An Inventory of Air Pollutant Emissions from Biomass Open Burning in Thailand Using MODIS Burned Area Product (MCD45A1)

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Abstract: This study developed a methodology to estimate air pollutant emissions from biomass open burning in Thailand during 2009-2011 using country specific data and the 500-meter MODIS burned area product (MCD45A1) from MODerate-resolution Imaging Spectro-radiometer (MODIS). The spatial and temporal distributions of biomass open burning emissions were analyzed and displayed in the form of a 1 km × 1 km grid density map. The MCD45A1 burned area data were validated by ground checking. The results showed that between 2009 and 2011, the total area of burning ranged from 332,723 ha in 2009, to 410,636 ha in 2010 and to 144,419 ha in 2011, respectively. Also, it was found that forests and paddy fields constituted the most burned vegetation. Most of burned forests were situated in the northern and northeastern regions, and burned paddy fields were located in the central part of the country. Additionally, the peak period of biomass open burning was found to during December to April. The estimation of emissions of open biomass burning from 2009 to 2011 indicated that the amounts of CO_2, CO, CH_4, N_2O, and NO_X emitted were approximately 2,150,077 tons, 163,175 tons, 7,704 tons, 221 tons and 2,841 tons, respectively. They also emitted particulate matters $PM_{2.5}$, PM_{10}, and black carbon (BC) at amounts of 10,469 tons, 16,571 tons and 1,014 tons, respectively.

Keywords: Emission inventory, Agricultural burning, Forest Fire, MODIS product.

1. Introduction

Biomass open burning, especially forest fires and agricultural residue burnings is, an on-going manmade activity. Most of open biomass burning is due to anthropogenic land clearing for cultivation, hunting, and collection of wild products, therefore it can be accounted as either reemission anthropogenic source [1-2]. In addition to its direct effect on local people through air pollution, biomass open burning emissions may also contribute to global warming. The burning of biomass emits greenhouse gases including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). According to a national fire emissions inventory, the actual situation of fires requires that the estimation of emissions be as accurate as possible and reflect the conditions leading to fire emissions [2-4].

Thailand faces continuous air pollution problems from open biomass burning, especially during the dry season [5].The monthly values available basis indicated that January to April is the biomass intensive burning period, not only by Thailand but also by other countries in the Greater Mekong Sub region [6]. The location of hotspots was overlaid with a land use map from the LDD to identify land cover over the fire hotspot. This information is useful to allocate precise land cover-depended factors such as biomass loading and combustion efficiency. In year 2010, the area of burnt agriculture was 2,208 km^2 (paddy field 1,215 km^2, corn 670 km^2, sugar cane 323 km^2) and that of bunt forest was 7,228 km^2 (mixed deciduous 2,971 km^2, deciduous dipterocarp 1,552 km^2 and other types of forest 2,705 km^2). Fuel density of each land use type was obtained from local survey and measurement. For forest fire estimation in Thailand, Junpen and coauthors estimated that biomass density is 371.4 ton dry mass/km^2 for deciduous dipterocarp forest, 364.5 ton of dry mass/km^2 for mixed decidous forest, and combustion completeness is 0.78 for both deciduous dipterocarp forest and mixed deciduous forest [7]. For agriculture burning, biomass density is 237 ton/km^2, 620 ton/km^2, and 247 ton/km^2 and combustion completeness is 0.87, 0.2, and 0.39 for rice, corn, and sugar cane, respectively [3, 8].

At the present, assessing forest and crop residue burned area open biomass burning is important because of climate change, human health, or whatever. There are many factors which affect the degree to which an assessed burned area approximates the actual burned area. One of the biggest difficult accessing area of burned biomass. It is necessary to provide an overview of all data that can affect changes in both the temporal and spatial variations. In the past decade, the study of forest fire measurement and monitoring changes commonly used the Fire Hot Spot (FHS) [9]. Even though, the FHS product has been used to analyze past research work and despite high temporal accuracy, It is characterized by high uncertainty in its spatial accuracy. Researchers have pointed out that the use of estimation emissions of burn scar may provide better accuracy [7, 9-10]. The accuracy of estimating in burned area by FHS data coupled with ground measurements has been shown to give a high overestimation of the burned area by using active fire product from MODIS [7]. The FHS, known as MOD14, is onboard the Terra and Aqua satellites with 1 km × 1 km spatial resolution and is used to estimate the extent of the open biomass burning activity [7, 11]. The burned area reported from FHS data was estimated at 1.4 to 2.3 Mha, from 2005 to 2009, and was compared to MODIS data with satellite images from LANDSAT-5 TM. The comparison revealed that MODIS incorporated a high uncertainty within its data. The potential to assess burned areas has evolved from FHS. Although the ability of such data to provide information on change over time is accepted, there is still a limitation for the spatial variation [7].

The Forest Fire Control Division (FFCD) of the Thai Royal Forestry Department (TRED) reports that forest fires occur annually during the dry season from December to May. From 2009 to 2011, the forest fire statistics reported by the FFCD show annual forest fire burning to range from 4,078 to 13,308 ha [12]. The FFCD measured the size of the burned area using the tracking function on a Global Positioning System (GPS) and walking around the perimeter of the burned area. However, statistics reported by the FFCD show an underestimation of the actual biomass area burned [9]. The MCD45A1 burned areas were found to range between 22100 and 137700 ha year^{-1} which was between 0.5 and 4.7 times higher than the values reported by the FFCD. This was used to estimate the forested areas burned in Thailand during 2001- 2006 [13].

