Jurnal Silvikultur Tropika
*Journal of Tropical Silviculture*

Vol. 13 No. 1, April 2022, Hal 53-65
p-ISSN: 2086-8277
e-ISSN: 2807-3282

# THE HIGH POTENTIAL OF PEATLAND FIRES MANAGEMENT FOR GREENHOUSE GAS EMISSIONS REDUCTION IN INDONESIA

(*Pentingnya Pengelolaan Kebakaran Lahan Gambut untuk Penurunan Emisi Gas Rumah Kaca di Indonesia*)

**Bambang Hero Saharjo[1*], Nisa Novita[2]**

**(Received 28 December 2021 /Acepted 28 February 2022)**

***ABSTRACT***

The Copernicus Atmosphere Monitoring Service (CAMS) reported that increasing of GHG emissions from Indonesia in 2019 was mainly due to carbon-rich peatlands burning. About 1.65 million ha were burnt and a half million ha of peat were burned in devastating fire events in 2019, yet GHG (greenhouse gas) emissions released was almost nearly compared to the 2015 fires where 2.6 million ha areas were burnt. Thousands of acres of ecologically significant land were burned, resulting in toxic haze which threatening human health as well as disrupting natural forests and wildlife habitat. Peatlands consists of decomposed organic matter, and peat degradation will produce significant amount of GHG emissions, especially when the areas are burnt. The lowering ground water level (GWL) on peatlands will increase the sensitivity to the fires because of the drier condition of peat surface. The restoration efforts implemented in degraded peat ecosystem (i.e: rewetting and revegetation) seem like the best solution, if and if the fire prevention management activities are really well implemented. Fire suppression has high potential to reduce GHG emissions resulted from peat fires into the atmosphere. The success of peatland fire suppression will depend on the skill of fire brigades, strategy, and the availability of equipment, direct and indirectly in the ground. Lack of knowledge and experience to combat peat fires will spread more fires and potentially out of control fire break outs. Finally, this condition will produce significant amount of GHG emissions as dry peat burnt is difficult to control.

Key words: CAMS, GHG, peat fires, suppression, restoration

***ABSTRAK***

*Copernicus Atmosphere Monitoring Service (CAMS) melaporkan bahwa peningkatan emisi GRK hutan dan lahan Indonesia pada tahun 2019 terutama disebabkan oleh pembakaran lahan gambut yang kaya karbon. Sekitar 1,65 juta ha terbakar dan setengah juta ha gambut terbakar dalam peristiwa kebakaran hebat pada tahun 2019, namun emisi GRK (gas rumah kaca) yang dihasilkan hampir mendekati dibandingkan dengan kebakaran tahun 2015 di mana 2,6 juta ha area terbakar. Ribuan hektar lahan yang secara ekologis penting dibakar, mengakibatkan kabut asap beracun yang mengancam kesehatan manusia serta mengganggu hutan alam dan habitat satwa liar. Lahan gambut terdiri dari bahan organik yang terdekomposisi, dan degradasi gambut akan menghasilkan emisi GRK dalam jumlah yang signifikan, terutama jika areal tersebut terbakar. Penurunan muka air tanah (GWL) di lahan gambut akan meningkatkan kepekaan terhadap kebakaran karena kondisi permukaan gambut yang lebih kering. Upaya restorasi yang dilakukan di ekosistem gambut yang terdegradasi (yaitu: pembasahan dan revegetasi) tampaknya merupakan solusi terbaik, jika dan jika kegiatan manajemen pencegahan kebakaran benar-benar dilaksanakan dengan baik. Pemadaman kebakaran memiliki potensi tinggi untuk mengurangi emisi GRK akibat kebakaran gambut ke atmosfer. Keberhasilan pemadaman kebakaran lahan gambut akan sangat bergantung pada keterampilan petugas pemadam kebakaran, strategi, dan ketersediaan peralatan, baik langsung maupun tidak langsung di lapangan. Kurangnya pengetahuan dan pengalaman untuk memerangi kebakaran gambut akan menyebabkan lebih banyak kebakaran dan berpotensi menimbulkan kebakaran yang tidak terkendali. Terakhir, kondisi ini akan menghasilkan emisi GRK yang signifikan karena gambut kering yang terbakar sulit dikendalikan.*

*Kata kunci: CAMS, GRK, kebakaran gambut, pemadaman, restorasi*

---

[1] Forest Fire Laboratory, Forest Protection Division, Department of silviculture, Faculty of Forestry and Environment, IPB University, Indonesia
* Corresponding author's:
e-mail: saharjobambangh@gmail.com
[2] Yayasan Konservasi Alam Nusantara, Graha Iskandarsyah. Jl. Iskandarsyah Raya No.66 C, Kebayoran Baru, Melawai Jakarta Selatan, Indonesia 12160

## INTRODUCTION

Peat fires in Southeast Asia, particularly in Indonesia, are major cause of smog and particulate air pollution (Hayasaka *et al*., 2014; Reddington *et al*., 2014), with serious consequences for human health (Kunii *et al*., 2002; Kunii, 1999, Marlier *et al*., 2012; Wooster *et al*., 2012) and local blocking of sunlight that can suppress plant photosynthesis (Davies and Unam, 1999). In addition, peatland fires are responsible for forest habitat loss and degradation for flora and fauna, including those in marine systems (Jaafar and Loh, 2014; Posa *et al*., 2011; Yule, 2010). Fire suppression efforts, lost timber and crop resources, missed workdays, and travel disruptions incur high economic costs (Barber and Schweithelm, 2000; Tacconi, 2003; Ruitenbeek, 1999), It is estimated that Indonesia lost US$20.1 billion during the 1997/98 fire season alone (Varma, 2003). The World Bank reported (2016) that economic loss during Indonesia's 2015 fires is estimated exceed US $16 billion. Indonesia 2015 forest and land fires which burnt about 2.6 million ha had released about 1.74 Gt CO2-eq . Both national and international policies have been implemented to reduce fire impacts in Indonesia prior to the 2015 fire events (e.g., ASEAN Agreement on Transboundary Haze Pollution, Singapore's Trans- boundary Haze Pollution Act, and Indonesia's national law (Act No 41/1999) banning corporations from using fire to clear land for palm-oil plantations), but with limited success (Cattaua *et al*., 2016). Given the variety and severity of the consequences of tropical peatland fires in Indonesia, there is a high global interest to understand this changing disturbance regime and reduce fire occurrence (Harrison *et al*., 2009).

Fires in Indonesia have consequences from the local to global scale, including burning forest that serve as a home to endemic and endangered flora and fauna, emitting haze that compromises human health and impacts economies across the region, and converting peatlands from a major carbon sink to a major source of CO2. Identifying the sources of fire ignitions and LULC (Land Use Land Cover) classes associated with fire ignitions is a key factor for reducing fire on this landscape, which allow us to more pointedly target management and policy interventions (Cattaua *et al*., 2016).

Indonesia contains large areas of peatland that have been drained and cleared of natural vegetation, making them susceptible to burning (Kiely *et al*., 2019). Peat fires emit considerable amounts of carbon dioxide, particulate matter (PM) and other trace gases, contributing to climate change and causing regional air pollution. However, emissions from peat fires are uncertain, due to uncertainties in emission factors and fuel consumption (Kiely *et al*., 2019).

Who is responsible for ignitions in Indonesia is highly contested, and reports of the ignition sources are varied (Dennis *et al*., 2005; Page *et al*., 2009b), often resulting in a chain of finger-pointing (e.g., Suyanto, 2000). Although some large-holders clear the land mechanically, most forest clearing is involved fire(Stolle *et al*., 2003). Since fires set for clearing can 'escape' beyond their intended boundaries, both large and small holders have been held responsible (e.g., Stolle *et al*., 2003; Page *et al*., 2009b), which is commonly found in rainforest fires (Goldammer, 1991). Burning to clear land has been the traditional practice of smallholders and indigenous groups, and there is some evidence that smallholders' use of fire has been historically relatively small-scale and well-managed (Tomich *et al*., 1998; Bowen *et al*., 2000; Seavoy, 1973; Wibowo *et al*., 1997). However, this is likely not the case today. The scale of land cleared by fire has expanded with increased use of burning by both smallholders and larger-scale rubber and oil palm concessions (Brauer and Hisham-Hashim, 1998; Potter and Lee, 1998; Stolle *et al*., 2003). Originally, the Indonesian government blamed smallholder shifting cultivators for fire, but later publicly claimed that it was more likely larger- scale companies opening land on commercial plantations for palm oil, pulpwood, and timber, some of which was promoted by government policies themselves (Brown, 1998; Page *et al*., 2009b).

The problem of forest fires cannot be considered a simple issue as it involves multi actors such as local actors, large firms, and political economy actors, such as governors, regents, and regional level companies. Forest fires are not only driven by internal factors like types of peatlands and soils (Purnomo *et al*, 2019). External factors such as the dry climate also contribute to causing forest fires. The research proposed to know potential HGH emission reduction from peat fires.

