【Article】

The Effect of Deforestation on Regional Terrestrial Carbon Balance: A Case Study of Borneo Island

Arno Adi KUNTORO and Ade WAHYU
Graduate Student
Graduate School for International Development and Cooperation
Hiroshima University
1-5-1 Kagamiyama, Higashi-Hiroshima 739-8529, Japan
E-mail: arnoak@hotmail.com, wahyforester@yahoo.com

Takao YAMASHITA
Professor
Graduate School for International Development & Cooperation
Hiroshima University
1-5-1 Kagamiyama, Higashi-Hiroshima 739-8529, Japan
E-mail: tkoyamashita@hiroshima-u.ac.jp

Abstract

Rainforests play an important role in the inter-relationship of biosphere-atmosphere in the global and regional scale as one of the largest carbon storages in terrestrial ecosystem. Nowadays, rainforests are subjected to serious threats mainly due to human activities, such those occurring in Borneo Island, where the rapid land use changes in the last few decades may result in imbalance of natural carbon cycle and may lead to more intense environmental problems. As a regional dynamic vegetation model, the Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ-DGVM) is modified in this study to include the land use change aspect in the tropical forests. To analyze the effects of land use changes in Borneo Island, two scenarios are applied: without and with land use change scenario. Simulation results show that the increase in average Net Primary Production (NPP) over Borneo Island from 1960 to 2002 for each scenario is 2.44 GtC/year and 2.69 GtC/year, respectively. While the increase in heterotrophic respiration is 0.91 GtC/year and 2.41 GtC/year, respectively. If carbon losses by harvesting are included, the later scenario shows that the rate of carbon loss from 1960 to 2002 is 471.9 $gC/m^2/year$. As a result, more than 50% of terrestrial vegetation's carbon was taken away from Borneo Island during that period. In future, as compared to NPP, heterotrophic respiration tends to increase with higher rates and may lead to the change of Borneo Island's role from carbon sink to carbon source.

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1. Introduction

The increase of atmospheric CO_2 concentration in the last few decades has become one of the major environmental issues in both global and regional scales. Since the Industrial Revolution in late of 18^{th} and early 19^{th} centuries, the atmospheric CO_2 concentration has risen from around 280 ppm to nearly 390 ppm at present time (Denman et al., 2007). This increase mainly resulted from human activities, such as fossil fuel combustion and land use change (Denman et al., 2007). About 70% of the anthropogenic CO_2 emissions comes from fossil fuel burning, while 30% results from land use changes. About 45 % of CO_2 emission has remained in the atmosphere, 35% has been taken up by the oceans and 20% has been taken up by terrestrial ecosystem (Sabine et al., 2004). Tropical forests such as that in the Amazon and Indonesia play a crucial role in maintaining the atmosphere-biosphere carbon balance, due to their ability as carbon sink (CSIRO, 2007). Despite its important role, the rainforests are subjected to serious threats mainly due to human activities. Indonesia is one of the countries with largest annual net loss of forests in the world. The rate of forest loss in Indonesia was 1,312,000 ha/year in 1990 to 2000, and 1,871,000 ha/year in 2000 to 2005 (FAO, 2000; FAO, 2006). This aspect can be analyzed from terrestrial carbon balance point of view, and one of the possible ways is using computer model for vegetation dynamics, such as LPJ-DGVM, which is a process-based model of atmosphere and biosphere interactions that consist of vegetation dynamics, carbon and water balance module in the terrestrial ecosystem. LPJ-DGVM was developed by researchers from Lund University – Sweden, Potsdam Institute for Climate Impact Research – Germany, and Max-Planck Institute for Biogeochemistry, Jena – Germany. Since the model was developed for global scale analysis, some modification to include regional characteristic are needed for application in regional scale. The objectives of this study are: 1), to briefly describe about LPJ-DGVM; 2) to describe the modifications to include the local/regional characteristics, and 3) to examine the applicability of using LPJ-DGVM in analyzing the effect of deforestation in Borneo Island's terrestrial carbon balance. This paper is organized as follows: Section 2 briefly describes overview of the model, Section 3 describes model modifications, Section 4 describes data input, verifications and application for study case of Borneo Island, and Section 5 describes the potential and limitation of the model.

2. Overview of LPJ-DGVM

The early version of LPJ-DGVM (LPJ v1) was used to evaluate the global ecosystem dynamics (Sitch et al., 2003 and Gerten et al., 2004). LPJmL is an improved version that focused on agricultural plants and crops functional types (Bondeau et al., 2007). The most recent version, LPJmL v3, focused on river routing and irrigated agriculture. The three version of LPJ-DGVM above was developed using different computer-language programming. LPJv1 was developed in "Fortran", LPJmL in "C++", and LPJmL v3 in "C". For further development, LPJ-DGVM can be coupled with another model such as land surface and atmosphere model, which is mostly written in Fortran. For that reason, LPJ v1 is used in this study.

A complete carbon balance in a terrestrial ecosystem is affected by the factors of carbon storage within ecosystem, carbon fixed by photosyntesis, carbon released by respiration, added (imported) and removed (exported) carbon and other nonbiological carbon oxidation (Lovett et al., 2000). The original LPJ-DGVM focuses into three major carbon balance processes: 1) carbon gain from atmospheric CO_2, 2) carbon release to atmosphere from plant's autotrophic and heterotrophic activities, and 3) accumulation of carbon in vegetation bodies, litter and soil. Carbon gain process mainly occur in photosynthesis. The total amount of carbon fixed by photosynthesis processes can be termed as "Gross Primary Production (GPP)". Like other living things, plant also needs to

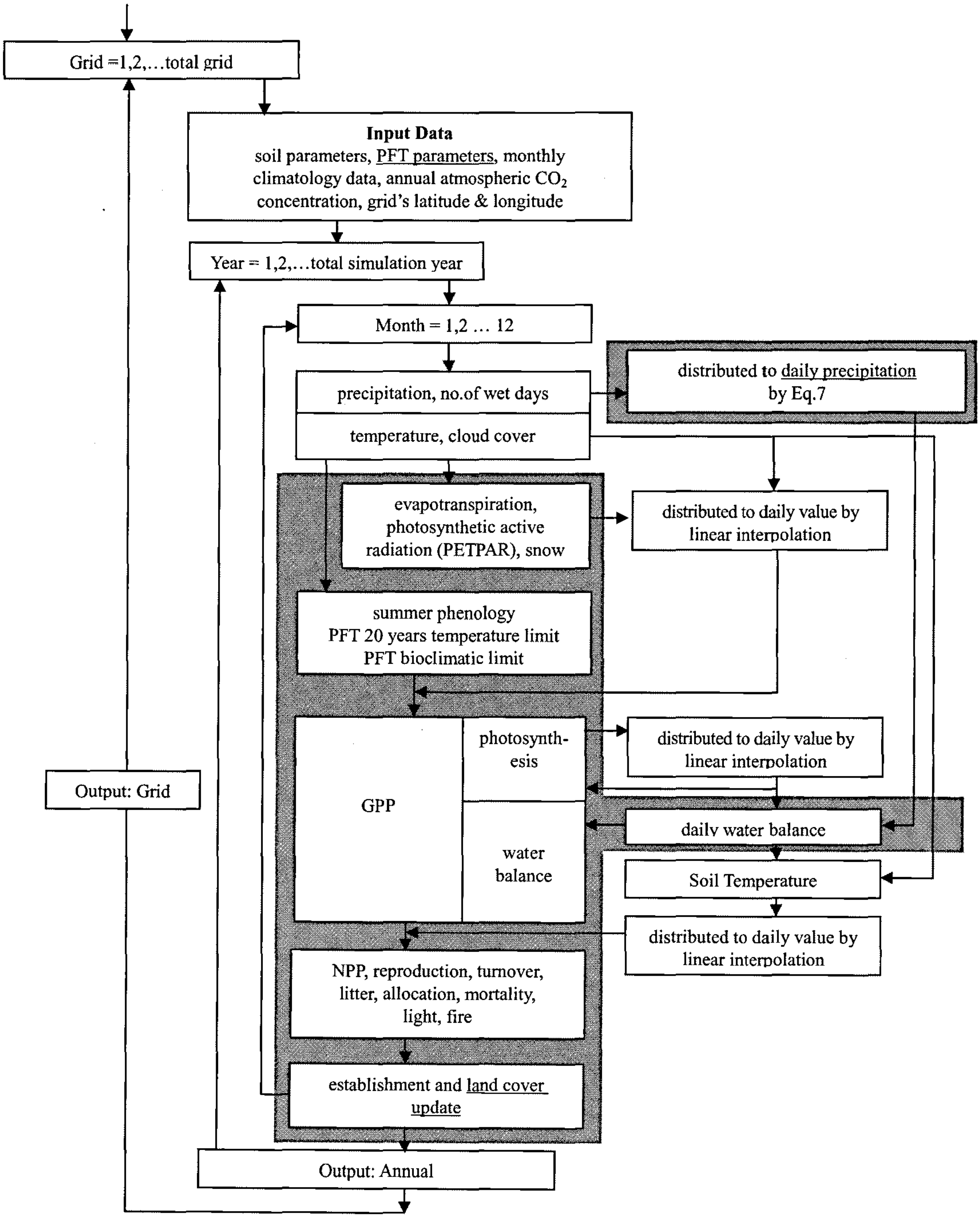


Figure 1: Flowchart for the modified LPJ-DGVM. The modified parts are represented by underlined words and the shaded background show modules affected by the modification.

consume some amount of biomass to survive with maintenance and growth. For example, root has its own respiration needs and so does sapwood and leaf. The usage of biomass by plant for these two purposes is termed as "Maintenance Respiration and Growth Respiration". The term of "Net Primary Production (NPP)" is usually used to describe the difference between biomass produced from photosynthesis and biomass used by plant respiration. As the plant grows, some part of it will become old and unnecessary for the plant, and then it will be replaced by new parts. This kind of process is termed as "turnover". The example of this process can be seen in a deciduous plant which drops its leaves by abscission before winter, and starts to grow its leaves again in spring. As some dead parts of vegetation fall above the ground or below the ground, the biomass contained on it will be accumulated and decomposed. Some parts will be released to the atmosphere, while the rest will be stored temporarily in the soil. This kind of process is termed as "decomposition" or "heterotrophic respiration". The term of "Net Ecosystem Production (NEP)" is usually used to describe the difference between NPP and heterotrophic respiration plus carbon losses associated with disturbance such as forest fire and harvest (Lovett et al., 2006). Although some researchers proposed the term of Net Biome Productivity (NBP) to account for carbon losses over global or regional scales (Schulze et al., 2000), in LPJ-DGVM, NEP term is used instead of NBP.