Therefore, this study develops and evaluates an emission estimation of open biomass burned area in Thailand for both forestland and cropland by using MODIS burned area product (MCD45A1) with a 0.5 km × 0.5 km spatial resolution. The higher spatial resolution is employed to reduce the uncertainty in estimation of burned area from satellite imagery [14-15]. The methodology of MCD45A1 burned area processing and analysis is presented, and the results are discussed. The air pollution from open biomass burning is calculated using a combination of assessed burned area and country specific data on forest fire and agricultural burning. To increase the accuracy of estimated emissions, we can calculate correction factor variables for burned area (BA), biomass burned fuel (BF), combustion (CF), and emissions (EF) [9, 12, 16]. Finally, for the emissions obtained in this study are compared with emissions presented by the FFCD and previous studies [7, 12]. The target emissions are CO_2, CO, CH_4, N_2O, $PM_{2.5}$, PM_{10}, NO_X, and BC. The results are shown in spatial distribution of MODIS burned area.

2. Experimental

2.1 Description of MODIS Burned Are product (MCD45A1)

MCD45 are identified by an alphanumeric code of three letters and two numbers; the burned area product is MCD45. MCD indicates that MODIS on board both Aqua and Terra satellite provide input data and 45 indicates the burned area product [14]. There are three different versions of the MODIS burned area product: the official MCD45A1 in MODIS Hierarchical Data Format, NASA Earth Observation System (HDF-EOS), and the Geotiff and Shapefile version. In our study we used the Geotiff version of the MCD45 monthly product, derived from standard MCD45A1 HDF version. The version shows a set of sub-continental windows, which are re-projected in the Plate Carree projection, and was developed by the University of Maryland Information for Resource Management System for the global detection of fires. (available at http://modis-fire.umd.edu/.) [14, 17-18]. The algorithm of the product uses a bi-directional reflectance (BRDF) model based on a change detection approach; removes all MODIS band 6 (Mid-Infrared, 1550-1750 nm) multitemporal tests, which cause omission errors on land surface with temperatures greater than 327.7K. It was used over certain forest and agricultural land and detects the burning per pixel by daily (range 1-366) gridded MODIS at 500 m x 500 m spatial resolution land surface reflectance time series [17]. It detects the approximate date of burning by locating the occurrence of rapid changes on MODIS aboard Terra and aboard Aqua satellites. This algorithm provides an analysis of the MODIS land surface reflectance bands' abilities to discriminate between daily temporal burned and unburned biomass on land surface [14, 17, 19].

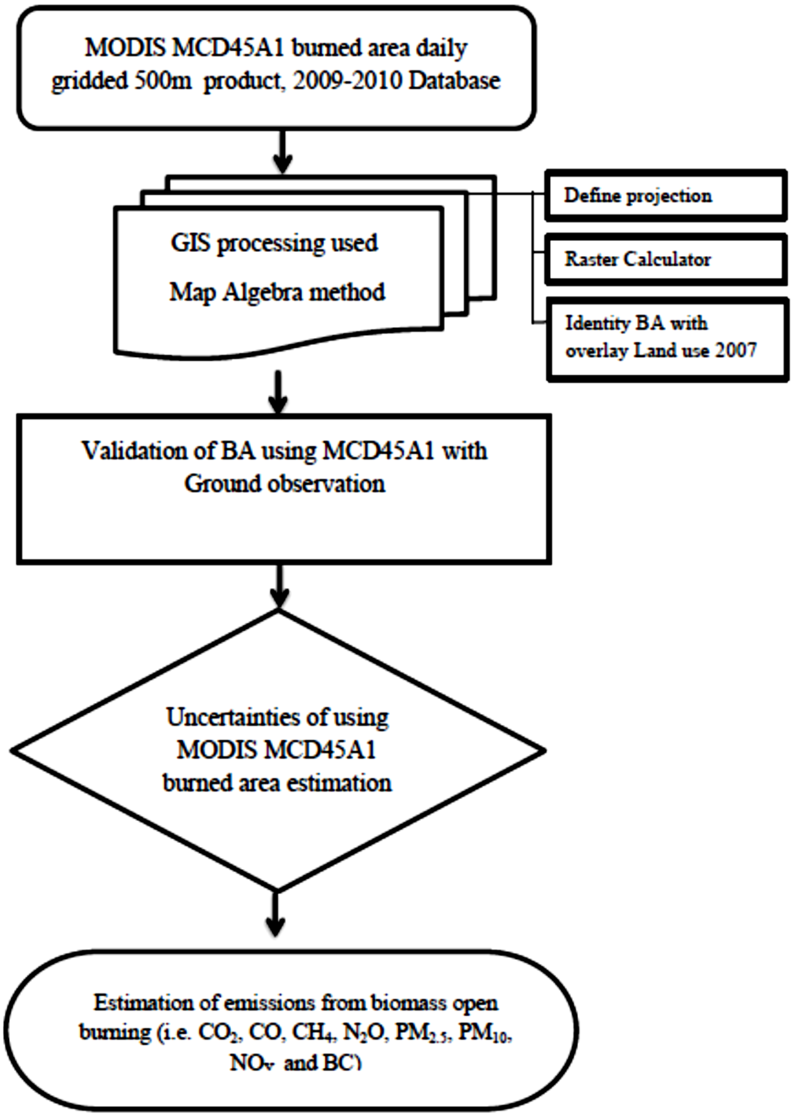

Figure 1. Flow chart of estimation of open biomass burning in Thailand derived from MODIS Burned Area Product (MCD45A1).

Figure 1 shows the flow chart of MODIS burned area product (MCD45A1) data processing. Geographic Information System (GIS) software was used to display, subset, and classify the data of the burned area for Thailand from 2009 to 2011. The data was available online through the Soundest Asia window from [18]. The area of study is only assessed for Thailand. The burned area data uses a Geotiffs format and gives the date in Julian days. The date is shown as either distinctly independent colors or in the same color. The world projection re-projected, as into the World Geodetic Systems (WGS) 1984 UTM Zone 47N projection coordinate system on geo-processing in ArcGIS programs. This was the first step identifying the data the area was burned. The date of burned area was processed using the raster calculator on map the algebra tool in ArcGIS program, and was used to analyze and fit data the to the obtained burned area data and convert the data into Shapefile format.