## METHOD

The research was conducted in the year 2020 with the main purpose to find out how much potential greenhouse gas emissions are produced as a result of forest and peatland fires that can be suppressed through control efforts, it is necessary to know how much peat land is burned, where the fires occur, what control measures should be taken. Answering these questions, this research was carried out through two major activities, namely literature studies and group discussions with experts in this regard, namely from the Ministry of Environment and Forestry.

### Literature review

Literature studies are carried out on both national and international journals, including reports on research results that can be accounted for and valid results. The focus of the study is aimed at: 1. Sources of Greenhouse Gas emissions from peat fires, 2. Estimates of Greenhouse Gas emissions resulting from fires that occur, 3. Efforts that have been made to reduce GHG emissions from peat fires which include what is meant by peat fires, monitoring and prevention systems are carried out, 4. Managing peat land not to burn in the right ways.

### Forum Group Discussion (FGD)

The forum discussion was held in order to share perceptions about the high potential to reduce greenhouse gas emissions through real peat management. Discussions are really needed to emphasize and strengthen each other about the need for proper peat management. This meeting was held several times together with a team of experts from the Ministry of Environment and Forestry with different backgrounds. Each meeting was attended by around 20-30 participants facilitated by the Ministry of Environment and Forestry.

## RESULTS AND DISCUSSIONS

### GHG emissions from Peatland fires

Press release made by CAMS (The Copernicus Atmosphere Monitoring Service). " As a very high number of forest fires rage across Indonesia, with thousands of acres of ecologically important land being burned causing a toxic haze", revealing how it has been monitoring fire effects. Using the CAMS Global Fire Assimilation System, data from the service shows that the daily estimated equivalent CO2 emissions are reaching a similar level to the devastating fires in the same period in 2015. The total so far for the area this year (1 August to 18 September) is approximately 360 megatons of CO2, compared to 400 megatons over the same period in 2015. Data also shows that in recent days the activity in Indonesia, particularly in Kalimantan, has been well above the 2003-2018 average. Air quality is thought to be equally as poor as the 2015 fires". "It is estimated that the Indonesian fires which started in August, pumped out at least 708 megatons of CO2 until the end of November 2019".

The fires were mainly caused by the burning of carbon-rich peatlands and drier than average conditions. What also stood out was that the daily total fire intensity was higher than the average of the last 16 years. Thousands of acres of ecologically significant land were burned, causing a toxic haze, threatening the health of the local population as well as the natural forests and wildlife. Fortunately, the fire intensity and the volume of emissions started to decline in October and was down to 48 megatons of estimated CO2 in the first two weeks of November. The reason for this was rain in southern Kalimantan through October although some fires continued in southern Sumatra".

In undisturbed peat forests, peat C stocks are relatively stable. Disturbance, especially drainage, greatly increases $CO_2$ emissions from biological oxidation (decomposition) of peat because a larger volume of peat and litter is exposed to toxic conditions (KFCP, 2014). Enhanced release of $CO_2$ from biological oxidation is often the major source of GHG following the disturbance of forests on peat. The rate of $CO_2$ emissions depends on the quality of decomposable substrate for microorganisms and thus the rate may change over time. $CO_2$ emissions can continue for many decades until all the aerated peat is decomposed (KFCP, 2014).

Total greenhouse gas from $CO_2$, CO, and $CH_4$ emission from forest and peat fire was calculated from peat fire in Sumatera, Kalimantan and Papua. These three were the largest gaseous carbon compounds emitted by peat fire and contributed more than 95% of total carbon emitted (Christian *et al*., 2003; Stockwell *et al*., 2014; Stockwell *et al*., 2016). Emissions of $CO_2$ are much greater than the $CO_2$ equivalents of the non-$CO_2$ GHG emissions in fire The other trace gaseous and particulate carbons were usually neglected (Setyawati and Suwarsono, 2015). Fire can be a major source (and the dominant source in major fire years) of GHG emissions (both $CO_2$ and non-CO2) from tropical peatland, especially after drainage or forest removal, and during El Nino years (KFCP, 2014).

Ignitions in Indonesia, as in many parts of the tropics, are primarily of anthropogenic origin (Bompard and Guizol, 1999; Bowen *et al*., 2000), resulting in either accidental or deliberate fires. The human contribution to changing fire regimes and our capacity to manage fire remains somewhat uncertain (Bowman *et al*., 2009; Bowman *et al*., 2011). Thus, a key component to understand changing fire regimes in the tropics is to identify the sources of fire ignitions and the land use/land cover (LULC) classes associated with fire ignitions (Cattaua *et al*., 2016).

Fire causes from human activities mostly originated from swamp shrub burning and land clearing for farming (Thoha *et al*., 2019). Carbon emissions as a result of fires in peatlands are particularly high, as peat is extremely rich in belowground organic carbon (Cattaua, 2019) ; peat-swamp forest with a depth of 10 m can store 12–19 times the amount of carbon as other tropical forest types (FRIM-UNDP/GEF, 2006). Mean annual $CO_2$ emissions from decomposition of deforested and drained peatlands and associated fires in Southeast Asia are estimated at _2000 Mt $CO_2$ $y^{-1}$ (Hooijer *et al*., 2006). However, there is annual variability in emissions during El Niño phases of ENSO far

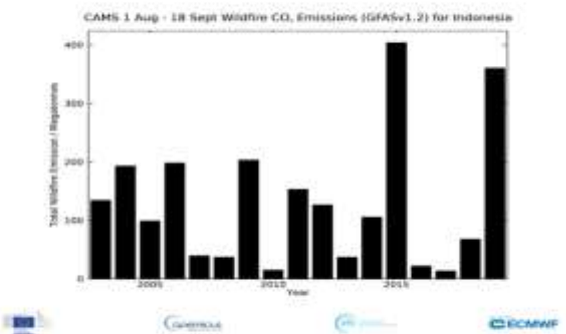

Figure 1 total estimated $CO_2$ equivalent emissions calculated for Indonesia between 1 August and 18 September for all years between 2003 and 2019. Credit: CAMS/ECMWF

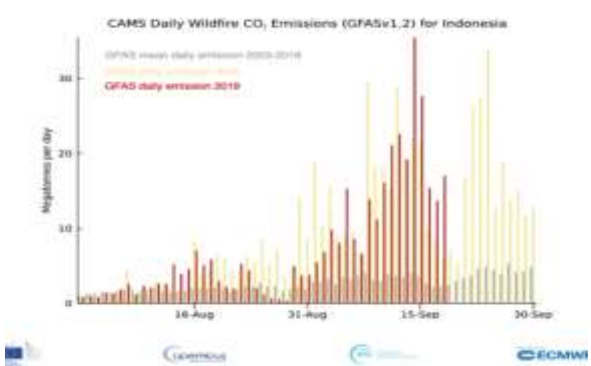

Figure 2 Daily total estimated $CO_2$ equivalent emissions, comparing 2019 (in red) with 2015 (in yellow) and the 2003-2018 mean (in grey), showing the comparability of recent emissions to the same days in 2015. Credit: CAMS/ECMWF

exceed those from non-El Niño periods (van der Werf *et al*., 2008). Over 90% of these peat emissions come from Indonesia, which has the one of the largest amounts of tropical peat carbon globally (Page *et al*., 2011; Page *et al*., 2006; Rieley *et al*., 1996; 7). It is estimated that 0.81–2.57 Gt C were released from Indonesia's peatlands during the 1997/98 fire season alone due to peat and vegetation combustion (Page *et al*., 2002).

Fire is also used as an agricultural tool to clear vegetation (Carlson *et al*., 2012; Page *et al*., 2002). These human disturbances can make peatlands particularly prone to fire. In 2015, 53% of fires in Indonesia occurred on peatland, which made up only 12% of the land area (Miettinen *et al*., 2017). Fires on peatland can burn into these underground organic layers and smoulder for weeks after the surface fire has gone out (Roulston *et al*., 2018), resulting in substantially greater emissions compared to surface vegetation fires. Peat fires are estimated to contribute 3.7% of global fire carbon emissions (van der Werf *et al*., 2017). In Indonesia, peatland fires are the largest contributor to fire emissions in the region (Reddington *et al*., 2014; van der Werf *et al*., 2010). For the fires in 2015, Wooster *et al*., (2018) found that 95% of the particulate matter (PM2.5) emissions came from peatland fires, and Wiggins *et al*., (2018) estimated that 85% of smoke plumes detected in Singapore originated from peat fires.

**GHG emission calculating and estimation**

As peatland is composed of organic matter, peat decom¬position produces a significant amount of greenhouse gases (GHGs); carbon dioxide (CO2) aerobically, methane (CH4) anaerobically and nitrous oxide (N2O) both aerobically and anaerobically. Global warming potential (GWP) of CH4 and N2O is 28 and 265 times larger than CO2, respective¬ly, over a 100-year period, and those GWP values do not include climate-carbon feedbacks (IPCC, 2014), and N2O is an important ozone-depleting substance emitted into the atmosphere (UNEP, 2013).

GHG emissions from fires that burn above-ground fuels are reasonably well understood, but are very different in character to peat fires that are very poorly understood (KFCP, 2014). Smouldering peat fires produce more CO relative to CO2, and there can be significant loss of C as other volatile compounds. In an excellent study in which the smouldering of blocks of peat was realistically achieved under a range of moisture contents, Rein *et al*., (2009) found that only 60% of the C in combusted peat was emitted as CO andCO2 (i.e. there were emissions of many other volatile C compounds). This contrasts with about 95% of combusted C released as CO2 and CO for surface fires.