For a given conditions (temperature, soil type, precipitation, etc), LPJ-DGVM simulates potential natural vegetation landscape rather than simulating a human-induced landscape. Therefore, to include the effect of land use changes and other regional characteristics, this part has to be improved. In this study, the original model is modified mainly in the following three major parts: 1) plant functional types (PFT) parameters, 2) computation of daily precipitation and 3) land cover update due to anthropogenic processes.

Figure 1 shows model of the modified LPJ-DGVM model flowchart. Standard LPJ-DGVM model uses **0.5^o x 0.5^o degrees grids** (about 55 km square near equator). In LPJ-DGVM, PFT distribution in each grid represented as "fractional coverage" instead of "spatial coverage". Its mean that one grid may consist of different PFT and coverage area, without considering the exact location of each PFT within the grid. Each grid considered as one unit analysis (i.e. 1-dimensional computation) with no interaction among neighboring grids. The **datasets** needed for the model are: monthly mean temperature, monthly mean precipitation, number of rain-day in a month, monthly mean cloud cover, annual global atmospheric CO_2 concentrations and soil type. The standard output of LPJ v1 is the mean annual values which computed from monthly or daily values. There are two procedures used in LPJ v1 to distribute monthly data into daily values: by linear interpolation and by other specific computation. Mean monthly values assumed as equal as daily values in the mid of the month ($\pm 15^{th}$ day of each months), and linear interpolation between the two mid-month-values into daily-values used in most of the cases in LPJ v1. Specific computation only applied to generate daily rainfall values which depend on monthly rainfall and number of rain days in a month.

Potential evapotranspiration is affected by the factors of climatology and other daily and seasonal variations due to earth and sun movement. Mid-month potential evapotranspiration in each grid is computed in monthly time steps as function of climatology (temperature and cloud cover) and grid location (latitude and longitude). Daily potential evapotranspiration is used in water balance computation. Other computation such as mid-month **photosynthetic active radiation** and **day-length** which varies seasonally, also computed in monthly time steps. LPJ v1 provide a subroutine for **snow** computation as function of temperature, precipitation and snow accumulation from the previous time step. However, this subroutine is not used in this study. Vegetations are affected by the air temperature. Each PFT has its own **bioclimatic limit** which controls many of its processes. Moving **average of 20 years** coldest and warmest monthly temperature is used to account for the plant ability to survive in abrupt temperature changes. Another aspect which is affected by temperature is **leaf phenology** processes, such as the time of both abscission and growing period of summergreen PFT. Phenology computation processes is conducted in monthly time steps using mid-month daily air temperature value.

There are two main processes in **GPP** computation: **photosynthesis** and **water balance**. Water balance is computed in daily time steps, using daily precipitation, daily evapotranspiration and other vegetation parameters. Many water-related processes are computed in water balance subroutine, such as actual evaporation and evapotranspiration, soil water availability and surface runoff. One of the important results of water balance computation is "daily canopy conductance" that is a function of evaporation demand and supply. This output will be used as one of the input in photosynthesis computation. Photosynthesis computation is conducted in monthly time steps so that daily canopy conductance is averaged into monthly values. **Soil temperature** computed in monthly time steps using monthly temperature and monthly average of soil water availability. Daily soil temperature is interpolated from its mid-monthly values and used in soil carbon balance computation.

Further carbon balance computations are computed in several different parts. Growth and maintenance respirations are computed in NPP subroutine. **Maintenance respiration** is computed in daily time steps, while **growth respiration** and **NPP** are computed in monthly time steps. **Reproduction** is used to account for the amount carbon used to produce plants reproductive organs. The amount of reproduction cost is assumed as a constant fraction of NPP and computed in annual time steps.

LPJ v1 uses three carbon pools: vegetation, litter and soil pools. In **turnover** computation, specific fraction of vegetation carbon pool transferred into other carbon pool, e.g.: leaf and root carbon transferred into litter carbon pool, while sapwood transferred into heartwood. This computation is conducted in annual time steps. Carbon from **litter pool** transferred into **soil pool**. From soil pool, about 70% carbon transferred directly into atmosphere while the rest of 30% stored in soil carbon pool. About 98.5% of stored carbon in soil pool transferred into fast pool and 2.5% into slow pool. Later, both fast and slow soil carbon pools transferred into atmosphere. These processes are mainly affected by soil temperature and soil water content. These computations are conducted in monthly time steps. After respiration and reproduction needs are fulfilled, the remaining carbon is allocated into leaf, wood and root. Carbon **allocation** for each tissues pool is affected by soil water availability. In general, more carbon is allocated to root in dry years, while in wet years more carbon is allocated to sapwood. This computation is conducted in annual time steps.

In LPJ v1, reduction of plant density can be caused by several factors, such as light competition among PFTs, low growth efficiency, negative carbon increment, extreme high temperature conditions and natural fire. Woody PFTs are more dominant than grass PFT in **light** competition. LPJ v1 use 95% as maximum coverage of woody plant in a grid so that in the later stage of establishment, grass PFT tends to be reduced to the minimum value of coverage, that is, 5% of total grid. **Mortality** due to growth efficiency is computed as a function of vegetation carbon increment and vegetation carbon pool, while mortality due to extreme high temperature condition is computed as a function of monthly temperature and plant characteristics. Natural fire is computed as a function of daily temperature, soil water content, litter carbon pool and length of fire season.

LPJ v1 is modified to include the effect of anthropogenic land use change in terrestrial carbon balance. PFT coverage in each grid is **updated** every year within simulation period using actual land cover data. If the data shows the reduction of woody PFT, wood carbon is assumed to be harvested by logging activities and taken away from the ecosystem, while leaf and root carbon are transferred into litter carbon pool. **Establishment** of adaptive PFT and removal of less adapted PFT resulted in carbon balance computation. Carbon from non-survive PFT is transferred into litter pool, while in survived PFT more carbon is added into vegetation pool.

3. Modification of LPJ-DGVM

3.1 PFT Parameters

3.1.1 Establishment stages and PFT types

The original model uses 10 types of PFTs consisting of eight woody and two herbaceous PFT. As a tropical ecosystem, three PFT are used: tropical broadleaved evergreen, tropical broadleaved raingreen and tropical grass. Borneo's rainforests are dominated by some vegetations species. In terms of tree intensity and basal area, the most dominant families are *Euphorbiaceae, Dipterocarpaceae* and *Lauraceae* (Matius et al., 2000). Those dominant families have different characteristics that distinguish one another. Examples are the growth rate and lifetime of trees. *Euphorbiaceae* which is the family of pioneer trees, has a fast growth rate but short lifetime, while *Dipterocarpaceae* and *Lauraceae* which are the family of primary trees, have a relatively slow growth rate but long lifetime.

In terms of establishment stages, Ashton (1998) classified those trees as pioneer of gap phase, late successional dominant, late successional non dominant and late successional sub canopy, respectively. Toma et al. (2000) has another classification criteria based on sensitive to water. In general, pioneer trees are more sensitive to drought than primary trees. To include those characteristics into the model, a new PFT is added while other PFT is modified. Newly added PFT is Pioneer Tree, while Raingreen Tree modified into Late-Successional Non-Dominant Tree.

3.1.2 Water-related PFT parameters

Fraction in root: In the LPJ-DGVM, total soil water content in root zone is calculated by the following equation:

$$w_r = w_1.f_1 + w_2.f_2 \quad (1)$$

where:

w_r = total soil water content in root zone (mm)
w_1 = fraction of available water at upper layer soil (depth = 500 mm)
w_2 = fraction of available water at lower layer soil (depth = 1000 mm)
f_1 = fraction of active fraction of roots uptaking water from lower soil layer
f_2 = the remainder in the top layer = $(1 - f_1)$

For tropical PFT, the original model use f_1=0.85 for evergreen tree, 0.6 for raingreen tree and 0.8 for grass. For the modified PFT, f_1=0.6 is used for pioneer tree by assumption that this type of tree has similar root characteristics to raingreen tree. Late-successional non-dominant tree use f_1=0.85 since it can be classified as evergreen tree.

Water scalar value: In LPJ-DGVM leaf abscission begin and end if water scalar falls below and rises above its minimum value, respectively. Primary trees are classified as evergreen tree which do not shed their leaves in normal conditions. However, grasses and pioneer trees are more sensitive to drought, so that these PFTs have higher values of water scalar than primary trees. For the modified PFT, water scalar = 0.2 is used for pioneer tree by assumption that this type of tree has similar leaf characteristics to raingreen tree, while late-successional non-dominant tree use water scalar = 0.0.