The methodology for estimating burned area from open biomass burning is divided by the source of open burning, such as forest fire area and agricultural burning. The type of burned area is classified by using GIS software, and a spatial analysis tool is used for calculating, processing, and extracting burned area data. The burned area is categorized by overlaying and identifying the burned area data on a land use map from 2007 (shown in Figure 2, which was developed by the Thai Land Development Department (LDD) [20]. A spatial resolution of 0.5 km × 0.5 km per pixel was used to represent burned areas. Finally, the results of the spatial and temporal variation of burned area are adjusted with a factor derived from ground observation. Biomass burning emissions are presented in a grid map with grid squares of 10 km × 10 km spatial resolution. The sizing of the grid map is a suitable resolution for forest fire management plans, and is used to cover the period from 2009 to 2011 [9].

2.2 Validation of burned area estimated from MCD45A1 product

For this study, the burned area was determined using the MCD45A1 estimation of burned land area, and validated with the ground truthing method. The procedure of burned area estimation from biomass burning includes there steps. First, identify burned area from MCD45A1 for the time period under consideration. The data from the MODIS sensor on Terra and Aqua satellites has the capability to find burned area of biomass. Due to no real time data being available over Thailand, we used MOD14 data to obtain the position of the burned area in each type of vegetation. The study is divided by the source of burning and then compared with FHS and ground observation. Usually, the peak of fire and on transboundary haze are observed during fire year January to march in ASEAN the region, Thailand [6].

We sampled burned area experiment study sites for forest burning in March, 2013, at Chiang Mai province, in the northern region, of Thailand and for the Agricultural burning from January to March, 2013 at Nakhonratchasima, Phatchabun and Ayutthaya province, in the northeast and central regions of Thailand. The ground survey relates the MCD45A1 and observation measurement. Second, we tracked the area burned and determined the correlation between MCD45A1 and ground observation measurement at the sampling experiment study sites by tracking the contour of burned area by handheld GPS Gamin60sx units. Finally, we made a graph of biomass burning by biomass type. We used simple linear regression analysis where the regression equation is described as $y = a+bx$. For the regression equation, y is the value of the burned area as measured by ground observation, x is the MCD45A1 burned area, b gives the constant change and a unit change in y as a result of a unit change in x, and a takes a value of zero. A standard r^2 value estimation equation is suitable to be used for determination of the correlation coefficient.

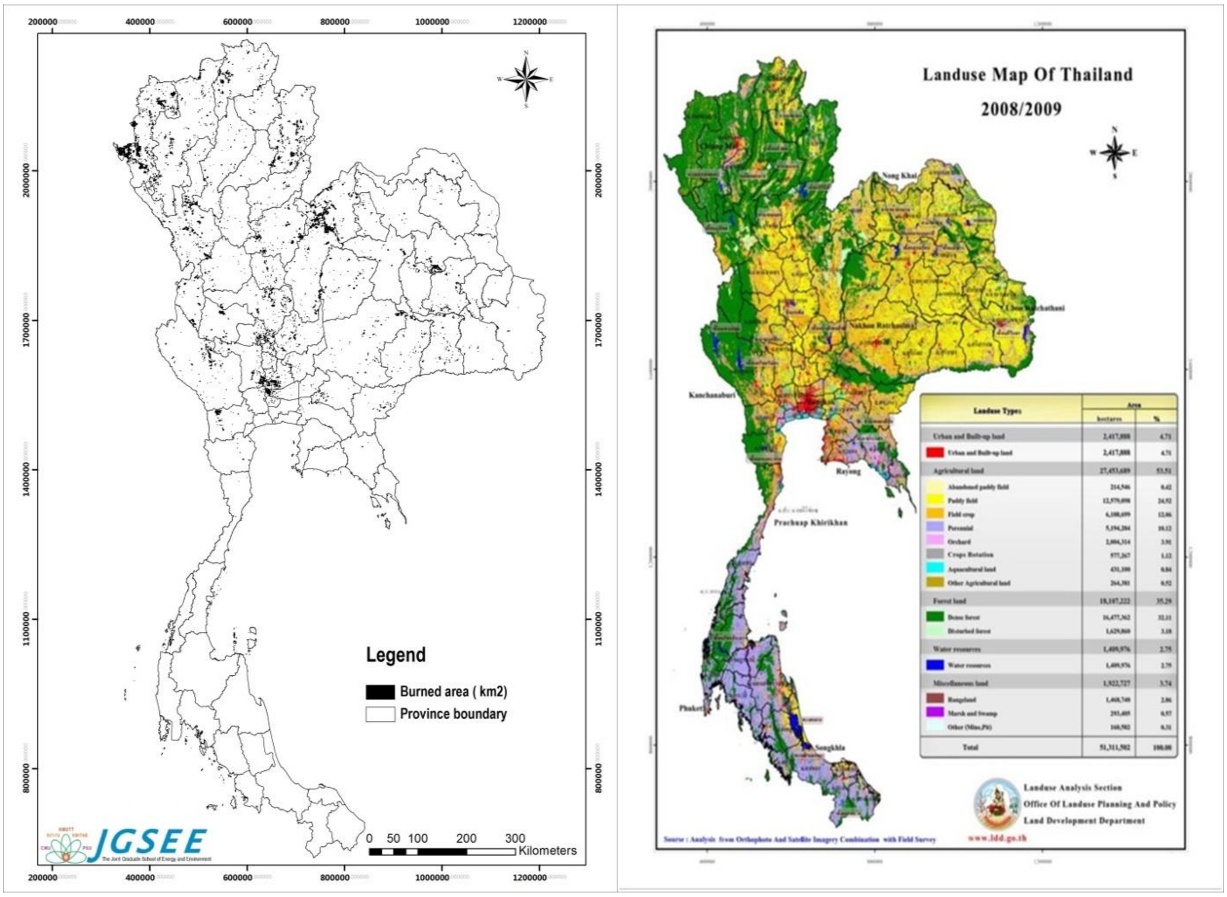

Figure 2. Area burned derived from MODIS Burned Area Product (MCD45A1) identity with land use map information, Thailand.