The emission factors (EF, g/kg of fuel burnt) for the combustion of above-ground biomass in tropical forests (IPCC, 2006) are 1580 (CO2), 6.8 (CH4), and 0.2 (N2O). After adjusting for the GWP of these gases, CO2 is ~ 10 fold more important than methane, and ~ 25-fold more important than N2O. However, release of the non-CO2 GHGs is significant because they represent long-term net GHG emissions from fire, in contrast with CO2 that can be re-fixed by re-growing vegetation (KFCP, 2014).

To estimate CO2 emissions from peat decomposition, it is necessary to measure or estimate the net (root free) emissions of CO2 (KFCP, 2014). Separating the root respiration from the CO2 flux (resulting from peat decomposition) is a major challenge. This is made more difficult by the heterogeneous nature of peat forests, as is the scaling of fluxes over both space and time. Consequently, there exists only a very modest amount of reliable data on net (root free) CO2 emissions from peat decomposition in tropical peatlands that can be used for the calculation of emissions in a GHG accounting methodology.

When peat forests are disturbed, the peat typically begins to subside (KFCP, 2014). The subsidence rate is correlated, to some extent, with drainage depth (depth of the water table) across a wide range of environmental conditions, suggesting that it may be a useful proxy for the rate of peat decomposition. However, a range of other factors such as vegetation cover and prior fire disturbance also affect subsidence, although their effects are difficult to quantify. Couwenberg *et al*., (2009) in their survey of the literature found a linear relationship between subsidence rate and water depth for Southeast Asian tropical peat soils, with subsidence increasing by 0.9 cm a-1 for each 10 cm of additional drainage depth. This is substantially more than in other parts of the world (Hooijer *et al*., 2006; Couwenberg *et al*., 2009).

Total annual GHG emissions were estimated by multiplying the area affected by drainage and fire by an activity specific emission factor (EF). In addition, direct emissions from drained organic soils were also accounted for to cover all relevant gases. Separate EFs were used for peat biological oxidation, direct N2O and CH4 emissions from drained organic soils, and peat fires (Krisnawati *et al*., 2015). EFs from peat biological oxidation, N2O and CH4 were derived from the 2013 Supplement to the 2006 IPCC Guidelines for National GHG Inventory on Wetlands (IPCC, 2014), for which most of the figures were generated from studies in Indonesia. EFs from peat fires were adopted from the studies in Indonesia reported by Page *et al*., (2014) which used the information on depth of burn for the first and subsequent fires, peat bulk density and carbon content values, but adapted to meet international reporting requirements following the approach described in Equation 2.8 IPCC (2013) (Table 1). These emission factors have been considered to be more representative of normal fire conditions than the emission factors presented in the IPCC 2013 (Hooijer *et al*., 2014; Konecny *et al*., 2016).

To calculate annual CO2-C and Non-CO2 emissions from organic soil fire using this following equation (IPCC, 2014).

$$L_{fire} = A \times MB \times C_f \times G_{ef} \times 10^{-3}$$

Where:

Lfire = amount of CO2 or non-CO2 emissions, e.g. CH4 from fire, tonnes
A = total area burnt annually, ha
MB = mass of fuel available for combustion, t ha-1
Cf = combustion factor, dimensionless

Gef = emission factor for each gas, g kg-1 dry matter burnt
Mass of fuel available for combustion = burnt area (m2) x burnt depth (m) x bulk density (t m–3)

Emission factor values used to calculate carbon emission from peat fires are listed in Table 1. Emission factor for Kalimantan peat fire was the average of emission factors from three previous studies (Stockwell *et al*, 2014; Stockwell *et al*, 2016; Setyawati *et al*, 2017). Because there were no previous studies for Papua and West Papua peat fires, therefore we used emission factor for CO2 of 1,111 g/kg by extrapolating peat carbon mass fraction of 0.3053 for hemic peat (Wahyunto *et al*, 2006)) to the regression linear equation of emission factor for smoldering peat fire (Setyawati, 2017). The corresponding emission for CO and CH4 can be calculated by multiplying their emission ratio, by using CO2 as a reference species, with the calculated emission of CO2 by applying the equation below (Penmann *et al*, 2003):

$$E = ECO_2 \text{ x } \frac{ER_x}{CO_2}$$

where Ex is amount of emission of x (CO or CH4) (ton), ECO2 is amount of emission of CO2 and ERx/CO2 refers to emission ratio of x with respect to CO2 (mol/mol). For the purpose of this study, therefore ERCO/CO2 is 0.153 mol/mol and ERCH4/CO2 is 0.029 mol/mol (Setyawati and Suwarsono, 2015).

Roulston *et al*. (2018) and Wooster *et al*. (2018) found that EFs for tropical peat fires could be underestimated by a factor of three (PM2,5 EF from peat fires is assumed to be 9.1 g kg-1 in the Global Fire Emissions Database (GFED4), compared to 24 g kg-1 suggested by Roulston *et al*., 2018, and 28 g kg-1 suggested by Wooster *et al*., 2018). There are large variations in EFs for peat in Indonesia (Kiely *et al*, 2019).

In one study measuring emissions from peat fires in central Kalimantan during 7 d in 2015, PM2,5 EFs were found to vary between 6 and 30 g kg-1 (Jayarathne *et al*., 2018). Kuwata *et al*. (2018) used measurements from Indonesian peatland fires to estimate EFs of PM10 of 13±2 g kg-1 in 2013 and 19±2 g kg-1 in 2014.

Tansey *et al*. (2008) used an analysis of MODIS hotspots and MODIS burned area in a peat swamp in Indonesia to estimate 15–16 ha of burned area per hotspot. However, 60% of burned areas did not have an identified hotspot, implying an area burned per MODIS hotspot of approximately 40 ha. Over areas defined as peatland, we therefore assumed a burned area of 40 ha of peat burnt per hot spot, smaller than the 100 ha assumed for vegetation fires (Kiely *et al*, 2019).

Table 1 Emission factors (g/kg dry peat burned) used for the calculation of carbon emission (Setyawati and Suwarsono, 2015)

| | Sumatra (Christian *et al*,2003) | Kalimantan (Stockwell *et al*, 2014) |
|---|---|---|
| CO2 | 1,73 | 1,677 |
| CO | 210,3 | 221 |
| CH4 | 20,8 | 13,1 |

New measurements of tropical peat combustion have led to an upward revision of particulate emission factors, leading to a suggestion that some fire emission inventories may underestimate particulate emissions from peat fires (Kiely *et al*, 2019). The WRF-chem model along with extensive observations of PM to make a revised estimate of PM emissions from Indonesian fires during August–October 2015 (Kiely *et al*, 2019). Kiely *et al*, (2019 agree that total emissions agree with estimations by Wooster *et al*. (2018) (9,1±3,2) and Jayaranthe *et al*. (2018) (6±5,5 Tg from peat fires).

Kiely *et al*, (2019) find that emissions from peat combustion make up a substantial fraction of total fire emissions from the region. We estimate that peat combustion contributed 55% of total CO2 emissions and 71% of primary PM2,5 emissions during September–October 2015 (Kiely *et al*, 2019). Peat combustion contributed 76% of fire-derived surface PM2,5 concentrations over Sumatra and Borneo during this period. This highlights the importance of peat fires and the need for better estimates of emissions from peat combustion Kiely *et al*, (2019).

The depth of peat burn is a crucial factor controlling emissions from peat fires but it is poorly constrained (Kiely *et al*, 2019). We found that using satellite remotely sensed soil moisture to control the assumed depth of peat burn improved the simulation of PM, with the correlation between simulated and measured PM increasing from 0.48 with fixed peat burn depth to 0.56 with soil moisture control (Kiely *et al*, 2019). There is little data available on the relationship between surface soil moisture and burn depth, more work on this could lead to further improvement in the simulation. Work is also needed to examine whether this is consistent for years other than 2015 (Kiely *et al*, 2019).

## GHG emission Reduction from Peatland Fires

### Peatland Fires

Burning peat is difficult to extinguish and the flames can creep beneath the surface so land fires can spread out of control (Thoha *et al*., 2019). Dry peat with very low moisture levels due to drought and irreversible drying in the dry season becomes a combustible fuel, being a detected hotspot area in high density. the dried peat cannot absorb water anymore if it is dampened and will be easily burned (Agus and Subiksa, 2008),

Agribusiness companies, smallholders and small-scale farmers have cleared land by means of fire in often fragmented and degraded landscapes (Carmenta *et al*., 2017). Perceived economic benefits of clearing land through burning (i.e., it is cheap, easy and effective) have driven agribusiness companies and smallholders to use fire as a means for preparing, developing and maintaining agricultural and plantation lands (Purnomo *et al*., 2017; Simorangkir, 2007; Luca Tacconi, 2016). Relatedly, small-scale farmers have cleared land by means of fire – a farming method that is referred to as slash-and-burn – to prepare agricultural land, generate natural nutrients, enhance soil fertility, eliminate destructive weeds and increase production yield (Henley, 2011; Kleinman, Pimentel, & Bryant, 1995; Padoch *et al*., 2007). In the same line, environmental activists have advocated for the practice of slash and-burn by small-scale farmers and consider commercial land clearing by means of fire environmentally destructive (Jong, 2017; WWF, 2006). While exuberant use of natural resources, seismic land-use change and land clearing by means of fire within Indonesia's forest and peat landscapes have been responsible for the occurrence of large-scale fires (Cochrane, 2003; Luca Tacconi, 2016; Varkkey, 2013), research shows that stakeholders' actions concerning the fires appear to have perpetuated the fires' recurrence (McCarthy, 2013; Thung, 2018; Wijedasa *et al*., 2017).