Resistance index: In the LPJ-DGVM, the fraction of individuals which burnt by natural forest fire is calculated by the following equation:

$$fire\ disturbance = (1 - resistance\ index)(fraction\ of\ grid\ burnt\ by\ natural\ fire) \quad (2)$$

The original model use resistant index = 0.12 for evergreen tree, 0.5 for raingreen tree and 0.01 for grass. For the modified PFT, *resistance index* = 0.5 is used for pioneer trees by assuming that these type of trees have similar resistance characteristics with raingreen trees. Late-successional non-dominant tree use resistance index = 0.12 by assuming that these type of trees have similar resistance characteristics with evergreen tree.

3.1.3 Lifetime-related PFT parameters

Turnover period: The original model uses leaf and root turnover period = 2 years for evergreen trees and 1 year for raingreen trees or grass. The modified PFTs use turnover period value = 2 years for primary tree by assuming that these trees are classified as evergreen trees, while pioneer trees use turnover period value = 1 year by assuming that these trees have similar leaf and root characteristics with raingreen trees.

3.1.4 Growth-related PFT parameters

LPJ-DGVM uses the following equations to calculate sapwood cross section area (m^2), tree diameter (m), tree height (m) and crown area (m^2).

$$sap_{xsa} = \frac{lm_{ind}.sla}{latosa} \quad (3)$$

$$height = \frac{sm_{ind}}{sap_{xsa}.woodens} \quad (4)$$

$$stemdiam = \left(\frac{height}{allom2}\right)^{\left(\frac{1}{allom3}\right)} \quad (5)$$

$$crownarea = (allom1.stemdiam)^{reinickerp} \quad (6)$$

where,

sap_{xsa} = sapwood cross section area (m^2)
lm_{ind} = leaf mass individual(gC)
sla = specific leaf area (m^2/gC)
latosa = ratio of leaf area to sapwood
sm_{ind} = sapwood mass individual(gC)
height = tree height (m)
wooddens = wood density (gC/m^3)
stemdiam = tree diameter (m)
$allom_1$ = allometric constant in Eq.6
$allom_2$ = allometric constant in Eq.5
$allom_3$ = allometric constant in Eq.5 = 0.92
crownarea = projection of canopy area (m^2)
reinickerp = reinickerp coefficient

Wood density: The original model uses the same value of wood density for each woody PFT, that is: 200 kgC/m^3. From the data of 22 species of tropical primary tree and 4 species of pioneer tree, the World Agroforestry Centre (www.worldagroforestrycentre.org) shows that the average of wood density of tropical trees ranges from around 300 kg/m^3 (pioneer tree) to 1000 kg/m^3 or more (primary trees). Since carbon content in woods is about 45-50%, this study use 200 kgC/m^3 and 400 kgC/m^3 for the wood density of pioneer trees and primary trees, respectively.

Allometric constant: The original model uses the same allometric constant. Despite the differences in fraction of root in the soil, drought and fire resistance index, biomass turnover period and leaf longevity, the same allometric constant may result in the same growth characteristic in establishment phase. The original model use $allom_1 = 100$ and $allom_2 = 40$ for all woody PFTs. In actual conditions, pioneer tree has faster growth rate than primary tree. This characteristic can be represented by higher $allom_1$ and $allom_2$. Primary dominant trees have earlier successional stage than primary non-dominant trees, so that primary dominant trees have higher $allom_1$ than non-dominant trees. The modified PFT use $allom_1 = 300$ and $allom_2 = 60$ for primary dominant trees; $allom_1 = 100$ and $allom_2 = 60$ for primary non-dominant trees, and; $allom_1 = 500$ and $allom_2 = 60$ for pioneer trees.

Maximum crown area and latosa: The original model uses maximum crown area = 15 m^2 and latosa = 8000 for all woody PFTs. However, in the late stage of successional process, primary trees have higher stand, bigger diameter and larger crown area. These characteristics can be represented by higher maximum crown area and latosa. In the late stage, pioneer trees gradually decrease and replaced by dominant trees. The modified PFTs uses the following maximum values for crown area and latosa, 300 m^2 and 9000 for primary dominant trees; 15 m^2 and 3000 for primary non-dominant trees; 15 m^2 and 4000 for pioneer trees; and 0 m^2 and 6000 for grass. The adjusted PFT parameters are shown in **Table 1**. All these parameters are subjected to verification process. Verification results are shown in section 4.

3.2 Daily precipitation computation

In general, the LPJ-DGVM uses monthly data for model input. If daily time step is required, monthly data are interpolated into daily data by simple linear interpolation or by another specific calculation. To generate daily rainfall from monthly data, LPJ uses the following equation:

$$dval_{prec} = (-ln(random\ number)^{r_2}(mprec)^{r_1}) \qquad (7)$$

where,

r_1 = coefficient, =1.0 (default value)

r_2 = coefficient, =1.2 (default value)

mprec = monthly precipitation

random number = evenly distributed random real number, greater than or equal to 0 and less than 1

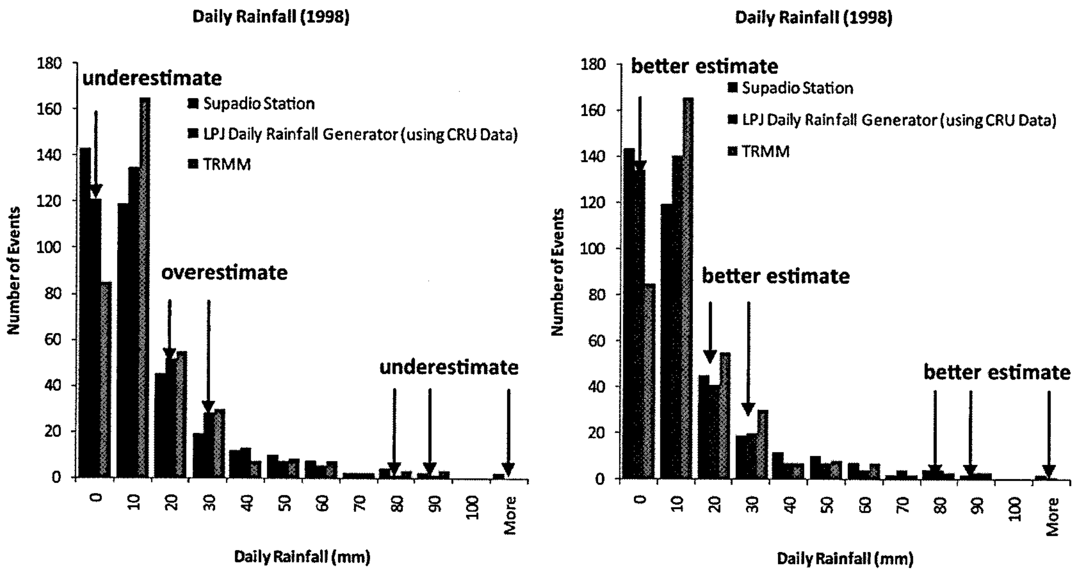
The usage of r_1 and r_2 default values tends to produce a very high daily rainfall that seems impossible to occur. For example, the monthly average precipitation in Pontianak, West Kalimantan, is around 300 mm/month. If we use this value together with uniform distribution of random number (between 0 and 1), the probability of daily rainfall greater than 100 mm is around 60% which is not likely to occur in the actual conditions. To deal with this problem, the LPJ-DGVM applies normalization procedure, that is, adjusting the sum of daily rainfall computation resulted from Eq. 7 to be equal to the monthly accumulated rainfall. However, the procedure tends to overestimate the small rainfall events, and underestimate the high rainfall events as compared to local station data. The example results can be seen in the case study of Pontianak in 1998. In this study, the value of r_1 and r_2 are adjusted to 0.43 and 1.33, respectively. Comparison of daily precipitation data from Supadio station which is located in Pontianak, Tropical Rainfall Measuring Mission (TRMM) data and model results using Climate Research Unit (CRU) TS.2.1 monthly data are shown in **Figure 2**. Modified model results show better estimation at both low precipitation events and high precipitation events.

Table 1: Modified PFT Parameters

No	Parameters	LPJ v1 (Sitch et al, 2003)				Modification			
1	Establishment Stage*	LSDT	LSnDT	PG	PT	LSDT	LSnDT	PG	PT
2	PFT**	TrBE	TrBR	TrG	-	TrBE	TrBE	TrG	TrBE
3	Fraction of roots in upper soil layer	0.85	0.6	0.8	-	0.85	0.85	0.8	0.6
4	Photosynthetic Pathway (C3/C4)	C3	C3	C4	-	C3	C3	C4	C3
5	Water scalar value at which leaves shed by drought	0.0	0.2	0.1	-	0.0	0.0	0.1	0.2
6	Fire resistance index	0.12	0.5	0.01	-	0.12	0.12	0.01	0.5
7	Leaf turnover period (years)	2	1	1	-	2	2	1	1
8	Leaf longevity (years)	2	1	1	-	2	2	1	1
9	Root turnover period (years)	2	1	1	-	2	2	1	1
10	Tree maximum crown area (m^2)	15	15	0	-	300	15	0	15
11	Wood density (kgC/m^3)	200	200	-	-	400	400	-	200
12	Allometric coefficient 1	100	100	100	-	300	100	100	500
13	Allometric coefficient 2	40	40	40	-	60	60	40	60
14	Latosa (leaf to sapwood)	8000	8000	8000	-	9000	3000	6000	4000

* : LSDT (Late Successional Dominant Tree); LSnDT (Late Successional Non Dominant Tree); PG (Pioneer Grass); PT (Pioneer Tree)