2.3 Parameter used for estimating biomass open burning emission

Seiler and Crutzen have developed an equation to estimate emissions from biomass combustion [21]. The equation calculates the release of emissions by multiplying the mass of biomass combusted with the mass of emissions emitted per unit biomass combusted (the emission factor) The equation is provided as follows:

$$E_j = \sum_i (M_i \times EF_{ij}) \times 10^{-3} \quad (1)$$

Where E_j is the emission from biomass combustion of trace gases (j) CO_2, CO, CH_4, N_2O, NO_X, $PM_{2.5}$, PM_{10}, and BC (tons); M_i is the mass of vegetative biomass combusted (i) (tons dry matter); EF_{ij} is the emission factor of the trace gas or the constant of emissions emitted (j) per mass of biomass combusted (g/kg dry matter) and i is the vegetation type (e.g. savanna, grassland, tropical forest, or agriculture residue). As biomass is burned through forest fire and agricultural burning processes, the estimation of combusted biomass relies on 3 factors; (1) the burned area as forest fire, agriculture burning, or savanna burning; (2) the mass of biomass burning per unit area by type of biomass burned. The type of biomass that is suitable for the type of fire is important for accurate emissions estimations, for example leftover harvest residue for the case of agricultural burning, or above ground biomass per area (in crown forest) for forest fires; and (3) the amount of combustible biomass that is not completely burned. Thus, there is a need to assess the ratio between mass of biomass combusted and mass of total biomass. The ratio is known as the combustion efficiency and is used to adjust the true value of burned biomass. Therefore, mass of biomass combusted is estimated using Equation 2.

$$M_i = A_i \times BD_i \times C_i \quad (2)$$

Where A_i is the area of biomass burned or burned area (ha); BD_i is mass of biomass burned per area or biomass density (tons/ha); and C_i is the combustion factor (dimensionless) [21].

Biomass fuel

This study uses country specific data on biomass data which is reported by the Garivait et al., [2007], to the National Research Council of Thai government. The forest biomass fuel was reported at about 3.76 tons/ha [9]. The biomass density of agriculture residue was reported as 2.37 tons/ha for rice paddy fields, 6.20 tons/ha for corn, and 24.7 tons/ha for sugarcane [3]. The biomass fuel is show in Table 1.

Combustion factor

The combustion efficiency of forest fire in deciduous forests is assumed to be representative of forest fire behavior in Thailand. A combustion efficiency of 0.79 for forest fires is thus used [7, 9], and is shown in Table 2. The combustion efficiencies for agriculture burning are reported as 0.87 for rice, 0.20 for corn and 0.39 for sugarcane by the Thai Pollution Control Department (PCD, 2005) and are used in this study [3].

Emission factor

This study uses emission factors that are reported by Andrea and Merlet for CO_2, CO, CH_4, N_2O, $PM_{2.5}$, NO_X, BC, and PM_{10} from tropical forest fires and agricultural residues [2]. The emission factors are shown in Table. 3.

Table 1. Biomass fuel of tropical forest and agricultural residues.

Biomass Fuel (tonns/ha)			
Forest[a]	Rice paddy[b]	Corn[c]	Sugarcane[c]
3.76	2.37	6.20	24.70

[a]Junpen, A., and Garivait, S., 2011,[b]Cheewaphongphan, P. and Garivait, S., 2012, [c]PCD, 2005

Table 2. Combustion Factor of tropical forest and agricultural residues.

Combustion Factor			
Forest[a]	Rice paddy[b]	Corn[c]	Sugarcane[c]
0.79	0.87	0.20	0.39

[a]Junpen, A., and Garivait, S., 2011,[b]Cheewaphongphan, P. and Garivait, S., 2012, [c]PCD, 2005

3. Results and Discussions

3.1 Estimation of burned area using MODIS Burned Area Product (MCD45A1)

The analysis of MODIS product employs different algorithms for estimating fire data and may influence the spatiotemporal characteristics of burning [22-23]. The peak of burned area occurred from in the February to March. Moreover, we found that diferncees in elevation slope of the burned area were significant. In most the flat areas, MCD45A1 had acceptable detection of burned area which was identified as agricultural burning. It was accurate at finding rice paddy and sugarcane burned areas in the central region. For the high elevation slope from 5 to >15% based on ground survey, we identified the burned area as forest fire and corn burned area in the northeastern and northern regions. (shown in the Figure 5: the correlation between ground observation measurement and burned area product). From 2009 to 2011, the overall burned area of both forest land and crop land was estimated at about 887,778 ha. The largest expanse of burned area was observed in 2010, at about 410,636 ha. The smallest expanse of burned area of open biomass burning was observed in 2011, at about 144,419 ha. For 2009, 2010, and 2011, the burned area resulting from forest fire was approximately 187,178, 264,257 and 69,053 ha, respectively, and the burned area from agricultural burning was approximately 145,545, 146,379, and 75,366 ha, respectively. Hence, the total burned biomass was computed at 26,539 tons dry matter, which includes burned forest biomass at 15,460 tons dry matter and burned agricultural biomass at 11,078 tons dry matter. The annual information of burned area is shown in Table 4.

