ESTIMATION OF TOTAL CARBON EMISSION FROM FOREST FIRES: CASE STUDY OF BORNEO ISLAND

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Abstract: The availability of combustible materials and their flammability are important aspects in forest fires studies, especially to predict the total carbon emission to the atmosphere. From point of view of earth system modeling, Dynamic Global Vegetation Model (DGVM) provides most of the basic computations for simulating the interactions between terrestrial ecosystem and the atmosphere, including carbon accumulation in vegetation bodies, litter and soil/peat, by considering the effect of climate conditions and its variability. In this study, a modified Lund Potsdam Jena Dynamic Global Vegetation Model (LPJ-DGVM) for application in tropical area is used to simulate the total amount of carbon emitted to the atmosphere in Borneo Island from 1980 to 2006. Simulation results show that the annual average carbon emission from forest fire in Borneo Island is 0.02 to 0.06 GtC/y, with the highest emission during 1997-1998 El-Niño event, which is about 0.05 GtC if only considering the burned of aboveground vegetation, to about 0.62 GtC by also considering the burned of peat layer.

Keywords: DGVM, forest fire, carbon emission, Borneo

INTRODUCTION

Tropical forests together with tropical peatlands are one of largest carbon storage in the terrestrial ecosystem. With average carbon stock per hectare about 157.1 t/ha, the total carbon stored in Asia and South East Asia was about 44.5GtC, in which about 31%was located within Indonesian territory [1]. The total areas of tropical peatlands were estimated about 38 million ha which mostly located in Southeast Asia. Total peat carbon stored in this region was about 50.4GtC, with more than 90% was located in peatlands area in Indonesian territory [2]. In general, tropical forests and tropical peatlands act as a carbon sink.About 30% of Indonesian land territory is located in Borneo. Most area of this island was covered by rainforest. However, rapid land cover changes since the early 1970s has reduced its forest cover to about 71% in 1980s with further decrease up to 54% in 2000s [3]. Many studies suggest that large scale deforestation and forest fire might contributes to more CO_2 emission to the atmosphere such those occurred during an extreme El-Niño in 1997-1998 which was followed by a large forest fire in Borneo Island [4],[5].

Forest fires can be analyzed from three aspects: combustible materials, their flammability and fire sources. This study is focused in the analysis of the availability of combustible materials, which is closely related to the estimation of total carbon pool in vegetation, litter and soil/peat and their flammability. Fire sources in human induced landscapes are quiet complex to be modeled. Such analysis should include various factors such as demography, distance of disturbed area to the forest boundary, road, etc., which is mostly beyond the capability of the current DGVM.

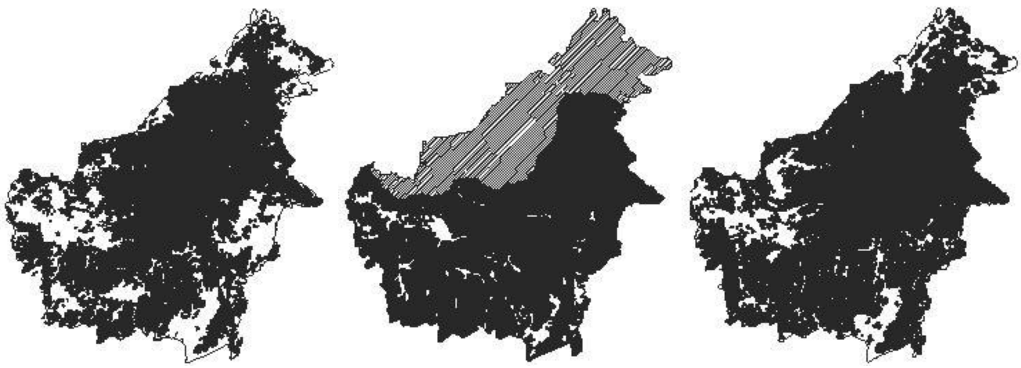
Many studies focused on field investigation and direct measurement, for example:[4],

[6], [7],[8], while other studies focused on GIS application, for example [9],[10],[11]. Lund-Postdam-Jena Dynamic Global Vegetation Model (LPJ-DGVM) is a model which was originally developed for global scale analysis [12]. In this study, a modified LPJ-DGVM is used for regional scale analysis to simulate the total carbon emission from forest fire in Borneo Island from 1980 to 2006.

