peat soil holds water content on the peat surface in the range of 300–400% of its dry matter. When the fire event started affecting, the weight-based of water content measured was very low (65–78%) and below the critical point of fire susceptibility. The water level depths were > 1 m under peatland surface and caused dry peat surface material easier to burn and spread fires once the flammable surface layers were ignited.

Carbon loss through soil CO_2 emission

Soil respiration ranged from 64.4 to 209.8 Mg ha^{-1} year^{-1} after the fire (Figure 3), with an annual mean and SE of 126.9 ± 9.8 Mg ha^{-1} year^{-1} or when separated to only soil CO_2 emission following Malhi (2012) was approximately 61.9 ± 4.8Mg ha^{-1} year^{-1} CO_2 emission. The annual mean CO_2 emission post-fire was about 42% greater than emission recorded by Astiani (2014) from unburnt peatland, which in the dry and wet seasons were 47.4 and 40.2 Mg ha^{-1} year^{-1} respectively (Astiani 2014). Post-fire CO_2 soil respiration increased until the 9th month after the fire, then declined, reaching stable emission 11 months post-fire (Figure 2).

Multilinear regression on site factors influencing soil carbon emission showed, that peat surface H_2O content, subsurface water depth and monthly precipitation significantly influenced soil CO_2 emission (Figure 3). When accumulated, total carbon loss on fire which are from the combustion of aboveground, peat soil and soil CO_2 emission were 516.33 and 61.9 Mg CO_2-e ha^{-1} respectively. Overall estimation of peat carbon losses due to peatland forest fires was huge. Peatland fires should be prevented to cut back these huge emission into the atmosphere. In undisturbed peatlands, most of the peat carbon stock is typically protected from belowground fires, and resistance to smoldering may build up for peat carbon stored in tropical regions over long time scales (Turetsky et al. 2015). However, peatland drying due to human activity, i.e. canal development, could lead to more frequent fires and reduced carbon stocks. Environmental changes, particularly in the form of drainage and forest clearing, threaten the stability of peatland and make it susceptible to fire (Page et al. 2002). During El-Niño events especially, fire prevention awareness efforts need to be increased.

Water table fell 30–110 cm one to three years after canal development in a Kalimantan peatland (Astiani 2014, Astiani et al. 2018). Dessicated peatlands are not only prone to fire (Ketridge et al. 2015) but also increased soil CO_2 emission (Astiani et al. 2016). While the total soil peat C pool assessed for this peatland forest area is large (1500 tonnes ha^{-1}, Astiani 2014), peat soil biomass loss due to fire cannot be excused. Significant carbon losses from peatland fires (10% of C stocks ha^{-1}) has significant negative

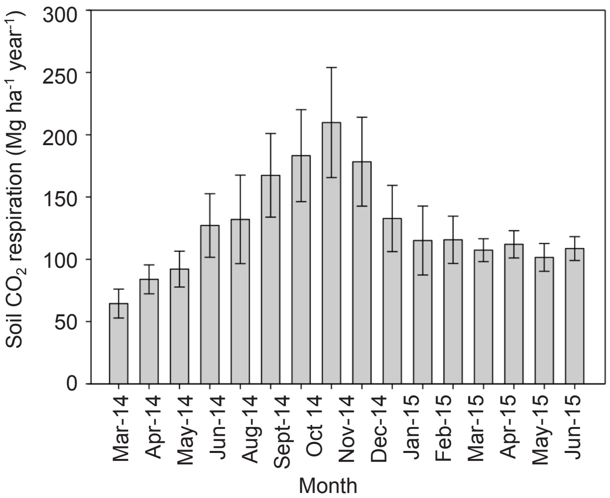

Figure 2 Mean monthly post-fire peatland soil CO_2 emission (± standard error) from the burnt plots

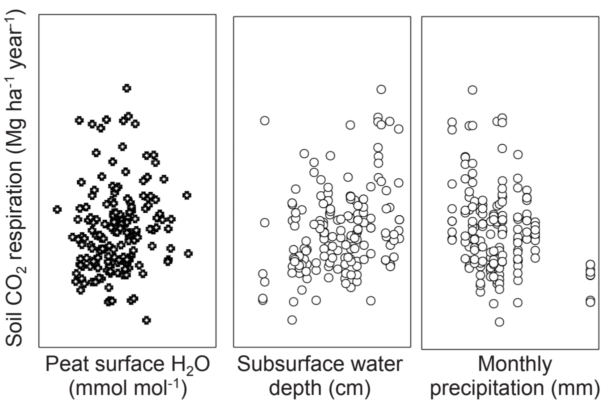

Figure 3 Site factors that significantly dictated peat CO_2 emission on burnt peatland

impacts on the local and global carbon budget and atmospheric CO_2 emission. Based on the accelerated CO_2 emission up till 9 months post-fire recorded in this study, tremendous increases in CO_2 emission may occur when peatland fires are extensive. Hydrological restoration of impacted areas should be implemented in order to mitigate peat CO_2 emission from peatlands.

CONCLUSIONS

Results of our study showed that fire event at a tropical peatland forest caused large losses of biomass aboveground and from peat soil. Increased peatland soil CO_2 emission up till 9 months post-fire and the 46% increase in CO_2 emission compared with non-burnt areas, support the need for concrete fire prevention efforts especially during dry periods.

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