Figure 3 present the monthly distribution of burned area in Thailand from 2009 to 2011. Analysis of the monthly temporal distribution of the burned area indicates that open biomass burning occurred starting in December, and increased through the month of April, with the peak of fire occurring during February and March. These five months are representative of the forest fire season, in addition to when farmers have cleared their lands by burning for preparation of the next planting season during this period.

Table 3. Emission factor of tropical forest and agricultural residues (Andreae and Merlet, 2001).

Forest type	Emission factor of tropical forest and Agricultural residues (g/kg dry matter burned)							
	CO_2	CO	CH_4	N_2O	$PM_{2.5}$	PM_{10}	NO_X	BC
Tropical Forest	1,580 ± 90	104 ± 20	6.8 ± 2.0	0.2 -	9.1 ± 1.5	8.5 ± 2.0	1.6 ± 0.7	0.66 ± 0.31
Agricultural residues	1,515 ± 177	92 ± 84	2.7 -	0.07 -	3.9 -	13 -	2.5 ± 0.10	0.69 ± 0.13

Table 4. The annual burned area derived from MODIS burned area product (MCD45A1) in Thailand during 2009-2011[a].

Fire year (ha)	2009	2010	2011
Evergreen forest	18,310	49,022	5,829
Deciduous forest	129,771	190,315	49,012
Other forest	39,097	24,920	14,212
Total	187,178	264,257	69,053
Rice paddy	92,638	83,231	57,298
Corn	13,283	21,726	4,232
Sugarcane	7,816	4,831	3,018
Other agricultural	31,807	36,592	10,818
Total	145,545	146379	75,366
All Total	**332,723**	**410,636**	**144,419**

[a]Burned area (ha), The analysis of MCD45A1 data indicated that there was no fire during Jun-Sep 2009, May-Sep 2010 and May-Nov 2011 are missing

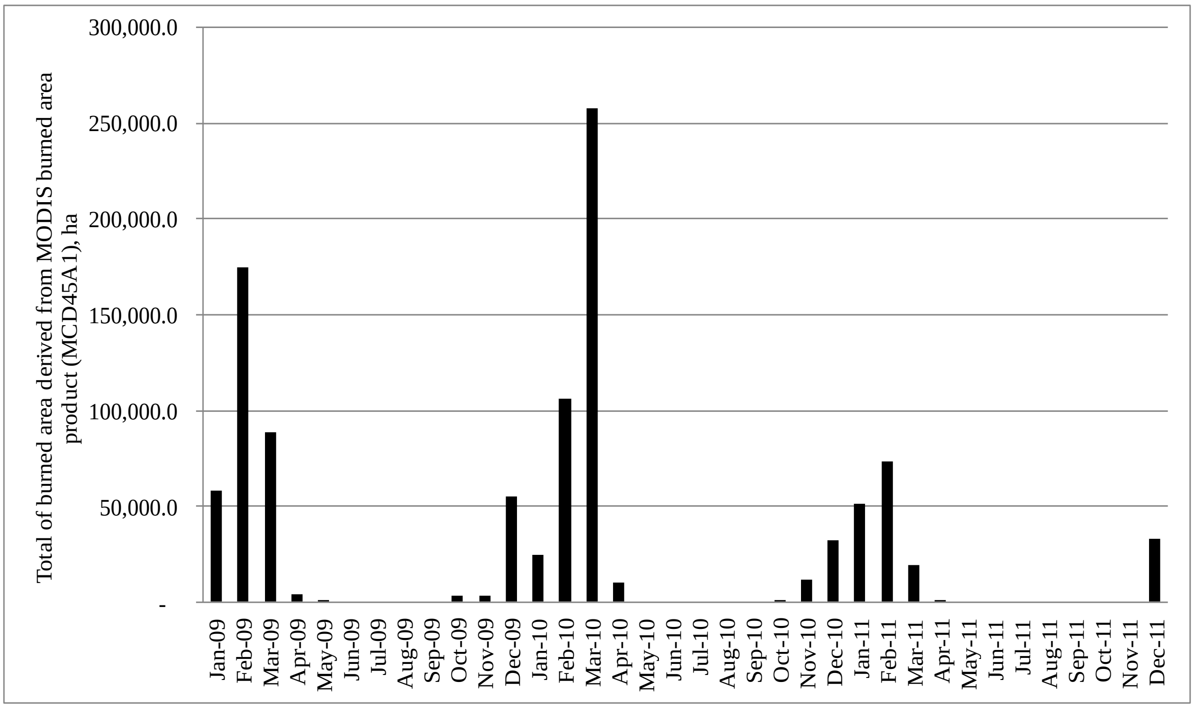

Figure 3. Monthly distribution of burned area from open biomass burning in Thailand during 2009 to 2011.

We compared the forest fire burned area reported by the FFCD and the results from this study. For the years of 2009-2011, the overall forest fire area reported by the FFCD and our results were about 26,755 and 520,600 ha, respectively. The largest area of forest fire burning was seen in 2010, which this study the FFCD reported at about 13,308 and 264,300 ha of overall forest area, respectively. The second highest annual range of forest fire burning was in 2009, and was at about 9,369 and 187,200 ha of overall forest area, respectively.. The third highest area of forest fire burning was observed in 2011 and was about 4,078 and 264,300 ha of overall forest area. A study by Junpen, A. [2011] yielded results using FHS for year 2009 of about 1,576,600 ha burned. Comparison of the findings of our study with FHS at 1 km × 1 km spatial resolu tion found that our study provided an approximate estimation 8.4 times lower than by the Junpen study [2011]. The methods of this study were developed to assess burned area and resolve the discrepancy between pixel size of biomass burning imagery and actual size of the burned area [7]. The comparison of annual burned area estimates derived from FHS data, and MCD45A1 in Thailand from 2009 to 2011 is shown in Table 5.