** : TrBE (Tropical Broadleaved Evergreen); TrBR (Tropical Broadleaved Raingreen); TrG (Tropical Grass)



a) LPJ v1 model b) modification

Figure 2: Daily precipitation values in the original LPJ v1 and after modification

3.3 Gross photosynthesis and temperature inhibition function

LPJ-DGVM uses photosynthesis model that considers the gross photosynthesis rate as a function of two potentials, the light limited photosynthesis rate (j_e) and the Rubisco limited photosynthesis rate (j_c).
The light limited photosynthesis rate (molC/m^2/h) is given by:

$$j_e = \frac{c_1 . APAR . c_{mass} . c_q}{dayl} \quad (8)$$

the Rubisco limited photosynthesis rate is given by:

$$j_c = \frac{c_2 . vm}{24} \quad (9)$$

and the daily gross photosynthesis rate a_{gd} (gC/m^2/day) is given by:

$$a_{gd} = \frac{\left(j_e + j_c - \sqrt{(j_e + j_c)^2 - 0.4 . \theta . j_e . j_c}\right)}{2\,\theta} dayl \quad (10)$$

where,
$APAR$ = actual photosynthesis active radiation flux (J/m^2/day)
c_{mass} = atomic mass carbon, = 12.0
c_q = conversion factor = 4.6 x 10^{-6}
c_1, c_2 = function of temperature and atmospheric CO_2 concentration, respectively
vm = catalytic capacity of Rubisco
θ = colimitation (shape) parameter = 0.7
$dayl$ = daylength (hours)

The LPJ-DGVM calculates c_1 and c_2 as a function of temperature as follow:

$$c_1 = (t_{stress})(\alpha_{c3})\left(\frac{p_i - \Gamma_*}{p_i + 2.0\,\Gamma_*}\right) \quad (11)$$

$$c_2 = \frac{p_i - \Gamma_*}{p_i + k_c\left(1.0 + \frac{pO_2}{k_o}\right)} \quad (12)$$

where:
p_i = non-water-stressed intercellular CO_2 partial pressure in Pa
Γ_* = CO_2 compensation point (CO_2 partial pressure, Pa)
k_o = Michaelis constant of rubisco for O_2
k_c = Michaelis constant for CO_2
pO_2 = O_2 partial pressure in Pa

The original model calculates temperature inhibition function (t_{stress}) as follow:

$$t_{stress} = (low)(high) \quad (13)$$

where,

$$low = \frac{1}{1 + \exp\left(k1(k2 - temp)\right)} \quad (14)$$

$$high = 1.0 - 0.01\ exp(k3(temp - x3)) \qquad (15)$$

$$k3 = log\left(\frac{\left(\frac{0.99}{0.01}\right)}{x4 - x3}\right) \qquad (16)$$

$$k1 = \frac{2\log\left(\frac{1}{0.99} - 1\right)}{x1 - x2} \qquad (17)$$

$$k2 = \frac{x1 + x2}{2} \qquad (18)$$

where,

x1 = low temperature limit for CO_2 uptake

x2 = lower range of temperature optimum for photosynthesis

x3 = upper range of temperature optimum for photosynthesis

x4 = high temperature limit for CO_2 uptake

For tropical PFTs the default values of *x1*, *x2*, *x3* and *x4* in the LPJ v1 are given in **Table 2** as follows:

Table 2: Default values of temperature inhibition function parameter

x_i	Temperature (°C)		
	PFT1	PFT2	PFT10
x1	2	2	6
x2	25	25	20
x3	30	30	45
x4	55	55	55

where,

PFT1 = tropical broadleaved evergreen trees

PFT2 = tropical broadleaved raingreen trees

PFT10 = tropical grass (C4)

In comparison to Eq.13, another approach of temperature function was introduced by Jones (2000):

$$t_{stress} = \frac{2(temp + B)^2(temp_{max} + B)^2 - (temp + B)^4}{(temp_{max} + B)^4} \qquad (19)$$

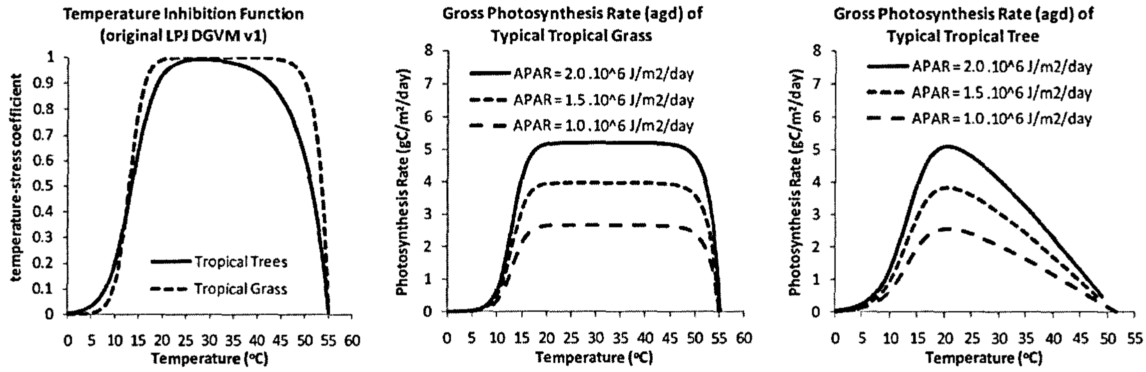
where,

$temp_{max}$ = temperature at which the t_{stress} reaches a maximum of 1.0

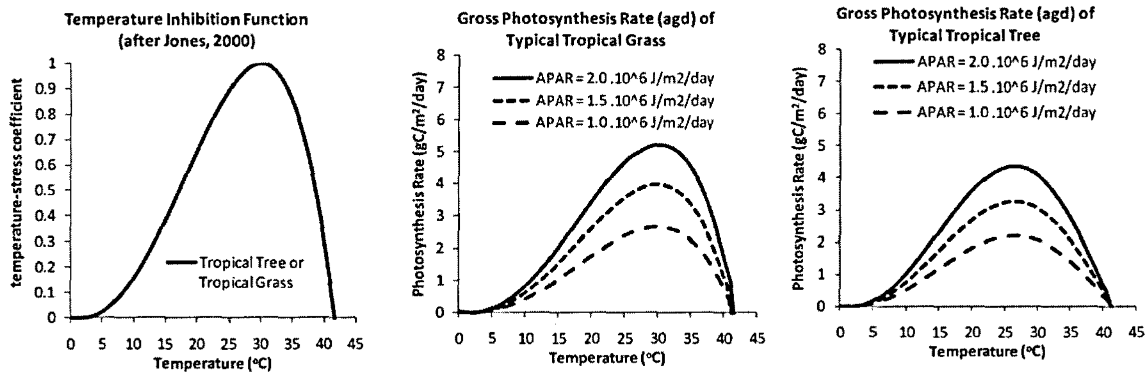
B = constant (negative B represents the lowest temperature at which t_{stress} reaches a minimum of 0.0)

To examine which computation has better result, these two approaches are compared to calculate the gross photosynthesis rate with several assumptions: Atmospheric CO_2 concentration = 350 ppmv and no water stress. Figure 3 show the comparison between the original model and the modified computations.

The optimum temperature for photosynthesis (calculated by LPJ v1 equations) ranges 25 to 30°C as shown in the upper panel in Figure 3. The optimum temperature (calculated by Jones equation) shows 30°C as shown in the lower panel in Figure 3. These results indicate that *light limited photosynthesis rate* (j_e) and *rubisco limited photosynthesis rate* (j_c) computed by original LPJ v1 equations tend to skew to the left (to the lower temperature), compared with Jones equation.



(a) LPJ-DGVM v1 equations (2003)



(b) Modication by Jones equation (2000)

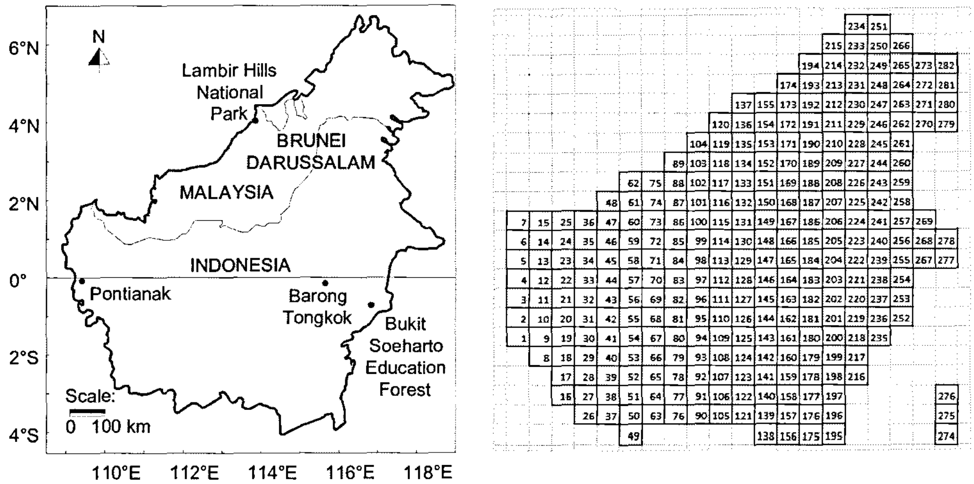
Figure 3: Temperature inhibition function (left) and gross photosynthesis rate for tropical grass (middle), and for tropical tree (right). (a) LPJ-DGVM v1 equations (2003), (b) Modication by Jones equation (2000)

Tompset (1998) give the approximation of optimum germination temperatures of 31 species of *Shorea*, which can be classified as primary trees. The results suggest that the optimum temperature for germination of *Shorea* varies from **26 to 31°C**. For tropical trees, LPJ v1 gives the optimum gross photosynthesis rate at **20°C** (the upper panel of Fig.3), while the modified computation using Jones equation gives the optimum gross photosynthesis at **27°C** (the lower panel of Fig.3). This results shows that Jones equation may give better photosynthesis limit parameters than the LPJ v1.