MATERIALS AND METHODS

Study Area

Borneo Island is located between 108°45'E and 119°30'E, 7°15'N and 4°15'S, with total area about 734.000 km^2. Wood-log productionsfrom Borneo islandwere very high during the mid of 1980s until late of 1990s and suddenly decreased after 1998. Together with illegal logging, the high wood production is one of the main causes of the rapid decrease of forest cover in this island. Deforestation in Borneo Island also leads to the increase of forest fire occurrence. One of the largest forest fire event was occurred in 1997-1998, resulted in 3 to 4.5 million hectares of forest loss in Borneo Island [13],[14]. Forest degradation in Borneo Island is shown in Figure 1.



1950* 1980** 2000**

Figure 1. Forest Degradation Map in Borneo Island

Source:
* Ministry of Forestry, Republic of Indonesia; ** [3]

Carbon Emission From Forest Fire

In general, decomposition is affected by external factors (e.g.: temperature and soil moisture) and internal factors (e.g.: litter type). The effects of temperature and soil moisture on decomposition have been widely recognized and study on this field is progressing as people awareness on the effect of global warming to carbon sequestration is also increasing [15].
One of the most commonly used equations to describe mass decay in decomposition is the first-order equation [16],[17]. This equation can be written as:

$$\frac{x}{x_0} = 1 - e^{-kt} \quad (1)$$

where$x$ is the remaining mass, x_o is the initial mass, k is the decay constant and t is the

time in years.
In general, leaf and fine woody materials are decomposed faster than root and coarse woody materials. Therefore, different decay coefficient for different sources of litter materials (leaf and woody) is used in the model. The following constants are used:

$k_{10}leaf = 0.1$ (2)

$k_{10}branch = k_{10}root = 0.3$ (3)

where$k_{10}leaf$, $k_{10}branch$, and $k_{10}root$ are the decay rate at 10°C for leaf, branch and root, respectively.
In LPJ v1, litter and soil decomposition are computed by using the following equations:

$$k_{dec} = k_{10}k_T k_m \quad (4)$$

$$k_T = exp\left(308.56\left(\frac{1.0}{56.02} - \frac{1.0}{T_{soil} + 273.0 - 227.13}\right)\right) \quad (5)$$

$$k_m = \frac{(1-e^{-1.0\,w})}{(1-e^{-1.0})} \quad (6)$$

where$k_{dec}$is the decomposition rate, k_{10} is the decay rate at 10°C, k_T is the temperature response of decomposition, k_m is the moisture response of decomposition, T_{soil} is the soil temperature (°C) and w is the soil moisture content.
These set of equations are used for general type of soil. In this study, moisture responses of decomposition equations suggested by [18] are added into the model for application in peat soil.

$$k_{m\_peat} = 1 - \left(\frac{w_{opt} - w}{w}\right)^5 \quad \text{for } w < w_{opt} \quad (7)$$

$$k_{m\_peat} = 1 - (1 - 0.025)\left(\frac{w - w_{opt}}{1 - w_{opt}}\right)^3 \quad \text{for } w \geq w_{opt} \quad (8$$

wherek_{m_peat} is is the moisture response of decomposition for peat soil andw_{opt} is the optimum soil moisture content = 0.75.

Computation of Fire Module

In LPJv1, area affected by fire is computed as function of litter availability, tree resistance
index and length of fire season.

$$A = I_{fire}\ exp\left[\frac{I_{fire} - 1}{a_1(I_{fire}-1)^3 + a_2(I_{fire}-1)^2 + a_3(I_{fire}-1) + a_4}\right] \quad (9)$$

$$I_{fire} = \frac{1}{n_{day}}\sum_{day=1}^{n_{day}} P_{fire} \quad (10)$$

$$P_{fire} = exp\left[-\pi\left(\frac{d_{sw}}{m_e}\right)^{2.0}\right] \quad (11)$$

$$m_e = \sum_{pft=1}^{npft}\frac{litter_{ag\,pft}}{litter_{ag\,total}} flam_{pft} \quad (12)$$

where A is thearea affected by fire, I_{fire} is the fire index, a_1 to a_4 are constants, n_{day} is the number of day in a year (365 or 366), P_{fire} is the length of fire season, d_{sw} is the daily soil water content, m_e is the moisture factor, $litter_{agpft}$ is the above ground litter for each tree “Plant Functional Type” (PFT), $litter_{ag\,total}$ is the total above ground litter and $flam_{pft}$ is the flammability index (constant for each PFT).
Carbon flux from forest fire are computed using the following equations:

$$\mathrm{Cflux}_{\mathrm{atm}_{\mathrm{veg}}} = \mathrm{A}\,.\,(1-\mathrm{resist}_{\mathrm{tree}})\,.\mathrm{nind}.\,(\mathrm{lm}+\mathrm{sm}+\mathrm{hm}+\mathrm{rm}) \quad (13)$$