The annual spatial distributions of burned areas from biomass burning during 2009 to 2011 with high-density burned areas (>1.0 km^2 per grid) are shown in the dark color grid, while low-density burned area (0.01-1.00 km^2 per grid) are shown in the light color grid (Figure 4). The spatial distribution of burned area also shows that a large amount of burned area occurred in deciduous forests that are situated in northern Thailand, along the western border with Myanmar and the Huai Kha Khaeng Wildlife Sanctuaries. Within the cores of the deciduous forests, steep sloping topography made it difficult to access and control forest fire. Most forest fires burn continuously through the day and night, and quickly become a large fire that is easily detected by satellite imagery. Moreover, the highest density of burned area was found in the central part of Thailand. The area corresponds to rice paddy fields, which farmers usually burn after harvesting the rice.

Table 5. Comparison of the annual burned area derived from statistics of FHS and MODIS burned area product (MCD45A1) in Thailand during 2009 to 2011.

Year	Comparison of burned area estimation (ha)		
	FHS[a] (ha)	This study MCD45A1 (ha)	Ratio of BA from this study to BA from FHS[a]
2009	1,576,600	187,200	8.4
2010	-	264,300	-
2011	-	69,100	-
Total	-	520,600	-

[a]Burned area estimated by MODIS active fire product resolution 1km x1km studied by Agapol Junpen (2011)

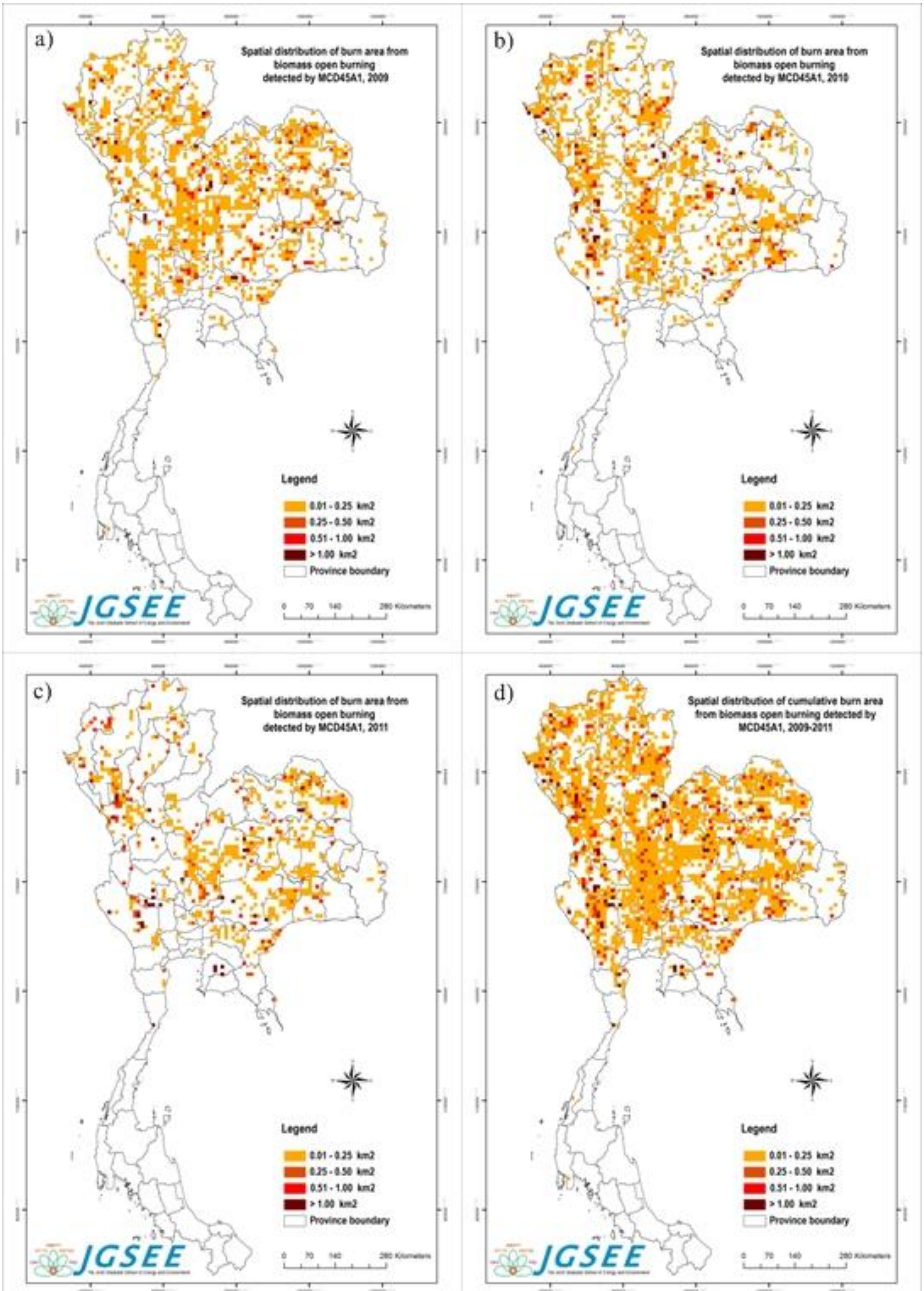

Figure 4. Burned area spatial distribution gridded by year for (a) 2009, (b) 2010, (c) 2011, and (d) cumulative burned area derived from MODIS MCD45A1 burned area product during 2009 -2011.

3.2 Validation of MCD45A1 burned area by ground tracking

The burned areas identified by ground tracking at the sampled burned area experiment study sites for forest burning and agricultural burning, at Chiang Mai, Nakhonratchasima, Phatchabun and Ayutthaya provinces, Thailand are shown in Figure 5.