The choice of strategy in suppressing wildfires and carrying out prescribed burning depends largely on how the fire is expected to behave i.e., its rate of the spread, direction of travel and intensity (Saharjo, 2006). The aspects of fire behaviour which are prerequisites for the start and spread of fire are flammable fuels, sufficient heat energy to bring fuels to the ignition temperature and adequate of oxygen (Lorimer 1990). How and why fire behave is determined by a number of inter related factors such as fuel, weather, topography and seasonal changes and tome of day (Lorimer 1990).

Thoha *et al*., (2018) also found that unmanaged land almost burns every dry season. Other causes of fire are clearing of land for dry agricultural land, for paddy fields, for having land tenure, clearing of areas around the gold mine, clearing land to dispose of pests, wildfire from hunting, wildfire from fishing activities, wildfire from smoking activities, timber harvesting and conversion from secondary forests to plantations (Thoha *et al*., 2019). Research of Akbar *et al*., (2011) in the Kapuas peatland area found that the sources of land fires also came from farmers and fishers. In addition to the marsh bushes, galam forest was also a source of fire that many people mentioned.

Human activities mostly originated from shrubs swamp burning and land clearing for farming, while hotspot density was determined by peat depth, land cover, accessibility and human activities (Thoha *et al*., 2017). There are lots of reasons for the use of fire in land preparation, but the most prominent motive is economic consideration (Murniati and Suharti, 2018).

Cattaua *et al*., ( 2016) results support previous research that most fires occur in non-forest or degraded areas (including oil palm in Gaveau *et al*., 2014; Miettinen *et al*., 2007) and that emissions from fire are associated with highly degraded areas (Marlier *et al*., 2015a), by showing both that the majority of fires are ignited in non-forest and highlighting that fires actually start in non-forest rather than merely just occur in non-forest (with the possibility that ignition started there or elsewhere).

Different fuel characteristics (potency, moisture, bed depth, and type) at the same level of peat decomposition will have significantly different fire behavior as it happened also on the depth of peat destruction except fibric (Saharjo, 2006). The same condition occurred in the fire behavior at different level of peat decomposition (Saharjo, 2006).

In the year 2016, Indonesian President decided to established Peatland Restoration Agency (PRA/BRG). The establishment of PRA was motivated by the massive forest and land fires in 2015. That year was the worst period in the history of forest and land fire in Indonesia during the last 18 years. The fire occurring from June to November had burned 2.6 million hectares of land and resulted in thick smoke and haze. One of the factors which triggered the fire is the practice of draining, causing the peatland to be more prone to fire, particularly during the dry season. However, a further analysis on the peatland fire indicated a rather complex and systematic problem situation, while the data and knowledge on the characteristics of the peat ecosystem and the safe appropriate technology to manage the peatland were still too limited.

According to MoEF's data, it had been recognized that fires in the peatlands area especially the 7 provinces PRA mostly increased very significant except Papua (Table 3). It clearly shown that South Sumatra province peatland fires were the highest among others province with the increasing about 6,460 %, followed by Jambi with 3,870 %, Central Kalimantan 640 %, Riau 186 %, West Kalimantan 150 % and Papua -7.3 % (Table 3 ).

Table 2 Indonesian Forest and land fires areas 2015-2019 in the BRG restoration area (MoEF, 2019)

| Province | 2015 | 2016 | 2017 | 2018 | 2019 | 2015-2019 | % |
|---|---|---|---|---|---|---|---|
| South Sumatra | 646,298.80 | 8,784.91 | 3,625.66 | 16,226.60 | 328,457.00 | 1,003,329.97 | 18.8 |
| Central Kalimantan | 583,833.44 | 6,148.42 | 1,743.82 | 47,432.57 | 303,881.00 | 943,039.25 | 17.67 |
| West Kalimantan | 93,515.80 | 9,174.19 | 7,467.33 | 68,422.03 | 151,070.00 | 329,669.35 | 6.18 |
| South Kalimantan | 196,516.77 | 2,331.96 | 8,290.34 | 98,637.99 | 136,428.00 | 442,205.06 | 8.29 |
| Riau | 183,808.59 | 85,219.51 | 6,866.09 | 37,236.27 | 90,233.00 | 403,636.46 | 7.56 |
| Jambi | 115,634.34 | 8,281.25 | 109.17 | 1,577.75 | 56,593.00 | 182,195.51 | 3.41 |
| Papua | 350,005.30 | 185,571.60 | 28,767.38 | 88,626.84 | 104,981.00 | 758,952.12 | 14.22 |
| Total area burned Indonesia | 2,611.411.44 | 438,363.19 | 165,483.92 | 529,266.64 | 1,592,010.00 | 5,336.535.19 | |

## Hotspot detecting

Increasing number of hotspots occurs when monthly rainfall decreases (Thoha *et al*., 2019). Most high fire activities are located in peatland, swamp shrubs, close to road, close to river and far away from villages (Thoha *et al*., 2019). Hotspot density has various relationship with peat depth, land cover, accessibility, and human activities.

The hotspot density increases as the distance from rivers and canals decrease 4 (Thoha *et al*., 2019). Closer to the river, denser hotspots are detected. The density of the hotspots will decrease and no hotspot is found in areas over 6 km from the river. This is related to the activities of people who utilize rivers and canals, such as picking and transporting timber, hunting, fishing, and farming (Thoha *et al*., 2019). According to Hecker (2005) and Hooijer *et al*., (2008), more than 4000 km of canals have been built in the ex-peat land area of the Ex-PLG which provides access to the peatlands that allows a lot of community activities to take place.

Hotspot density also increases with the decreasing distance to roads (Thoha *et al*., 2019). The highest density of hotspots is found in areas 1 km away from the road (Thoha *et al*., 2019). Roads provide access to communities and corporations to conduct a variety of activities that cause the land vulnerable to cultivation (Thoha *et al*., 2019). Many people clear the land by burning, generally close to the road. Activities that cause burning land are smoking activity and clearing land for getting land tenure. Analysis of Boer *et al*., (2007) also showed that significant portions of fires in Central Kalimantan occur close to the road network, which can also predict the important causes of fire.

The number of hotspots is inversely proportional to rainfall. According to the time, August-October is the time of hotspot in Kapuas District. The high number of hotspots does not always indicate the fires occurred in regions of Kapuas District. Hotspot density as an indication of fire activity is determined by the presence of peatlands, land cover, accessibility, and human activities. Areas with the densest hotspots are generally distributed on peat soil sites with marshland bush cover, close to the river, close to the road, some distance from humans and on farmland and plantation cultivation fields (Thoha *et al*., 2019).

Generally, hotspots increase when rainfall decreases (Thoha *et al*., 2019). Study by Tata *et al*., (2018) also found a similar pattern in Pelalawan District of Riau Province that the majority of hotspots usually occurred in June to August. Rainfall is very influential on the water content of fuel, especially on peatlands. As rainfall increases, peatlands will store large amounts of water so the water content of the fuel increases and they are difficult to burn (Thoha *et al*., 2019). When the rainfall decreases, the water content of the peat decreases. Peat with low moisture is very susceptible to burning (Thoha *et al*., 2019). Taufik et a.l (2011) and Syaufina *et al*., (2004) found that rainfall greatly affected the dynamics of groundwater and groundwater level. Both fluctuations are strongly influenced by the dynamics of rainfall soaking the soil. In low rainfall season, water level falls on critical thresholds that cause peatlands highly flammable (Wosten *et al*., 2008).

The highest density of hotspots is at a distance of 3-5 km from the center of the village (Thoha *et al*., 2019). In the year when the incident of high fires occurred in 2002, 2006 and 2009, the highest density was found in the area 6-10 km away from the village center (Thoha *et al*., 2019). In areas which are very close to the villages, people tend to take good care of their land so they are relatively safe from fires. In the center of the village, there are many community settlements and public facilities, so it generally gets intensive supervision and care (Thoha *et al*., 2019).

## Managing Peatlands

Indonesia has over 13,34 million ha of peatlands (Anda *et al*. 2021), which is over 12% of its forest land spreading across islands of Sumatra, Kalimantan, Sulawesi and Papua . This is the one of largest tropical peatland areas in the world after Brazil (Gumbritch *et al*.2017), followed by Democratic Republic of Congo, with the peatland area reaches 9 million ha, and the Republic of Congo with the area reaches about 5.5 million ha (Miles *et al*., 2017).