4. Application of Modified LPJ-DGVM

4.1 Borneo Island

Borneo is the world's third largest island that consists of 3 countries. The Northern part is under Malaysia and Brunei Darussalam while the Southern part is under Indonesia. It lies between 108°45'E and 119°30'E, 7°15'N and 4°15' S, with the total area almost 734.000 km^2. Location of vegetation's observation sites and rainfall gauge used in this study are shown in **Figure 4.a.** The mesh distribution used in this study is shown in **Figure 4.b.**



a. Location of observation station b. 0.5° x 0.5° mesh distribution

Figure 4: Location of observation site/station and mesh distribution

4.2 Input Data

In this study, monthly climatology data from 1903 to 2002 are used. This datasets is provided by Climate Research Unit (CRU), University of East Anglia (New et al., 2002, Mithcell and Jones, 2005) that can be accessed through http://www.cru.uea.ac.uk/~timm/grid/CRU_TS_2_1.html. These datasets known as CRU TS2.1 are constructed with the global network of meteorological observation stations. It provides 1901 to 2002 monthly series data in 0.5° x 0.5°grid system covering the global land surface excluding Antarctica, with nine climate variables of temperature, diurnal temperature range, daily minimum and maximum temperatures, precipitation, wet-day frequency, frost-day frequency, vapor pressure and cloud cover. The LPJ v1 uses four variables of mean temperature, precipitation, wet-day frequency and cloud cover. Atmospheric CO_2 concentration data is taken from Mauna Loa CO_2 observation station, Hawaii, United States (19.539°N; 155.578°W). CO_2 concentration is assumed to be homogenously distributed over the grids. Zobler (1999) provided classification of soil properties of the world in 1° x 1° grid. For better representation of shorelines, the 1° x 1° data are divided into four 0.5° x 0.5° in this study. Both datasets are available from the website (http://www.daac.ornl.gov.)

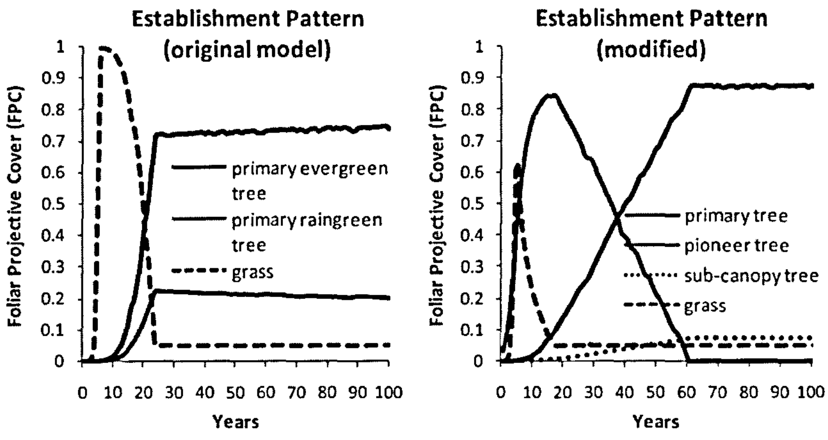
4.3 Model Verification

The simulation results are compared to observation data and other research results in the following three aspects: establishment pattern, tree growth characteristics (diameter, height and density) and NPP. In terms of establishment, the model should produce similar pattern to observation data both in vegetation types and development stages. In terms of growth characteristics, the model results should range within acceptable values in average diameters, heights and trees density of observation data. For NPP, the model results should fall between maximum and minimum values of the same vegetation type computed by global-satellite-based NPP product by NASA.

4.3.1 Establishment pattern

To capture the local establishment patterns following a disturbance event, the model results are compared to the field survey data of a secondary forest after traditional slash-and-burn agriculture in Barong Tongkok, Kutai Regency, East Borneo, by Okimori and Matius (2000), where the field investigation was conducted at five sample locations with different ages. Their results are summarized as (1) the field of two-years-old shrub was dominated by pioneer vegetations with average height around 5 m, (2) shrubs would be replaced by pioneer trees, (3) the field of fifteen-years-old stand was dominated by pioneer trees with canopy height ranges from 10 to 20 m, (4) there were no dominant species found in the field of thirty-years-old stand, both primary and pioneer trees were found with canopy height ranges from 10 to 30 m, (5) in the field of forty-years-old stand, pioneer trees was gradually replaced by primary trees with canopy height ranges from 10 to 30 m, (6) the seventy-years-old stand consist of primary dominant trees and sub-canopy trees with canopy height ranges from 10 to 40 m.

Two model results of establishment patterns following the disturbance event at year 0 are shown in **Figure 5**. The original model shows that in the early stage of the establishment process, the field is dominated by grass. Grass gradually decreases by about 20 years since the disturbance event, then woody vegetation starts to dominate the field with primary evergreen trees are more dominant than raingreen trees. The modified model shows different pattern comparing with the original model. The result shows that in the early years of the establishment stage, herbaceous plants and pioneer trees dominate the field. About fifteen years after the disturbance event, the field is dominated by pioneer trees. The pioneer trees gradually decrease as primary trees continue to grow. About thirty to forty years after the disturbance event, pioneer trees and primary trees seem to occupy almost the same area. Finally, about seventy years after the disturbance event, primary trees dominate the area. From these two model results, the modified model seems to be in better agreement with the field survey data.



* *Year 0 = disturbance event*

Figure 5: Establishment pattern following the disturbance event at year zero for both the original and the modified

4.3.2 Growth Characteristics

To capture the tree-growth characteristics (i.e.: diameter, height and tree density) the model results were compared to field survey data by Okimori and Matius (2000), Toma et al. (2000), and Aiba and Nakashizuka (2005). Okimori and Matius conducted their research based on field investigation of a secondary forest after traditional slash-and-burn agriculture in Barong Tongkok, Kutai Regency, East Kalimantan. Toma et al. (2000) conducted their research based on monitoring plots which were established in 1988 in Bukit Soeharto Education Forest (BSEF), Mulawarman University, East Kalimantan. In 1982-1983, large forest fires occurred in East

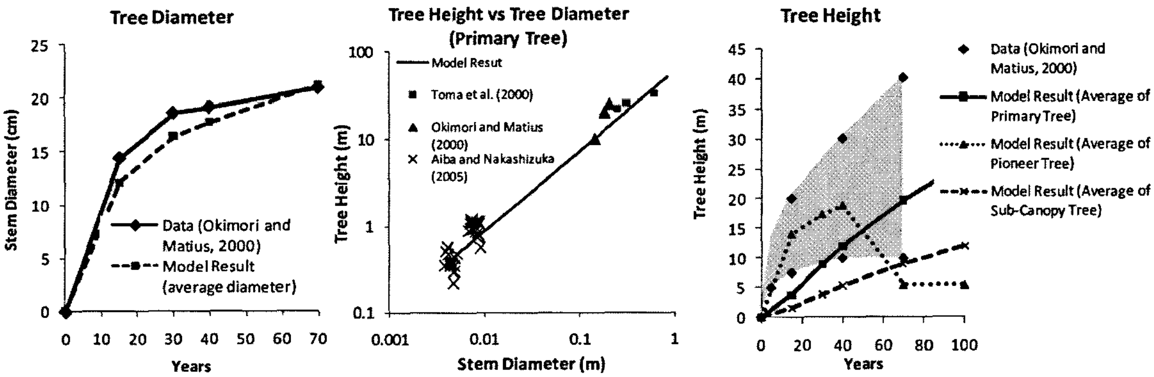


Figure 6: Tree diameter and tree height (observation versus model results).

Table 3: Tree Density (observation versus model results)

Species	Type	Tree Density (ind/ha)		Basal Area (m^2/ha)	
		Data	Model	Data	Model
Dipterocapaceae	Primary tree	37.3	46.7	10.9	24.9
E.Zwageri	Primary tree	20.0		1.6	
Macaranga	Pioneer tree	22.7	1.1	0.6	0.0
Others	Other	229.0	44.8	12.3	3.3
			Total	25.4	28.2

* Data from Toma et al., 2000

Borneo, burning some parts of BSEF. There were three categories of forest damages by fire, i.e.: Light Disturbed Stand (LDS), Medium Disturbed Stand (MDS), and High Disturbed Stand (HDS). Tree density, tree diameter, and tree height in LDS data are used to verify the model results for the case of undisturbed-mature forest stand. Aiba and Nakashizuka (2000) conducted their research based on study of dipterocarp forests at Lambir Hills National Park, Sarawak, Malaysia. Sapling samples of several species of *Shorea* were collected to determine their allometric characteristics. Comparison between observation data and model results are shows in **Figure 6** and **Table** 3. Figure 6 shows the comparison in terms of diameter and height, while Table 3 shows the comparison of tree density.

The results show that tree diameter and height calculated by the LPJ-DGVM are slightly deviated from the field data, but they still fall within the range of maximum and minimum value. However, the model shows relatively large deviation from field data in tree density, especially for the pioneer trees and other trees (sub-canopy tree, etc). Since the total basal area calculated by the LPJ-DGVM model seems to be relatively close to the data, it is expected that the results of the model in predicting the total carbon balance in Borneo does not largely deviate from the actual conditions.