Combining the MCD45A1 burned area estimations with ground observation measurements use an adjustment factor for the forest fire and agricultural residue burning in this study. Figure 6(a) shows the rice paddy fields area, with the shown burned area product (MCD45A1) correlating linearly with the size of the burned area. The linear correlation is described by the slope regression line y=0.8677x (r^2=0.9765) with a confidence of 97.65%., Figure 6(b) shows the sugarcane area, and is described by the slope regression line y=0.770x (r^2 = 0.9808) with a confidence of 98.08%., Figure 6(c) shows the corn area. Our study found that the elevation slope factor at the experiment plot significantly effected burning. If the slope elevation of the BA is ≤ 5 percent the slope regression line was y = 0.6566X (r^2 =0.7254), with a confidence of 72.54%, and if the slope of the burned area ranges between 5 to 10 percent the slope regression line y=0.5255X (r^2 = 0.7647), with a confidence of 76.47%. Figure 6(d) shows the forest fire area. If the slope elevation of BA is ≤ 15 percent the regression line is described by y = 0.6401x (r^2= 0.7991), with a confidence of 79.91%. If the line slope elevation of BA is > 15 percent, the regression line is described as y = 0.5275X (r^2=0.8750) with a confidence of 87.50%.

Furthermore, the study found that for the MCD45A1 burned area product, the coefficient of determination follows a positive linear relationship ground observation in this study. For the four types of biomass burning (paddy fields, sugarcane, corn and forest fire), sugarcane has the highest coefficient of determination (r^2 = 0.9808), followed by paddy fields (r^2 =0.9765), corn slope (≤ 5% r^2 = 0.7254; 5-10% r^2 = 0.7647), and forest fire (≤ 15% r^2= 0.7991; >15% r^2 =0.8750). The summary of the results for the adjusted factor of forest fire and agricultural residues burning are shown in Table 6.

Figure 5. Ground observation measurement tracking at the sampled burned area experiment study sites: (a) paddy fields burned area, (b) sugarcane burned area, (c) corn burned area. and (d) forest burned area.

Table 6. The result of Correlation Coefficient between burned area product (MCD45A1) and ground measurements of open biomass burning in Thailand.

Biomass burning Type	Burned area slope correlation faction	Correlation Coefficient between MCD45A1product and ground observation from this study	r^2	Confidence (%)
Rice area	-	0.8677	0.9765	97.65%
Sugarcane area	-	0.7700	0.9808	98.08%
Corn area	Slope ≤ 5%	0.5255	0.7647	76.47%
	Slope 5-10%	0.6566	0.7254	72.54%
Forest fire area	Slope ≤ 15%	0.6401	0.7991	79.91%
	Slope > 15%	0.5275	0.8750	87.50%