Those emission was about 60% of the 2030 target using Business as usual (BAU) scenario, that was about 2.88 Gt CO2-eq totally as it mentions in Intended Nationally Determined Contribution (INDC). This meant that, fire prevention activities become very important as Indonesia have promised to reduce GHG emission about 29 % by the year 2030 (MoEF, 2018).

Tropical forests have a vital role in buffering the brunt of global environmental change. The forests act as a giant carbon sink, and well-preserved tropical forests can reduce global emission by at least 30% (Busch & Seymour, 2016; Turetsky *et al*., 2015). Unfortunately, tropical forest conservation efforts have faced a significant challenge from the occurrence of fires (Carmenta, Coudel, & Steward, 2018). Extensive fires have become more frequent and pervasive in tropical forests worldwide (Fernandes *et al*., 2017; Jolly *et al*., 2015). Indonesia has been identified as a hotspot of fires activities, a considerable proportion of which has come from within its peat landscape (Gaveau *et al*., 2015; Tacconi, 2016;

Table 3 Burned peatland in the PRA restoration area (MoEF, 2019)

| **Province** | **2018 (ha)** | **2019 (ha)** | **% Difference** |
|---|---|---|---|
| South Sumatra | 2,071 | 133,711 | 6,460 |
| Central Kalimantan | 27,516 | 175,915 | 640 |
| West Kalimantan | 39,573 | 59,729 | 150 |
| South Kalimantan | 9,902 | 11,305 | 114 |
| Riau | 33,867 | 62,965 | 186 |
| Jambi | 622 | 24,045 | 3,870 |
| Papua | 2,372 | 2,199 | -7,3 |
| **PRA Restoration area** | **115,923** | **469,869** | **405** |
| **Burned peatland area in PRA** | **125,340** | **480,178** | **383** |

Wijedasa *et al*., 2017). Due to their severity, frequency and cross-scale impacts, Indonesia's forest and peat fires are of particular concern both nationally and globally.

Drained peatlands are highly susceptible and frequently subjected to fire, resulting in significant greenhouse gas emissions (Field *et al*., 2016) and transboundary haze pollution that cause extremely severe human health problems (Kunii *et al*., 2002; Marlier *et al*., 2013), economic losses (World Bank, 2016) and international tension throughout the region. Fires are started for the purposes of land clearing and claiming, fishing, hunting, cooking and non-timber forest product collection (Sinclair *et al*., 2020). However, in drained, degraded landscapes, these surface fires are often difficult to control or properly extinguish, and can escalate into wildfires and persistent smouldering peat fires. Drainage also stimulates biological oxidation of peat in the upper peat profile, and the resultant greenhouse gas emissions are equal to if not greater than those from fire (Hooijer *et al*., 2014; Miettinen *et al*., 2017).

Results of research shown there was a tendency that low level of peat decomposition (fibric) will have lower rate of the spread of fire, higher flame height that directly related to fire intensity which finally resulted in less peat destroyed (Saharjo, 2006). This means that fire in the low level of peat decomposition was relatively difficult to be controlled. Among the three site Sapric, hemic, and fibric that burned, it had been found that fire in fibric site will be the most difficult to be controlled when fire blow up and sapric site will be the worst (Saharjo, 2006).

Management to reduce ignitions in degraded non-forest areas, in addition to reducing the probability of continued burning when ignitions do occur, will be pivotal in reducing fire across the landscape (Cattaua *et al*., 2016). This strategy is also key to preventing forest fires and the associated loss of habitat, as we found that the majority of forest fires start in non-forest. Achieving this goal among numerous smallholders is likely to prove even more difficult than reducing fire ignition and burning in oil palm concessions, however, as the latter have much greater capacity to implement consistent management policies over large areas and provide necessary management resources, and are under higher pressure to do so. There are some existing village-level fire teams (Regu Pemadam Kebakaran = RPK) and community groups for fire management (Kelompok Masyarakat Pengendali Kebakaran = KMPK1) operating in degraded, non-forest areas, but these groups are small-scale and under-funded. It is also easier to identify actors of illegal burning within concessions and bring prosecutions against a single concession holder, compared to numerous smallholders operating illegally in areas with ill-defined land ownership (Cattaua *et al*., 2016).

This approach is likely to be even more challenging in very remote areas that are not being frequented or cultivated by smallholders, as much of this land is discarded wasteland. In these areas, regeneration efforts, including reforestation and hydrological restoration, will be key for fire reduction on the landscape. In making this recommendation, we recognize that some previous projects focusing on restoration in this area appear to have failed due to a combination of insufficient or inconsistent funding, land tenure concerns, misinformation between project organizers and local people, etc. (e.g., Atmadja *et al*., 2014).

Research done by Putra *et al* (2018) in ex-MRP shown that, most of the fires in the study area occurred with GWL conditions of 30 – 39 cm below the peat surface, but fire occurrences with GWL of less than 10 cm below peat surface may strongly suggest that degraded peatlands are very vulnerable to fires even under relatively moist conditions. Therefore, degraded peatlands should be maintained in wet conditions with critical GWL of less than 10 cm below peat surface, to prevent the area from experiencing surface peat fires. Dry conditions of degraded peatland create a suitable condition for the fire to burn downward into deeper peat layers and ignite deep peat fires, resulting in devastating peat fires in the area.

Relationships between fire occurrences and GWL may suggest that the low GWL accelerated conditions where fires ignite with ease. In 2011, large number of fires started occurring in August following the drop of the mean GWL to – 33 cm, while in August 2012 fires began with a mean GWL of -34 cm. Usup *et al*. (2004), Putra and Hayasaka (2011), Susilo *et al*. (2013) and DeVries (2010) suggested critical groundwater level of 40 cm below peat surface to prevent fire. However, our findings suggest that shallower GWL below peat surface should be maintained to prevent peat fire occurrences in dry-degraded peatlands.

The groundwater level (GWL) could be one of the key indicators assessing fire risk in peatlands because the dryness of peat and the moisture content of surface peat are directly influenced by GWL (McKinnon *et al*, 1997). In its natural condition, peat always inundated with water (Murdiyarso and Adiningsih, 2006). However, our prolonged research observed the deficit of GWL in the area

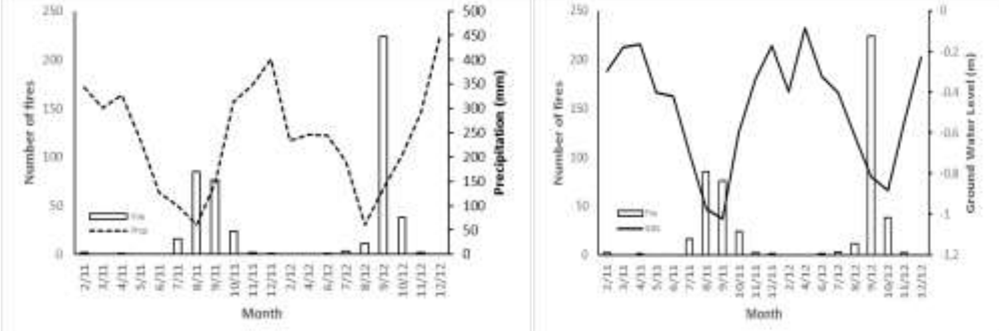


Figure 3 Relationships between number of fire occurrences and precipitation (left), and with GWL at study area (right) (Putra, 2011)

for the whole of the year (Putra *et al*, 2016), it was the unnatural phenomenon for the peat hydrology system. This study reveals the similar findings. The recent GWL in the area remains in negative value below peat surface for almost whole of the year. It may greatly explain the severe dry condition of the peat in the area and indicates the peat has lost its ability to absorbing and storing water (hydrophobic condition). This condition exacerbates peat burning conditions in the area.

Additionally, the underlying causes of fire can be both complex and site-specific (Dennis *et al*., 2005; Applegate *et al*., 2001; Bowen *et al*., 2000), and so management and policy actions need to take into account the diverse needs of all stakeholders. Important and complementary information that we cannot deduce through satellite data could be ascertained through interviews (e.g., motivations for lighting fires, willingness or ability to adapt alternative land clearing strategies, etc.). Institutional issues are also relevant to this conversation, as national and regional policies affect land use zoning (Stolle *et al*., 2003), and how these policies are implemented affects the behavior of stakeholders (e.g., communities and government agencies) on the ground. For example, when the customary laws under the marga system, which gave rights to forest resources to local communities, were replaced with current forest laws, local communities were left feeling marginalized, with little incentive to engage in fire-fighting efforts outside the boundaries of their plots (Bompard and Guizol, 1999). Recent law changes are now giving more forest rights back to communities, but there is concern that this too will lead to more forest destruction (Handadhari, 2015). Additionally, the underlying causes of fire can be both complex and site-specific (Dennis *et al*., 2005; Applegate *et al*., 2001; Bowen *et al*., 2000), and so management and policy actions need to take into account the diverse needs of all stakeholders. Important and complementary information that we cannot deduce through satellite data could be ascertained through interviews (e.g., motivations for lighting fires, willingness or ability to adapt alternative land clearing strategies, etc.). Institutional issues are also relevant to this conversation, as national and regional policies affect land use zoning (Stolle *et al*., 2003), and how these policies are implemented affects the behavior of stakeholders (e.g., communities and government agencies) on the ground. For example, when the customary laws under the marga system, which gave rights to forest resources to local communities, were replaced with current forest laws, local communities were left feeling marginalized, with little incentive to engage in fire-fighting efforts outside the boundaries of their plots (Bompard and Guizol, 1999). Recent law changes are now giving more forest rights back to communities, but there is concern that this too will lead to more forest destruction (Handadhari, 2015).