$$\mathrm{Cflux}_{\mathrm{atm}_{\mathrm{lit}}} = \mathrm{A}(1-\mathrm{resist}_{\mathrm{tree}})\,.\,\mathrm{nind}.\left(\mathrm{litter}_{\mathrm{ag}}\right) \quad (14)$$

$$\mathrm{resist}_{\mathrm{tree}} = \mathrm{c} \quad (15)$$

where *clux*$_{atmveg}$is the carbon flux to the atmosphere from burned vegetation, *A* is the area affected by fire, *resist*$_{tree}$ is tree resistance index, *resist*$_{tree}$is thetree resistance index, *nind* is the number of individual, *lm*, *sm*, *hm* and *rm* are the leaf, sapwood, heartwood and root mass, respectively, *clux*$_{atmlit}$is the carbon flux to the atmosphere from burned litter and *litter*$_{ag}$ is the litter carbon mass.

In the modified fire module, area affected by fire is computed as function of existing land cover type, tree resistance index, length of fire season and interannual climate variability.

$$\mathrm{A} = \mathrm{k}_3\mathrm{k}_4\mathrm{I}_{\mathrm{fire}}\,\exp\left[\frac{\mathrm{I}_{\mathrm{fire}}'-1}{\mathrm{a}_1'(\mathrm{I}_{\mathrm{fire}}'-1)^3+\mathrm{a}_2'(\mathrm{I}_{\mathrm{fire}}'-1)^2+\mathrm{a}_3'(\mathrm{I}_{\mathrm{fire}}'-1)+\mathrm{a}_4'}\right] \quad (16)$$

$$\mathrm{I}_{\mathrm{fire}}' = \frac{1}{\mathrm{n}_{\mathrm{day}}}\sum_{\mathrm{day}=1}^{\mathrm{n}_{\mathrm{day}}}\mathrm{P}_{\mathrm{fire}}' \quad (17)$$

$$\mathrm{P}_{\mathrm{fire}}' = \mathrm{k}_1\,\exp\left[-\pi\left(\frac{\mathrm{d}_{\mathrm{sw}}}{\mathrm{m}_{\mathrm{e}}}\right)^{\mathrm{k}_2}\right] \quad (18)$$

$$\mathrm{m}_{\mathrm{e}} = \mathrm{constant} = 0.95 \quad (19)$$

where *A* is thearea affected by fire, k_3 is the correction factor for inter-annual climate variability, k_4 is the correction factor for length of fire season, I_{fire} is the fire index, a_1’ to a_4’ are constants, n_{day} is the number of day in a year (365 or 366), P_{fire} is the length of fire season, d_{sw} is the daily soil water content, k_1 and k_2 are functions of land cover, m_e is the moisture factor, taken as constant.

Vegetation Fire Resistance

Some studies show that vegetation resistance index is strongly correlated with tree diameter, for example [4]. In LPJ v1, fire resistance index of each PFT is set as constant value (e.g.:evergreen tree = 0.2, raingreen tree = 0.5). To approximate the tree mortality rate due to forest fire as function of tree diameter, data from [8] and [19] are plotted together to obtain a regression function as follow:

$$\mathrm{mortal}_{\mathrm{tree}} = 0.6685\mathrm{D}^2 - 1.4439\mathrm{D} + 0.8784 \quad (20)$$

$$\mathrm{resist}_{\mathrm{tree}} = 1 - \mathrm{mortal}_{\mathrm{tree}} \quad (21)$$

where, *mortal*$_{tree}$ is the PFT fire mortality rate, *resist*$_{tree}$ is the PFT fire resistance index and D is the tree diameter.

Fraction Of Vegetation And Litter Consumed By Fire

In LPJ-DGVM, carbon pool is distributed into vegetation, litter and soil pools. During forest fire event, some fractions of these carbons are consumed by fire and released to the atmosphere. In LPJv1, it is assumed that all carbon pool in vegetation (leaf, wood and root) and litter in the burned area are entirely consumed by fire (Eq.13 and 14), while soil carbon is not affected by fire. A research from [20] suggest that only about 25% of above ground vegetation materials (mainly leaf and small woody parts) in the burned area are fully consumed by fire and emitted to the atmosphere, while root materials are less affected by fire. In case study of East Kalimantan, [4] shows that above ground litter materials were completely burned during 1997-1998 forest fire event. These approaches can be expressed in the following equations:

$$Cflux_{atm_{veg}} = A \,.\, resist_{tree} \,.\, nind \,.\, (0.25\ lm + 0.25\ rm + 0.25\ hm) \quad (22)$$