4.3.3 Net Primary Production

In late 1999, NASA's Earth Observing System (EOS) Terra was launched. The Moderate Resolution Imaging Spectroradiometer (MODIS) sensor is used to gather terrestrial vegetation data, including global vegetation primary production. MODIS primary production products (MOD17) is one of the most advanced monitoring products, with 1 km resolution at 8-day interval. MODIS NPP (MOD17) data is computed based on: global biome type (MOD12) which is retrieved annualy, fraction of photosynthesis active radiation absorbed by vegetation (FPAR) and leaf area index (LAI) data (MOD 15) which are computed at 8-day interval, daily surface climate conditions, which is derived from 1.00° x 1.25° Data Assimilitaion Office (DAO) data and Biome Parameter Look-Up Table (BPLUT). Although cloud contamination that occurs in tropical forest may result in uncertainties of MODIS output (Zhao et al., 2004), the NPP datasets are sufficient to be used for scientific applications (Running et al., 2004).

To be compared with model result, MODIS NPP results are transformed from 1 km square at 8 days interval into 0.5° x 0.5° grid at 1 year interval. In this case, a grid of 0.5° x 0.5° represents the average of 60 x 60 pixels of MODIS data. There are 46 series of MODIS data in a year. Each represents of 8 days averaged NPP data and the 46^{th} data contains the average of 5 or 6 days according to the year. MODIS categorized each pixel as different types of land use, including vegetation and water. At the shoreline where both land and ocean may exist in one 0.5° square grid, the results are averaged over the area with an assumption that NPP in ocean/water part is equal to zero. Annual NPP value is computed by summing all the 46 series of NPP value for each grid. However, the original LPJ-DGVM model does not consider the ocean part which may exist in a 0.5° square grid at the shoreline. To deal with this problem, correction factors are applied to each grid at the shoreline to adjust the NPP results by the following equation:

$$NPP' = NPP\left(\frac{A_{grid}-A_{ocean}}{A_{grid}}\right) \qquad (20)$$

where,

NPP' = corrected NPP value

NPP = original NPP value

A_{grid} = total grid area

A_{ocean} = total ocean area in a grid

Based on this approach, a 0.5° square grid with large ocean part may have smaller average of NPP value than the one in land dominant part. Comparison between NPP corrected by Eq.(20) and MODIS Terra is shown in **Figure 7.**

The average NPP over Borneo Island computed by LPJ-DGVM is slightly lower than that produced by MODIS. Although grid-to grid comparison show relatively good correlation, but at the same time it shows large deviation. Correlation coefficient between LPJ-DGVM and MODIS results ranges from 0.6 to 0.7, while the average relative error ranges from 35% to 39.2%.

Figure 8a and **8b** shows spatial variation of NPP over Borneo Island computed by MODIS and LPJ-DGVM. Spatial variations of GPP and NPP along 116.25°E are shown in **Figure 8c** and **8d.** Both MODIS and LPJ-DGVM use vegetation type parameters and LAI as data input. Spatial variations of forest cover and LAI along 116.25°E for each computation are shown in **Figure 8e** and **8f.** Figure 8c and 8d shows that GPP which is computed by LPJ-DGVM is lower than that produced by MODIS, but both computations produced similar value of NPP. Average GPP, NPP and Carbon Use Efficiency (CUE=NPP/GPP) computed by MODIS along 116.25°E line are **2391** gC/m^2/year, **936** gC/m^2/year, and **0.38** respectively, while GPP, NPP and CUE computed by LPJ-DGVM are **1580** gC/m^2/year, **986** gC/m^2/year, and **0.63** respectively. Figure 8e and 8f shows that in the forest area, LAI computed by MODIS are slightly higher than the one computed by LPJ-DGVM. Average of LAI computed by MODIS and LPJ-DGVM are **3.68** and **3.48,** respectively. The different results between MODIS and LPJ-DGVM can be analyzed from three aspects: land cover data, computation methods of NPP and meteorological data.

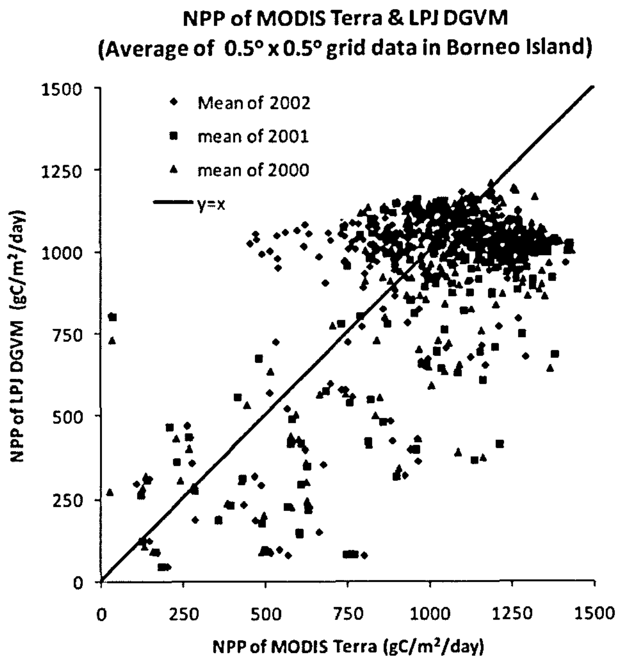
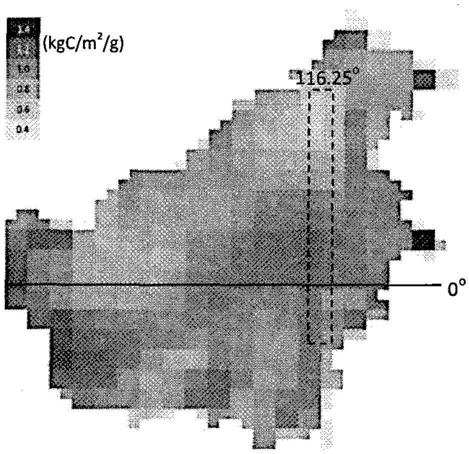


Figure 7: NPP average in Borneo Island corrected in LPJ-DGVM and MODIS Terra

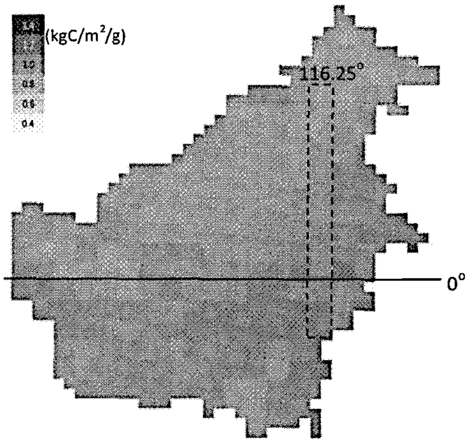
In this study, land cover data for LPJ-DGVM computation derived from digitized raster-image of Borneo Island with only two categories of land cover: "forest" and "non forest". Total area is calculated from each 0.5° x 0.5° grids, with maximum allowable forest cover in one grid, that is, 95%. For NPP computation, MODIS uses 13 classification of land cover (water, evergreen needleleaf forest, evergreen broadleaf forest, deciduous needleleaf forest, deciduous broadleaf forest, mixed forest, closed shrubland, open shrubland, woody savanna, savanna, grassland, cropland, urban or built-up area, and barren or sparsely vegetated area) with 1 km grid. The accuracies of land cover product (MODIS 12Q1) are 70-80% (Zhao, et al., 2005). Since each land cover classification uses different BIOME parameters, the misclassification of land cover may results in bias of NPP calculation product (Zhao, et al., 2005).

To be compared with LPJ DGVM spatial scale, every 60 x 60 grids of MODIS land cover data are averaged, represent 0.5° x 0.5° grid. To simplify the classification, all broadleaf, needleleaf and mixed forest are classified as "forest", while shrub, savanna, grassland, cropland, built-up, and barren area are classified as "non-forest". Portion of forest cover and LAI computed from MODIS and LPJ-DGVM are shown in **Figure 9.**

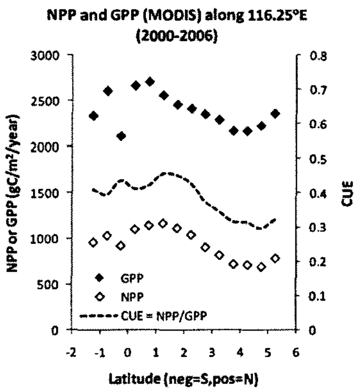
MODIS data shows different forest cover and LAI value than LPJ-DGVM. Although site A and B represent areas with similar forest cover by both MODIS and LPJ-DGVM, LAI computed by each method has different pattern. LAI data in MODIS is derived from the surface reflectance analysis which is retrieved every 8 days. In both example sites, LAI computed by MODIS varies within a year with relatively large fluctuation from 0 to 6. In LPJ-DGVM, LAI is computed annually from the vegetation growth analysis with average value 3.7. Average LAI computed by both methods fall between maximum and minimum value of tropical forest LAI data (Scurlock, Asner, and Gower, 2001). The difference between land cover and LAI data used by each method may result in different NPP value.