## CONCLUSION

Based on our analysis, proper peat management reduces forest and land fires risks and consequently avoid greenhouse gas emissions through prevention activities. There is a high opportunities to reduce greenhouse gas emissions resulted from peat fires. However, because there are still some differences in principles and calculations, the uncertainty remains high.. It clearly shows that good management of peatlands to control forest and land fires events will bring a significant positive contribution in country’s reducing greenhouse gas emissions.

There is still large variation of EF which vary from 9.1 g/kg – 28 g/kg; as well as for CO2, CO, CH4, PM 2.5 and PM 10. within addition, peat burnt depth has also large variation, where there are many researchers still assume the default value, such as an average of 0.3 meter, 0.5 meter etc, that does not reflect the actual field condition. The other generalization data also occurred with bulk density. This situation will make the GHG emission at each species will caused under estimate or mostly over estimate. This situation especially case for Indonesia had been warned by Stockwell *et al* (2016, which mention that those field data support significant revision of the EFs for CO2 (−8%), CH4 (−55%), NH3 (−86%), CO (+39%), and other gases compared with widely used recommendations for tropical peat fires based on a lab study of a single sample published by Christian *et al* (2003)

## REFERENCES

Akbar A, Sumardi R, Purwanto H, Sabarudin MS. 2011. Studi sumber penyebab terjadinya kebakaran dan respon masyarakat dalam rangka pengendalian kebakaran hutan gambut di Areal Mawas, Kalimantan Tengah. *Jurnal Penelitian Hutan Tanaman*, 8: 287-300. [Indonesian]

Anda M, Ritung S, Suryani E, Sukarman, Hikmat M, Yatno E, Mulyani A, Subandiono RE, Suratman, Husnain. 2021. Revisiting tropical peatlands in Indonesia: Semi-detailed mapping, extent and depth distribution assessment. *Geoderma* Volume 402, 15 November 2021, 115235. https://doi.org/10.1016/j.geoderma.2021.115235

Applegate GBA, Chokkalingam U, Suyanto S, 2001. The underlying causes and impacts of fires in Southeast Asia final report. Bogor, Indonesia: Center for International Forestry Research (CIFOR), International Centre for Research in Agroforestry, SEA Regional Research Programme, USAID, USDA Forest Service.

Atmadja SS, Indriatmoko Y, Utomo NA, Komalasari M, Ekaputri AD. 2014. Kalimantan forests and climate partnership, central kalimantan, Indonesia. In: Sills EO, Atmadja SS, Sassi CD, Duchelle AE, Kweka DL, Resosudarmo IAP, Sunderlin WD. (Eds.), REDD+ on the Ground, A Case Book of Subnational Initiatives Across the Globe. CIFOR.

Barber CV, Schweithelm J. 2000. Trial by Fire: Forest Fire and Forestry Policy in Indonesia's Era of Crisis and Reform. World Resources Institute, Washington, D.C.

Bompard JM, Guizol P. 1999. Land management in the province of South Sumatra, Indonesia. Fanning the flames: the institutional causes of vegetation fires. European Union Forest Fire Prevention and Control Project. European Union Ministry of Forestry and Estate Crops, Palembang.

Bowen MR, Bompard JM, Anderson IP, Guizol P, Gouyon A. 2000. Anthropogenic fires in Indonesia: a view from Sumatra. In: Eaton P, Radojevic M. (Eds.), Forest Fires and Regional Haze in Southeast Asia. Nova Science, New York. Bowman DMJS, Balch JK, Artaxo P, Bond WJ, Carlson JM, Cochrane MA, DÄôantonio CM, Defries RS, Doyle JC, Harrison SP, Johnston FH, Keeley J E, Krawchuk MA, Kull CA, Marston JB, Moritz MA, Prentice IC, Roos CI, Scott AC, Swetnam TW, Van Der Werf GR, Pyne SJ. 2009. Fire in the earth system. *Science* 324, 481–484.

Bowman DMJS, Balch J, Artaxo P, Bond WJ, Cochrane MA, D'antonio CM, Defries R, Johnston FH, Keeley JE, Krawchuk MA, Kull CA, Mack M, Moritz MA, Pyne S, Roos CI, Scott AC, Sodhi NS, Swetnam TW, Whittaker R. 2011. The human dimension of fire regimes on Earth. *J. Biogeogr*. 38, 2223–2236.

Brauer M, Hisham-Hashim J. 1998. Fires in Indonesia: crisis and reaction. *Environ. Sci. Technol*. 32, 404A–407A.

Brown N. 1998. Out of control: fires and forestry in Indonesia. *Trends Ecol. Evol.* 13, 41.

Busch J, Seymour F. 2016. Why Forests? Why Now? The Science, Economics, and Politics of Tropical Forests and Climate Change. Washington, DC: Center for Global Development. Retrieved from http://cgdev.org.488elwb02.blackmesh.com/publication/ft/why-forests-why-nowpreview-science-economics-politics-tropical-forests-climate-change

Carmenta R, Coudel E, Steward A. M. 2018. Forbidden fire: Does criminalising fire hinder conservation efforts in swidden landscapes of the Brazilian Amazon? *Geographical Journal*, (February), 1–15. https://doi.org/10.1111/geoj.12255

Cattaua ME, Mark E. Harrisonb, Iwan Shinyob, Sady Tungaub, María Uriartea, Ruth DeFries. 2016. Sources of anthropogenic fire ignitions on the peat-swamp landscape in Kalimantan, Indonesia. *Global Environmental Change*. http://dx.doi.org/10.1016/j.gloenvcha.2016.05.005

Christian TJ, Kleiss B, Yokelson RJ, Holzinger R, Crutzen PJ, Hao WM, Saharjo BH, Ward DE. 2003. Comprehensive laboratory measurements of biomass-burning emissions: 1. Emissions from Indonesian, African, and other fuels *J. Geophys*. Res. 108 (D23) 4719 DOI:10.1029/2003JD003704, 2003

Cochrane MA. 2003. Fire science for rainforests. *Nature*, 421(6926), 913–919. https://doi.org/10.1038/nature01437

Couwenberg J, Dommain R, Joosten H. 2010. Greenhouse gas fluxes from tropical peatlands in south-east Asia. *Global Change Biol.*, 16: 1715-1732. https://doi. org/10.1111/j.1365-2486.2009.02016.x.

Davies SJ, Unam L. 1999. Smoke-haze from the 1997 Indonesian forest fires: effects on pollution levels, local climate, atmospheric CO2 concentrations, and tree photosynthesis. *For. Ecol. Manage*. 124, 137–144.

Dennis R, Mayer J, Applegate G, Chokkalingam U, Colfer CP, Kurniawan I, Lachowski H, Maus P, Permana R, Ruchiat Y, Stolle F, Suyanto Tomich T. 2005. Fire: people and pixels: linking social science and remote sensing to understand underlying causes and impacts of fires in Indonesia. *Human Ecol*. 33, 465–504.

DeVries B. 2010. Monitoring the Effects of Hydrological Restoration Efforts in Degraded Tropical Peatlands MSc Thesis Wageningen University Germany.

Fernandes K, Verchot L, Baethgen W, Gutierrez-Velez V, Pinedo-Vasquez M, & Martius C. 2017. Heightened fire probability in Indonesia in non-drought conditions: The effect of increasing temperatures. Environmental Research Letters, 12(5). https://doi.org/10.1088/1748-9326/aa6884

Field RD, van der Werf GR, Fanin T, Fetzer EJ, Fuller R, Jethva H, Levy R, Livesey NJ, Luo M, Torres O, Worden HM. 2016. Indonesian fire activity and smoke pollution in 2015 show persistent nonlinear sensitivity to El Niño-induced drought. *Proc. Natl*. Acad. Sci. 113, 9204–9209. https://doi.org/10.1073/pnas.1524888113.

FRIM-UNDP/GEF. 2006. Malaysia’s Peat Swamp Forests Conservation and Sustainable Use. United Nations Development Programme, Malaysia.

Gaveau DLA, Salim MA, Hergouac’h K, Locatelli B, Sloan S, Wooster M, Marlier ME, Molidena E, Yoen H, DeFries R, Verchat L, Murdiyarso D, Nasi R, Holmgren P, Sheil D. 2014. Major atmospheric emission from peat fires in Southeast Asia during non-drought years: evidence from the 2013 Sumatran fires Scientific reports 4:6112. DOI: 10.1038/srep06112

Goldammer JG. 1990. Tropical wild land fires and global changes: prehistoric evidence, present fire regimes, and future trends. In: Levine, J.S. (Ed.), Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications. MIT Press, Cambridge, MA.

Goldammer JG. 1991. Tropical wild land fires and global changes: prehistoric evidence, present fire regimes, and future trends. In: Levine, J.S. (Ed.), Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications. MIT Press, Cambridge, MA.