$$Cflux_{atm_{lit}} = A.\, resist_{tree} \,.\, nind \,.\, (1.0\ litter_{ag}) \quad (23)$$

$$Cflux_{lit_{lit\ ag}} = A \,.\, resist_{tree} \,.\, nind \,.\, (0.75\ lm + 0.75\ rm + 0.75\ hm) \quad (24)$$

$$Cflux_{lit_{lit\ bg}} = A \,.\, resist_{tree} \,.\, nind \,.\, (1.0\ rm) \quad (25)$$

where $cluxatm_{veg}$is the carbon flux to the atmosphere from burned vegetation, *A* is the area affected by fire, $resist_{tree}$ is tree resistance index, *nind* is the number of individual, *lm, sm, hm* and *rm* are the leaf, sapwood, heartwood and root mass, respectively, $cluxatm_{lit}$is the carbon flux to the atmosphere from burned litter, $litter_{ag}$ is the litter carbon mass, $cluxlit_{lit_ag}$is the carbon flux to the above ground litter from dead-unburned vegetation (leaf , sapwood and heartwood), $cluxlit_{lit_bg}$is the carbon flux to the below ground litter from dead-unburned vegetation (root).

Fraction of Peat Consumed By Fire

Carbon release to atmosphere from peatlands mainly caused by two factors: the lowering of soil water table and fires in degraded peatlands[20]. For the first factor, soil water table has positive feedback to carbon accumulation in peatlands. The high soil water table reduces decomposition rate, while accumulation of organic carbon in peat might also increases water holding capacity which maintain soil water table [21],[18]. For the second factor, soil water table has positive feedback for fire prevention. In case study of Central Kalimantan, [24] shows that peat is highly susceptible to fire if soil water level is less than the critical threshold of 40cm below peat surface.

In LPJv1, water balance computation uses 2 layers of soil: upper layer with 50cm depth and lower layer with 100cm depth. In general, soil water fraction is computed by:

$$w_i = \frac{uw_i}{whc_i d_i} \quad (26)$$

wherew_i is the soil water fraction, uw_i is the height of water table, whc_i is the water holding capacity as function of soil type and d_i is the height of soil layer (0.5m for upper layer, or 1.0m for lower layer).

In this study, it is assumed that peat layer is located at the top of soil layer. By applying the threshold of 40cm below surface with water holding capacity (*whc*) for peat soil = 0.8 and soil layer height of 50cm, then w_i‘=0.25

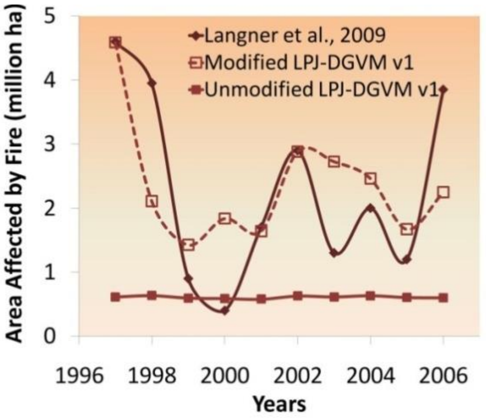
In further computation, soil water fraction value of 0.75 and 0.33 (slightly higher than the value of w_i’) are used to approximate the function of peat fire resistance as shown in Eq.27.

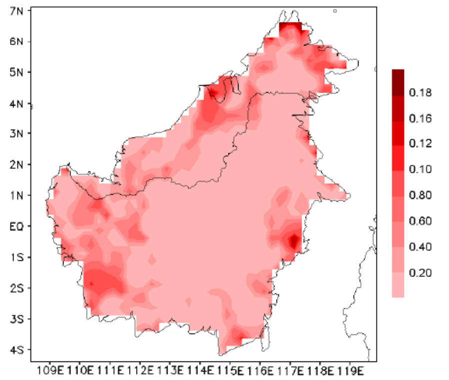
$$k_{peat} = c\frac{\sum_{day=1}^{n_{day}}(d_{sw}<0.33)}{\sum_{day=1}^{n_{day}}(d_{sw}<0.75)} \quad (27)$$

where*c* is a constant, d_{sw} is daily soil water fraction, and n_{day} is number of day in a year.