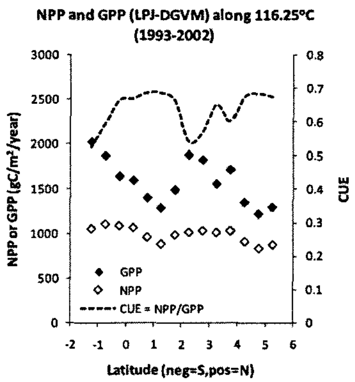
(a) NPP over Borneo Island (MODIS)
7 years average (2000-2006)



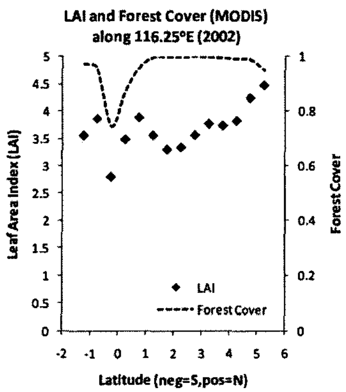
(b) NPP over Borneo Island (LPJ-DGVM)
10 years average (1993-2002)



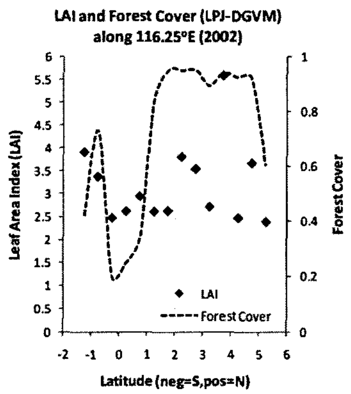
(c) NPP and GPP along 116.25° E (MODIS)



(d) NPP and GPP along 116.25 ° E (LPJ-DGVM)

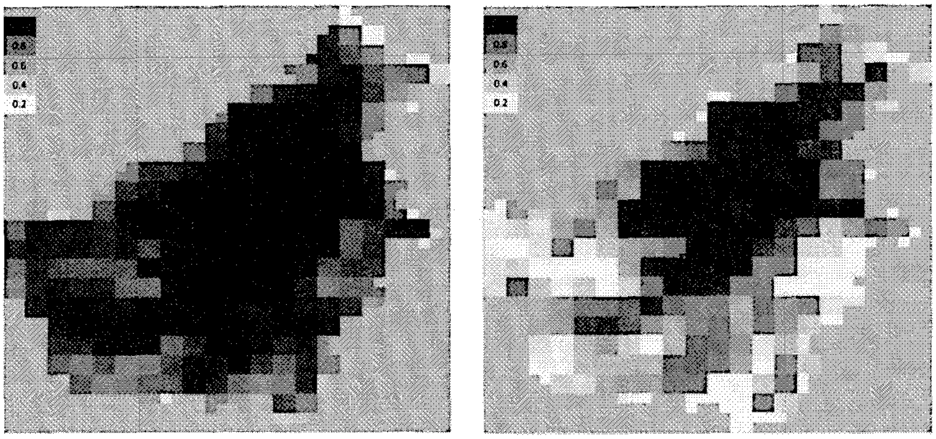


(e) LAI and Forest Cover along 116.25 ° E (MODIS)

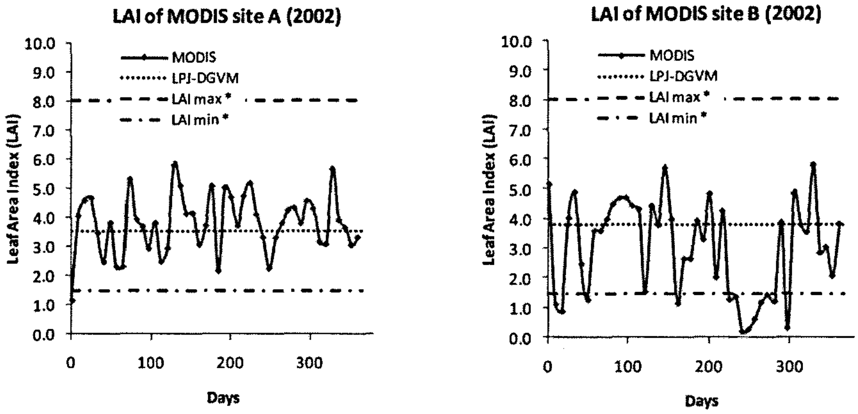


(f) LAI and Forest Cover along 116.25 ° E (LPJ-DGVM)

Figure 8: Annual NPP, GPP, LAI, and Forest Cover computed by MODIS Terra and LPJ-DGVM



a) MODIS land cover b) LPJ-DGVM land cover



* data from Scurlock, Asner, and Gower (2001)

c) LAI computed by MODIS and LPJ DGVM

Figure 9: Portion of forest area and LAI computed by MODIS and LPJ-DGVM

Table 4: Comparison of analytic results by MODIS and LPJ-DGVM

Parameter	2000	2001	2002
Average NPP (MODIS) (gC/m^2)	992.0	1002.3	894.7
Average NPP (LPJ-DGVM) (gC/m^2)	898.1	895.3	927.4
Correlation coefficient r	0.71	0.71	0.61
Average relative error δ (%)	37.8	39.2	35.0

NPP computations in LPJ-DGVM use monthly and annual meteorological data as input with spatial scale 0.5° x 0.5°. On the other hand, MODIS uses the daily assimilated meteorological datasets from DAO with spatial scale 1.25° x 1.00°. Both datasets has pros and cons. Meteorological datasets used in LPJ-DGVM have better spatial scale, but coarser in time scale, while DAO data have coarser spatial scale but better in time scale. Unfortunately, comparison between these two datasets can not be completed due to limited access to DAO data.

Although grid per grid computation may show different results, the grid average NPP over Borneo Island from LPJ-DGVM computation relatively close to the results of MODIS. Summary of comparisons between LPJ and MODIS data are shown in **Table 4.** For another comparison, NPP, GPP and CUE in various tropical forests are shown in **Table 5**. Compared with observation data, average of NPP computed by LPJ-DGVM falls within the range of minimum and maximum value of observation data, while average GPP is lower and average CUE is higher than observation data.

Table 5: GPP, NPP and CUE in various tropical forests

Location	Conditions	GPP	NPP	CUE	References
Gunung Mulu, Borneo	-	-	880-1200	-	Proctor, 1999
East Kalimantan, Borneo	Lightly disturbed forest	-	1470	-	Toma, et.al, 2000
East Kalimantan, Borneo	Moderately disturbed forest	-	1260-2060	-	Toma, et.al, 2000
East Kalimantan, Borneo	Heavily disturbed forest	-	1040-2180	-	Toma, et.al, 2000
Central Amazon, Brazil	-	3000	900	0.30	Chambers et al., 2000
Central Amazon, Brazil	-	3040	1560	0.51	Malhi et al., 1999
Various	Secondary forest	-	1500	-	Brown ad Lugo, 1990
Various	-	-	-	0.46	DeLucia et al., 2007

4.4 Scenarios

By comparing the satellite images from the mid 1980 to the beginning of 2000, it is found that about 13.2 million hectares of forests have been lost on Borneo Island (Stibig and Malingreau, 2003). Forest degradation maps in Borneo Island in 1950, 1980, and 2000 are shown in **Figure 10.** Black-shaded part represents forests area, white part represents non-forest area, and diagonal-hatch part represents no data.

To investigate the effect of land use change on Borneo Island's carbon balance, the following scenarios are considered in this study.

1) Without land use change: Borneo Island is considered as an undisturbed area such that vegetation dynamics are only affected by natural aspects. This scenario is similar to the original LPJ-DGVM purpose, that is, to simulate the potential natural vegetation landscape.
2) With land use change: Annual rate of land cover changes was computed based on available land cover maps in 1950, 1980 and 2000. Since the map mainly consists of two vegetation categories, those are, "forest" and "non-forest", all the "non-forest" areas are considered as shrub or grass. For the no data area in the northern part of Borneo Island in 1950s, whole forest cover area is assumed.

Standard LPJ-DGVM starts with the initial condition of bare ground and spins up for 1000 years by using the repeat of first 30 years climatology data. The spin-up computation is conducted until stable condition is obtained. 100-years simulation period from 1903 to 2002 is conducted for both scenarios. In the simulation period, the first scenario uses the original of LPJ-DGVM computation, while in the second scenario, land use change computation is applied. Annual rate of land use change is computed by linear interpolation between two available forest degradation maps (1950, 1980, and 2000), with exception in 1900 which used the model result in the end of spin up period. Since the rate of land use changes are different from one place to another, annual rate of changes are computed for each grid separately. The results of the two scenarios are shown in **Figure 11**.

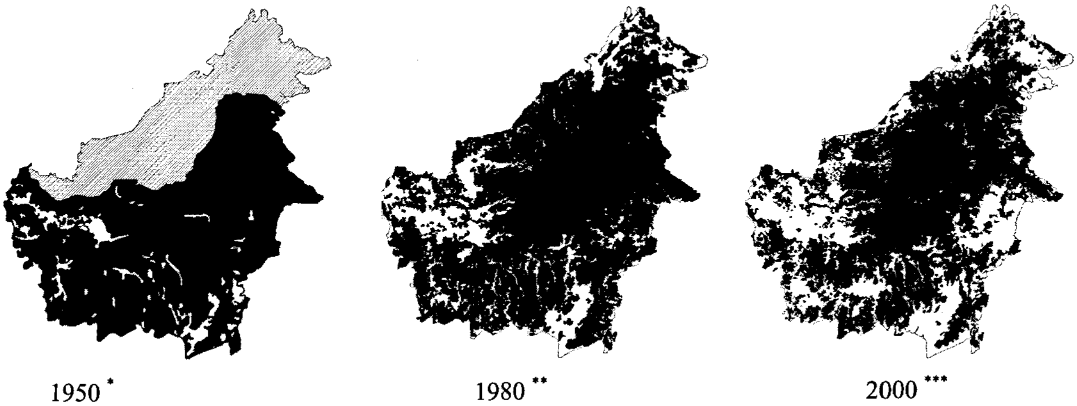


Figure 10: Forest degradation map in Borneo Island

Source:

* Ministry of Forestry, Republic of Indonesia

** World Conservation Monitoring Centre, Stibig and Malingreau, (2003)

*** Ministry of Forestry, Republic of Indonesia, Stibig and Malingreau (2003)

The increasing trend of NPP might be a result of: 1) increase of atmospheric CO_2 and temperature and 2) change of vegetation type from forest to non-forest vegetation such as grass and pioneer trees) with higher productivity rates. Several researches show that tropical C4 grass has higher photosynthesis compared with tropical trees. In this simulation the "non forest" area consist of grassland of C4 grass. The area occupied by grass and pioneer tree shows high rates of NPP. The increasing trend of heterotrophic respiration might come from: 1) decrease of woody tree vegetation, and at the same time, 2) increase of grass and pioneer tree.