Handadhari T. 2015. Bom Wakti Perusakan Hutan. Jakarta Globe.

Harris N, Minnemeyer S, Sizer N, Mann SA, Payne OA. 2015. With Latest Fires Crisis, Indonesia Surpasses Russia as World’s Fourth-Largest Emitter.].

Harrison ME, Page SE, Limin SH. 2009. The global impact of Indonesian forest fires. *Biologist* 56, 156–183.

Hayasaka H, Noguchi I, Putra EI, Yulianti N, Vadrevu K. 2014. Peat-fire-related air pollution in central Kalimantan, Indonesia. Environ. Pollut. 195, 257–266.

Hayasaka H. et al. 2014. Peat-fire-related air pollution in Central Kalimantan, Indonesia, Environmental Pollution. http://dx.doi.org/10.1016/j.envpol.2014.06.031

Hecker JH. 2005. Promoting Environmental Security and Poverty Alleviation in the Peat Swamps of Central Kalimantan, Indonesia Commissioned by the

Institute for Environmental Security, The Netherlands.

Heil A. 2007. Indonesian Forest and Peat Fires: Emissions, Air Quality, and Human Health. PhD thesis, Max Planck Institute for Meteorology, Hamburg, Germany.

Henley D. 2011. Swidden farming as an agent of environmental change: Ecological myth and historical reality in Indonesia. *Environment and History*, 17(4), 525–554. https://doi.org/10.3197/096734011X131503665515 3

Hooijer A, Silvius M, Wösten H, Page S. 2006. PEAT-CO2, Assessment of CO2 emissions from drained peatlands in SE Asia. Delft Hydraulics.

[IPCC] Intergovernmental Panel on Climate Change. 2006. IPCC guidelines for national greenhouse gas inventories. National Greenhouse Gas Inventories Programme. Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K. (eds). Japan: Institute for Global Environmental Strategies [IGES].

[IPCC] Intergovernmental Panel on Climate Change. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed T F Stocker (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press) pp. 1535.

Jaafar Z, Loh TL. 2014. Linking land: air and sea: potential impacts of biomass burning and the resultant haze on marine ecosystems of Southeast Asia. *Global Change Biol.* 20, 2701–2707.

Jayarathne T, Stockwell CE, Gilbert AA, Daugherty K, Cochrane MA, Ryan KC, Putra EI, Saharjo BH, Nurhayati AD, Albar I, Yokelson RJ, Stone EA. 2018. Chemical characterization of fine particulate matter emitted by peat fires in Central Kalimantan, Indonesia, during the 2015 El Niño, Atmos. *Chem. Phys*., 18, 2585–2600, https://doi.org/10.5194/acp-18-2585-2018, 2018.

Jolly WM, Cochrane MA, Freeborn PH, Holden ZA, Brown TJ, Williamson GJ, Bowman DMJS. 2015. Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications*, 6(May), 1–11. https://doi.org/10.1038/ncomms8537

Jong HN. 2017. Small farmers not to blame for peat fires: Walhi. The Jakarta Post. Retrieved from https://www.thejakartapost.com/news/2017/01/18/small-farmersnot-to-blame-for-peat-fires-walhi.html

Kalimantan Forests and Climate Partnership (KFCP). 2014. Methodology for Estimation of Greenhouse Gas Emissions from Tropical Peatlands in Indonesia.

Kiely L, Spracklen DV, Wiedinmyer C, Conibear L, Reddington CL, Archer-Nicholls S, Lowe D, Arnold SR, Knote C, Khan MF, Latif MT, Kuwata M, Budisulistiorini SH, Syaufina L. 2019. New estimate of particulate emissions from Indonesian peat fires in 2015, Atmos. *Chem. Phys.*, 19, 11105–11121, https://doi.org/10.5194/acp-19-11105-2019, 2019.

Kleinman PJA, Pimentel D, Bryant RB. 1995. The ecological sustainability of 48 slash-and-burn agriculture.pdf. *Agriculture, Ecosystems & Environment*, 52(2–3), 235– 249. https://doi.org/10.1016/0167-8809(94)00531-I

Konecny K, Ballhorn U, Navratil P, Jubanski J, Page S, Tansey K, Hooijer A, Vernimmen R, Siegert F. 2016. Variable carbon losses from recurrent fires in drained tropical peatlands. *Global Change Biology*, 22(4), 1469–1480.

Krisnawati H, Imanuddin R., Adinugroho WC, Hutabarat S. 2015. Metode Standar untuk Pendugaan Emisi Gas Rumah Kaca dari Sektor Kehutanan di Indonesia, Versi 1. Pusat Penelitian dan Pengembangan Konservasi dan Rehabilitasi, Badan Penelitian dan Pengembangan Kehutanan, Bogor, Indonesia.

Kunii O, Kanagawa S, Yajima I, Hisamatsu Y, Yamamura S, Amagai T, Ismail ITS. 2002. The 1997 haze disaster in Indonesia: its air quality and health effects. Arch Environ Health, Jan-Feb 2002;57(1):16-22. doi: 10.1080/00039890209602912

Kuwata M, Neelam-Naganathan G, Miyakawa T, Khan F, Kozan O, Kawasaki M, Sumin S, Latif T. 2018. Burning Using Continuous Observation Data. J. Geophys. Res., 123, 9828–9842, https://doi.org/10.1029/2018JD028564, 2018.

MacKinnon K, Hatta G, Mangalik A. 1997. The Ecology of Kalimantan. Oxford University Press.

Marlier ME, Defries RS, Voulgarakis A, Kinney PL, Randerson JT, Shindell DT, Chen Y, Faluvegi G. 2013. El Niño and health risks from landscape fire emissions in southeast Asia. *Nat. Clim. Chang*. 3, 131–136. https://doi.org/10.1038/nclimate1658

Miettinen J, Hooijer A, Vernimmen R, Liew SC, Page SE, 2017. From carbon sink to carbon source: extensive peat oxidation in insular Southeast Asia since 1990. Environ. Res. Lett. 12, 024014. https://doi.org/10.1088/1748-9326/aa5b6f.

Miles L, Ravilious C, García-Rangel S, Lamo X d, Dargie G, Lewis S. 2017. Carbon, biodiversity and land-use in the Central Congo Basin Peatlands. Cambridge, UK: United Nations Environment Programme.

Ministry of Environment and Forestry. 2018. Managing Peatlands to Cope with Climate Change: Indonesia's Experience.

Ministry of Environment and Forestry Republic of Indonesia. 2019. Emission Reduction Report for The Indoneisa-Norway Partnership.

Murdiyarso D, Adiningsih E. 2006. Climate anomalies, Indonesian vegetation fires and terrestrial carbon emissions. *Mitig Adapt Strat Glob Change*. 101 – 112.

Murniati SS. 2018. Towards zero burning peatland preparation: Incentive scheme and stakeholders' role. *Biodiversitas*, 19: 1396-1405.

Padoch C, Coffey K, Mertz O, Leisz SJ, Fox J, Wadley RL. 2007. The Demise of Swidden in Southeast Asia? Local Realities and Regional Ambiguities. Geografisk Tidsskrift-Danish Journal of Geography, 107(1), 29–41. https://doi.org/10.1080/00167223.2007.10801373

Page SE, Siegert F, Rieley JO, Boehm HDV, Jaya A, Limin S. 2002. The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature*. 420, 61–5.

Page SE, Rieley JO, Wüst R. 2006. Lowland tropical peatlands of southeast asia. In: Martini P, Martinez-Cortizas A, Chesworth W. (Eds.), Peatlands: Basin Evolution and Depository of Records on Global Environmental and Climatic Changes. Elsevier, Amsterdam.

Page SE, Rieley JO, Banks CJ. 2011. Global and regional importance of the tropical peatland carbon pool. *Global Change Biol*. 17, 798–818.

Penmann J, Gytarsky M, Hiraishi T, Krug T, Kruger D, Pipatti R, Buendia L, Miwa K, Ngara T, Tanabe K, Wagner F. 2003. Good practise guidance for land use, land use-change and forestry, IPCC National Green House Gas Inventories Programmes, IPCC Guidelines the Institute for Global Environmental Strategies (IGES) Japan.

Posa MRC, Wijedasa LS, Corlett RT. 2011. Biodiversity and conservation of tropical peat swamp forests. *Bioscience*. 61, 49–57.

Purnomo EP, Ramdani R, Agustiyara QP, Tomaro V, Samidjo GS. 2019. Land ownership transformation before and after forest fires in Indonesian palm oil plantation areas. *J. Land Use Sci.* 14, 37–51.

Putra E I, M A Cochrane, Y Vetrita, L Graham and B H Saharjo. 2018. Determining critical groundwater level to prevent degraded peatland from severe peat fire. E I Putra et al 2018 IOP Conf. Ser.: Earth Environ. Sci. 149 012027

Putra EI and Hayasaka H 2011 The effect of the precipitation pattern of the dry season on peat fire occurrence in the Mega Rice Project area, Central Kalimantan, Indonesia. *Tropics* 19 (4): 145 – 156

Reddington, C.L., Yoshioka, M., Balasubramanian, R., Ridley, D., Toh, Y.Y., 2014. Contribution of vegetation and peat fires to particulate air pollution in Southeast Asia. *Environ. Res. Lett.* 9, 094006.