RESULTS AND DISCUSSIONS

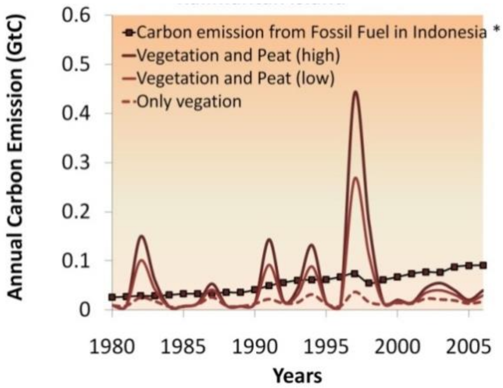
Carbon emission from forest fire is computed as function of area affected by fire, carbon accumulation (in vegetation, litter and soil/peat) and fraction of carbon consumed by fire. **Figure 2a** showscomparison of total area affected by fire in Borneo Island from 1997 to 2006 between the simulation result and the data compiled by [14]. Simulation result using the modified LPJ-DGVM shows nearly similar pattern although in some simulation years the result also shows underestimate (e.g.: 2006) and overestimate value (e.g.: 2000, 2002).

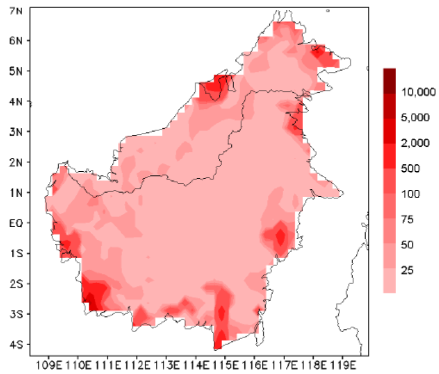




a) Total area affected by fire (1976-2006)

b) Average area affected by fire (1980-2006)





*source: (http://beta.worldbank.org/climatechange/dat

c) Carbon emission from fossil fuel (data) and from forest fire in Borneo Island (simulated), in GtC.

d) Annual average carbon emission from forest fire (1980-2006) in gC/m^2

Figure 2. Simulation result of area affected by fire and carbon emission from forest fire in Borneo Island

Figure 2b, 2c and **2d** shows simulation result from 1980 to 2006. Compared to hotspot distribution compiled [14], **Figure 2b** shows that area affected by fire simulated by using the modified LPJ-DGVM shows relatively similar pattern. Simulation result tends to be underestimates in some areas of Central Kalimantan. In West Kalimantan, simulation result shows similar pattern with the data but tend to be slightly overestimate in the West Coast area.

In case study of East Kalimantan during 1997-1998 forest fire, [4] shows that the average burnt depth of peat is about 50cm. Based on this event, three scenarios of fire emission are used: 1) High scenario by assuming ~50cm of peat is burned, 2) Low scenario by assuming ~25cm of peat is burned, and 3) by assuming no peat fire. **Figure 2c** shows simulation result of annual carbon emission from forest fire in Borneo Island from 1980 to 2006 in time series, based on the above scenarios. The result shows that the average carbon emission from 1980 to 2006 is between 0.02GtC/year (for no peat scenario) to 0.06GtC/year (for high scenario). For large forest fire event during 1997-1998, the total carbon emission from forest fire (two years cumulative) is between 0.05GtC (for no peat scenario) to 0.62GtC (for high scenario). During large forest fires (e.g.: 1982-1983 and 1997-1998), total carbon emission from forest fire in Borneo Island alone might be higher than the total carbon emission from fossil fuel in Indonesia.

CONCLUSIONS

In this study, a modified of LPJ-DGVM is used to simulate carbon emission from forest fire during period of 1980 to 2006. Simulation result of carbon accumulation shows relatively good result and still between the range of maximum and minimum of the data. During 1997-1998 forest fire event in Indonesia, the total carbon emission in Indonesia caused by the fire from some cited references are 0.81 to 2.57 GtC from peat fire and 0.05 GtC from overlying vegetation [4], 0.2066 GtC[23] and 0.493 GtC[5]. During the same event about 10 million hectares area were affected by fire. Some cited references are 9,745,000 ha [23] and 11,698,379 ha [5]. By assuming that 68% of the total carbon emission from Indonesia area were contributed from Borneo Island, it estimated that carbon emission from Borneo Island were about 0.138 to 1.745 GtC.

This analysis shows that modeling approach can be used to connect a detail and direct field measurement data, e.g.:[4] with a wider range of spatial analysis in GIS based data, e.g.:[5],[9]. Extrapolating a field measurement data into larger area and/or interpolating a GIS based data might result in bias due to the different conditions both in spatial scale, temporal scale and other local conditions. By using a model such as LPJ-DGVM, both data can be integrated to reproduce past and present event, which can be used further as basis for future mitigation plan to reduce carbon emission, especially from forest fires.

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