From year to year, vegetation carbon tends to decrease following the forest loss. Primary trees are long-lived vegetation. The result of photosynthesis is accumulated in primary trees bodies, mainly in the wood part. In general, forest areas tend to have higher litter carbon pool than grassland. This is because the dead leaves and trunks of the trees will fall into the ground to be a part of litter carbon. However, in the long term analysis, litter and soil carbon pools in "non forest" area tend to have higher increase rate than those in "forest area". Due to its short period of life, the high biomass production of grass or pioneer tree can not be stored in vegetation body for a long time. As the vegetation dies, the biomass will be transferred into soil and litter carbon pools, this may lead to the increase of heterotrophic respiration. As a result, the land use change from "forest" into "non forest" which is intensively occupied by grass and pioneer tree in the south and west parts of Borneo, results in a high rate of heterotrophic respiration despite the higher rate of NPP.

Net Ecosystem Production (NEP) is usually used to decide whether an ecosystem is autotrophic (for example, forest, lake, etc), or heterotrophic (for example, urban area). Autotrophic area is termed as "carbon sink", while heterotrophic is termed as "carbon source". Usually NEP is calculated with excluding carbon lost by harvest. Some researchers suggest that loss by activities such as harvest, lumber and logging, should be included in the NEP calculation to be defined as Net Biome Productivity (NBP).

The increase of average NPP over Borneo Island from 1960 to 2002, without land use change and with land use change scenario are: 2.44 GtC/year and 2.69 GtC/year, respectively. While, the increase of the average heterotrophic respiration is are 0.91 GtC/year and 2.41 GtC/year, respectively. If carbon loss by harvest is excluded, the results of with land use change scenario suggest that heterotrophic respiration tends to increase with higher rates than NPP. With simple linear trend line, without land use change scenario gives a relatively constant value of NEP in the future. On the contrary, with land use change scenario shows a decreasing trend, and in the next 30 years, Borneo Island may have a negative NEP. If carbon loss by harvest is included, the result of with land use change scenario indicates that from 1960 to 2002, 471.9 gC/m2/year was taken away, and at the present

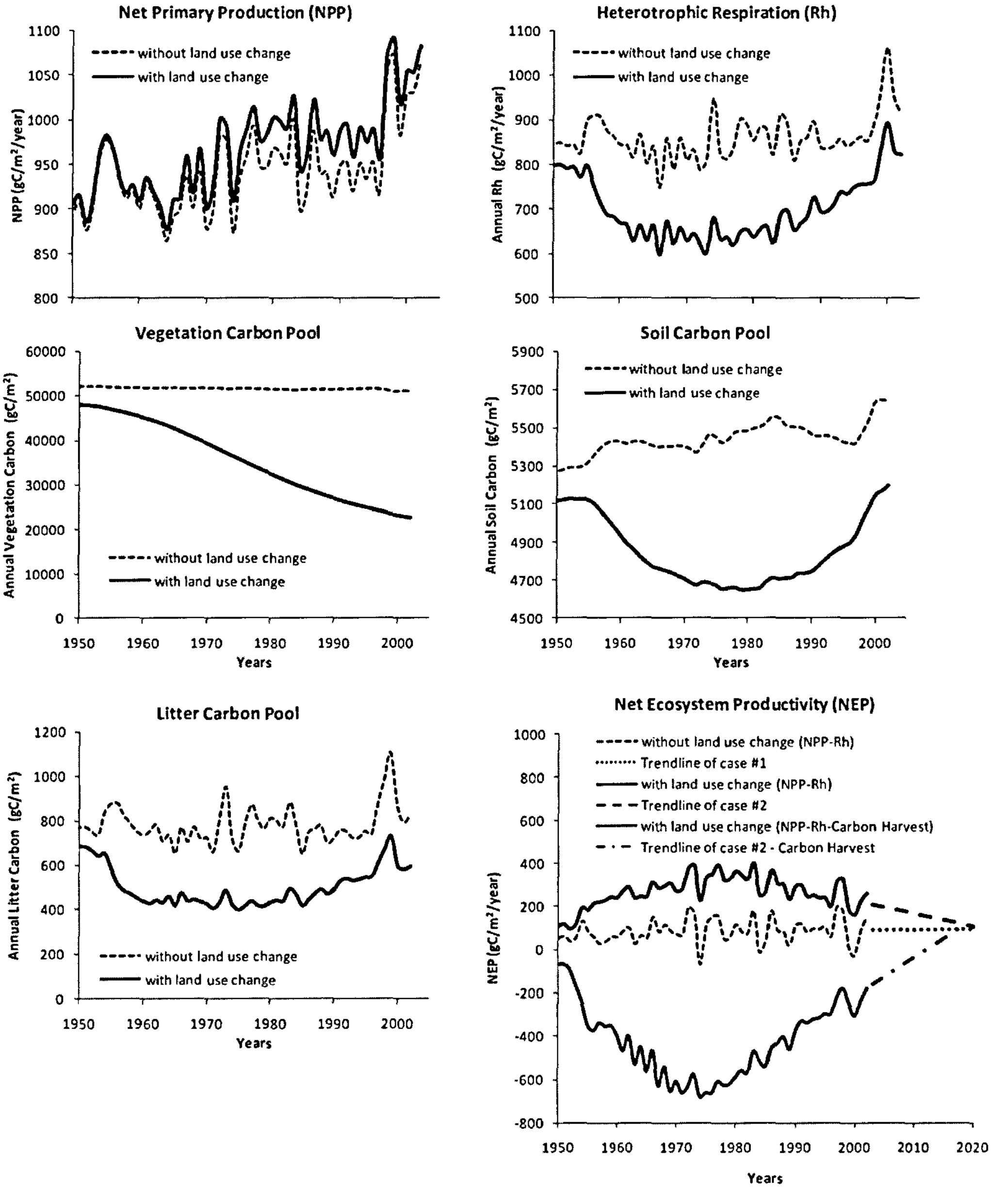


Figure 11: Average of Carbon Flux and Carbon Pool over Borneo Island.

Borneo Island already has a negative value of NEP. Anthropogenic deforestation and climate change are two aspects which need to be considered in the assessment of present and future carbon balance conditions. Some problems appear in the analysis of deforestation rate from land usage, such as: the usage of terms "forest" and "non-forest": whether "non-forest considered as bare land, grassland, cropland, or other type of vegetation; the removed vegetation biomass in the deforested area: whether harvested as wood product, transferred into atmosphere, litter, or soil.

To deal with the first problem, the "non forest" areas are considered as grassland with some modification in PFT parameters and computations to include the local/regional characteristics in vegetation dynamics. The model simulated the establishment pattern and the results are well compared with field survey data (in case of deforestation due to slash-and-burn agriculture activities). The model also well compared with field data in terms of vegetation type (grass/shrub, pioneer tree and primary tree), and dimension (diameter and height). Although in some areas the results of the model show different pattern from MODIS NPP data, they still fall within the range of acceptable values. For more detailed analysis, another modification in PFT parameters are needed to capture the role of other types of land cover, such as palm oil plantations and other important cash crops.

To deal with the second problem, in the deforested areas, trees with diameter higher than 5 cm are assumed as "wood product" and the rest are transferred into litter pool. In long term analysis of NEP or NPP, the model shows good results. Since maps used in this study do not distinguish between the forest losses due to human activities (logging, agriculture, etc) and wild fire, the portion of biomass which is transferred into the atmosphere due to fire event cannot be calculated directly. To simulate the mechanism and the effect of a specific event, such as large forest fire event that occurred in Borneo Island in 1997/1998, further development and more detailed data are needed.

5. Conclusions

The modified LPJ-DGVM as one of the models that is used in Asian Environment Simulator (AES) allows a further analysis of the role of the rainforests in regional terrestrial carbon balance. Simulation results suggest that deforestation in Borneo Island in the last few decades had caused the decrease of terrestrial carbon storage in vegetation, soil and litter pool. Deforestation may lead to more serious problems in the future such as forest fire, drought and flood.

Further development need to be conducted in terms of computation procedures and the usage of high resolution datasets. In this study, most of the LPJ-DGVM computations are still conducted in monthly time steps. Nowadays, many reanalysis climate data (temperature, precipitation, etc) with better temporal and spatial resolutions are available for public use. By using those datasets, computation time step can be increased for more comprehensive analysis in atmosphere-biosphere interrelationship.

Compared with observation data, the NPP values computed by the model are still falls within the acceptable value range. However, the GPP values are still tends to be underestimates. Based on this approach, LPJ-DGVM can be used for analysis of terrestrial carbon balance with relatively good result. However, if the model is used for analysis of atmospheric carbon balance, the result might be underestimates.

This study showed that the use of dynamic vegetation model is important for analyzing the past condition and projecting future trends of carbon balance under the increase of anthropogenic activities and the uncertainty of rapid climate change, particularly for regional case study such as Borneo Island.

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