Rieley, J.O., Ahmad-Shah, A.-A., Brandy, M.A., 1996. The extent and nature of tropical peat swamps. In: MALTBY, E., ImmirzI, C.P., Safford, R.J. (Eds.), Tropical Lowlands of Southeast Asia. IUCN, Gland, Switzerland.

Roulston, C., Paton-Walsh, C., Smith, T. E. L., Guérette, A., Evers, S., Yule, C. M., Rein, G., and Van der Werf, G. R.2018. Fine Particle Emissions from Tropical Peat Fires Decrease Rapidly with Time since ignition. *J. Geographys*., Res-Atmopsh 123, 5607-5617, https://doi.org/10.1029/2017JD027827, 2018

Ruitenbeek, J. 1999. Indonesia. In: Glover, D., Jessup, T. (Eds.), Indonesia's Fire and Haze: The Cost of Cataptrophe. Institute of Southeast Asian Studies (ISEAS)/ International Development Research Centre (IDRC), Ottawa.

Saharjo BH. 2006. Fire behavior in Pelalawan peatland, Riau Province. *Biodiversitas*, Vol.7(1): 90-93.

Seavoy RE. 1973. The shading cycle in shifting cultivation. Ann. Assoc. Am. Geogr. 63, 218–225.

Setyawati W, Damanhuri E, Lestari P, Dewi K. 2017. Emission factor from small scale tropical peat combustion IOP Conf. Series: Materials Science and Engineering, 180. P. 012113. doi:10.1088/1757-899X/180/1/012113

Setyawati W. 2017. Development of peat fire emission factor in Indonesia to support greenhouse gas inventory emission, case study: Kalimantan Doctoral Dissertation, Institut Teknologi Bandung.

Silviana SH, Saharjo BH, Sutikno S. 2019. Fire Risk Analysis based on Groundwater Level in Rewetting Peatlands, Sungaitohor Village, Kepulauan Meranti District, Riau Province.

Sinclair AL, Laura LBG, Erianto IP, Saharjo BH, Applegate G, Grover S P, Cochrane MA. 2019. Effects of distance from canal and degradation history on peat bulk density in a degraded tropical peatland. *Science of The Total Environment*. https://doi.org/10.1016/j.scitotenv.2019.134199.

Silviana SH, Saharjo BH, Sutikno S. 2019. Effect of wildfires on tropical peatland vegetation in Meranti Islands District, Riau Province, Indonesia. Biodiversitas, 20: 3056-3062.

Simorangkir D. 2007. Fire use: Is it really the cheaper land preparation method for largescale plantations?. Mitigation and Adaptation Strategies for Global Change, 12(1), 147– 164. https://doi.org/10.1007/s11027-006-9049-2

Stockwell CE, Yokelson RJ, Kreindeweis SM, Robinson AL, DeMott PJ, Sullivan RC, Reardon J, Ryan KC, Griffith DWT, Steven L. 2014. Trace gas emission from combustion of peat, crop residue, domestic biofuel, grasses and other fuels: configuration and fourire transform infrared (FTIR) component of the fourth fire lab at Missoula Experiment (FLAME-4). *Atmospheric chemistry and physics*. 14, 9727-9754.

Stockwell CE, Jayarathne T, Cochrane MA, Ryan KC, Putra EI, Saharjo BH, Nurhayati AD, Albar I, Black DR, Simpson IJ, Stone EA, Yokelson RJ. 2016. Field measurements of trace gases and aerosol emitted by peat fires in Central Kalimantan, Indonesia during the 2015 El Nino. *Atmospheric Chemistry and Physics Discussion*. DOI: 10.5194/acp-2016-411

Stolle F, Lambin EF. 2003. Interprovincial and interannual differences in the causes of land-use fires in Sumatra, Indonesia. *Environmental Conservation.* 30: 375–387.

Susilo GE, Yamamotoa K, Imaia T. 2013. Modeling groundwater level fluctuation in the tropical peatland areas under the effect of El Nino The 3rd International Conference on Sustainable Future for Human Security SUSTAIN 2012. *Procedia Environmental Sciences*. 17: 119 – 128.

Syaufina L, Nuruddin AA, Basharuddin J, See LF, Yusof MRM. 2004. The effects of climatic variations on peat swamp forest condition and peat combustibility. *Jurnal Manajemen Hutan Tropika*. 10 (1): 1-14.

Tansey K, Beston J, Hoscilo A, Page SE, Paredes Hernández CU. 2008. Relationship between MODIS fire hot spot count and burned area in a degraded tropical peat swamp forest in Central Kalimantan, Indonesia. *J. Geophys. Res*., 113, D23112. https://doi.org/10.1029/2008JD010717

Tata HL, Naendra BH, Mawazin. 2018. Forest and land fires in Pelalawan District, Riau, Indonesia: Drivers, pressures, impacts and responses. Biodiversitas. 19 (2): 494-501.

Tacconi L. 2003. Fires in Indonesia: Causes, Costs, and Policy Implications Jakarta, Indonesia. Center for International Forestry Research.

Taufik M, Setiawan BI, Prasetyo LB, Pandjaitan NH, Soewarso. 2011. Pengembangan Indeks Bahaya Kebakaran Di HTI Sbawi, Sumatra Selatan. *Jurnal Penelitian Hutan Tanaman.* 8(4): 215-223. [Indonesian].

Thoha AS, Saharjo BH, Boer R, Ardiansyah M. 2014. Spatiotemporal distribution of peatland fires in Kapuas District, Central Kalimantan Province, Indonesia. *Agric For Fisher*. 3 (3): 163-170.

Thoha AS, Saharjo BH, Boer R, Ardiansyah M. 2019. Characteristics and causes of forest and land fires in Kapuas District, Central Kalimantan Province, Indonesia. *Biodiversitas*. 20: 110-117.

Tomich TP, Fagi AM, DE Foresta H, Michon G, Murdiyarso D, Stolle F, Van Noordwijk M. 1998. Indonesia's fires: smoke as a problem, smoke as a symptom. *Agrofor. Today*. 10, 4–7.

UNEP. 2013. Drawing Down N2O To Protect Climate and the Ozone Layer. United Nations Environment Programme (UNEP), Nairobi, Kenya.

Usup A, Hashimoto Y, Takahashi H, Hayasaka H. 2004. Combustion and thermal characteristics of peat fire in tropical peatland in Central Kalimantan, Indonesia. *Tropics.* 14 (1):1-19 [6].

Van der Werf GR, Randerson JT, Giglio L, Collatz GJ, Mu M, Kasibhatla PS, Morton DC, DeFries RS, Jin Y, van Leeuwen TT. 2010. Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). *Atmos. Chem. Phys*. 10, 11707–35.

Varma A. 2003. The economics of slash and burn: A case study of the 1997/1998 Indonesian forest fires. *Ecological Economics*, 46: 159-71.

Varkkey H. 2013. Patronage politics, plantation fires and transboundary haze. Environmental Hazards, 12(3–4), 200–217. https://doi.org/10.1080/17477891.2012.759524

Wahyunto, Heryanto B, Bekti H, Widiastuti F. 2006. Peta-Peta Sebaran Lahan Gambut, Luas dan Kandungan Karbon di Papua / Maps of Peatland Distribution, Area and Carbon Content in Papua, 2000 – 2001 Wetlands International – Indonesia Programme & Wildlife Habitat Canada (WHC).

Wibowo AM, Suharti APS, Sagala HH, Noordwijk MV. 1997. Fire management on Imperata grasslands as part of agroforestry development in Indonesia. *Agrofor. Syst*., 36, 203–217.

Wooster M, Gaveau D, Salim M, Zhang T, Xu W, Green D, Huijnen V, Murdiyarso D, Gunawan D, Borchard N, Schirrmann M, Main B, Sepriando A. 2018. New Tropical Peatland Gas and Particulate Emissions Factors Indicate 2015 Indonesian Fires Released Far More Particulate Matter (but Less Methane) than Current Inventories Imply, *RemoteSens*.,10,495. https://doi.org/10.3390/rs10040495

World Bank. 2016. The Cost of Fire: An Economic Analysis of Indonesia's 2015 Fire Crisis (English). Indonesia Sustainable Landscapes Knowledge; Note No. 1. D.C World Bank Group, Washington. World Bank, 2016. The Cost of Fire: An Economic Analysis of Indonesia's 2015 Fire Crisis (English). Indonesia Sustainable Landscapes Knowledge; Note No. 1. D.C World Bank Group, Washington.

WWF. 2006. Forest fire prevention in Indonesia. World Wide Fund for Nature. Retrieved from http://wwf.panda.org/wwf_news/?77840/forest-fire-prevention-in indonesia

Wosten JHM, Clymans E, Page SE, Rieley JO, Limin SH. 2008. Peat-water interrelationships in a tropical peatland ecosystem in Southeast Asia Catena. 73: 212-224.

Yule C. 2010. Loss of biodiversity and ecosystem functioning in Indo-Malayan peat swamp forests. Biodiver. *Conserv.* 19, 393–409.