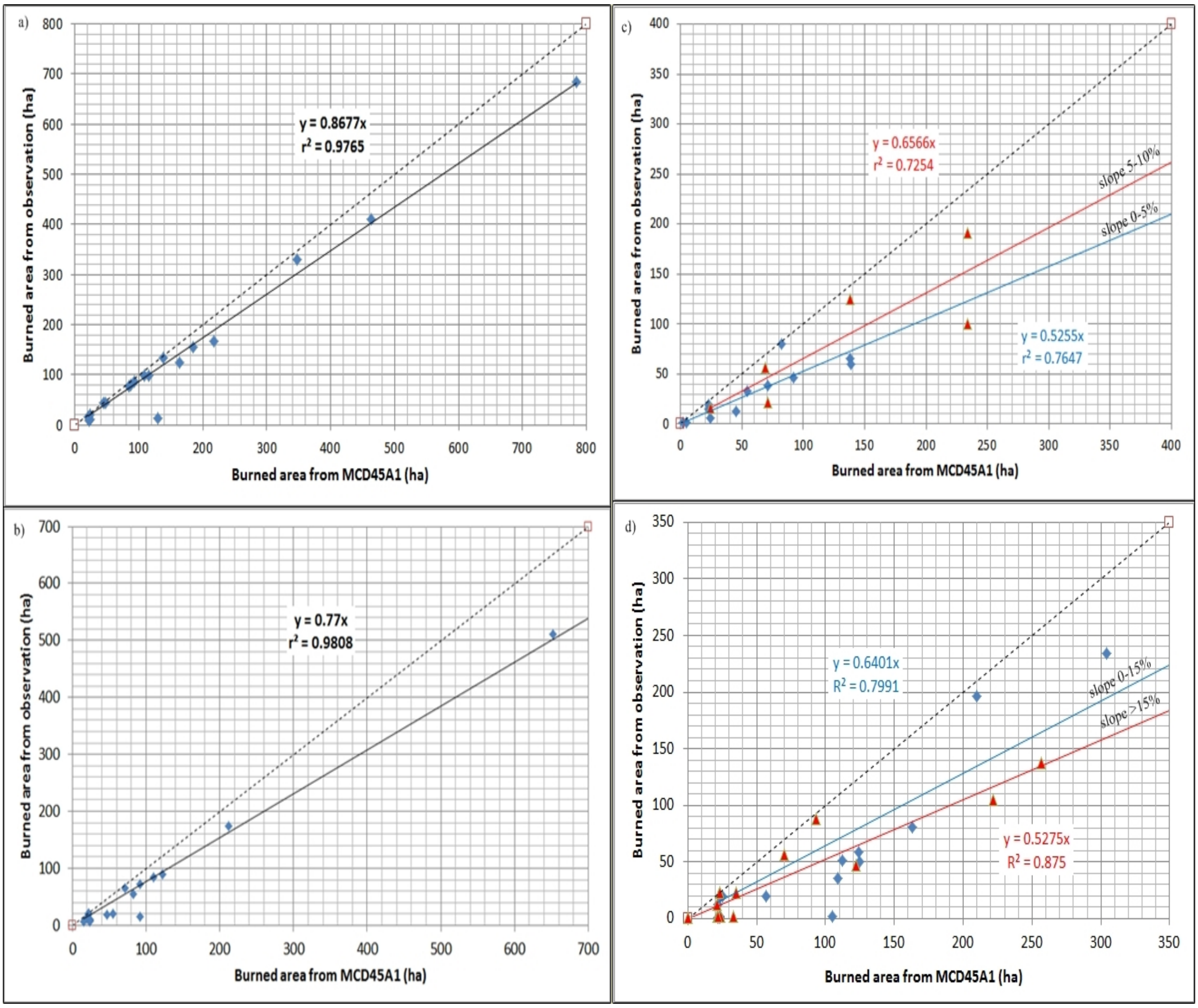

Figure 6. Correlation between ground observation measurement and burned area product for: (a) paddy fields area, (b) sugarcane area, (c) corn area. (The blue (◆) the slope evaluation shown is ≤ 5 percent and the red **(▲)** the slope evaluation ranges between 5 to 10 percent), and (d) forest area. The slope evaluation of the blue (◆) line shown is ≤ 15 percent and the slope evaluation of the red **(▲)** line was > 15 percent.

3.3 Estimation of Open biomass burning Emission

The estimation of emissions from open biomass burning from 2009 to 2011 approximated the amount of CO_2, CO, CH_4, N_2O, and NO_X at about 2,150,077 tons, 163,175 tons, 7,704 tons, 221 tons and 2,841 tons, respectively. Open biomass burning also emitted particulate matter $PM_{2.5}$, PM_{10}, and black carbon (BC) which was estimated at about 10,469 tons, 16,571tons and 1,014 tons, respectively. The trend of change in air pollutant emissions was similar to the trend of change in forest land and crop land fire of each year, as discussed. In year 2011, there was a natural disaster of mega flooding that covered Thailand, and thus forest fires, agricultural residue fires, and their resultant emissions are less than those of years 2009 and 2010. The summary of annual open biomass burning emission in Thailand during 2009 – 2011 is shown in Table 7.

The spatial distribution of emission procedure was generated from a reference grid at 10 km×10 km cell size to present the spatial density of emission estimation of CO during in 2009-2011 from open biomass burning. Thailand is identified as a high burned area density (> 1.0 km^2 per grid) and emitted air pollutan (> 50 tons of CO) emissions are shown in the dark red color grid), while low burned area density (0.01-1.00 km^2 per grid) that emitted air pollutants ranging between 1-50 tons of CO emission is shown in the light color grid is (Figure 7). Moreover, we compared total open biomass burning emissions in 2010 with GEEDv3.1. These estimated emissions were combined

Table 7. Summary of Annual open biomass burning emission in Thailand during 2009 – 2011.

Year	Burned biomass, A (Tons of dry matter)	Open biomass burning emissions, E (tons of trace gases)							
		CO_2	CO	CH_4	N_2O	$PM_{2.5}$	PM_{10}	NO_X	BC
2009	26,539	815,212	62,184	2,854	82	3,886	6,246	1,105	386
2010	15,460	984,890	72,554	3,684	106	4,988	7,484	1,226	457
2011	11,078	349,975	28,437	1,165	33	1,595	2,841	511	171
Total	53,077	2,150,077	163,175	7,704	221	10,469	16,571	2,841	1,014

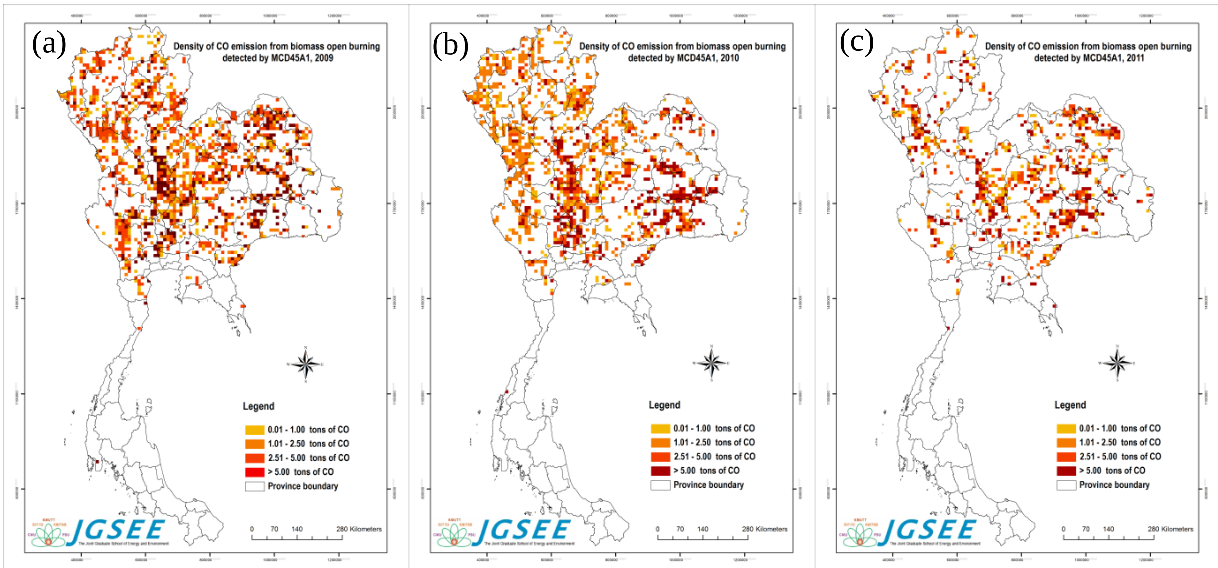

Figure 7. Distribution of CO gridded emissions estimated from open biomass burning for (a) 2009, (b) 2010, and (c) 2011, in Thailand (Grided (tons per 100km^2)).

Table 8. Comparison of the total open biomass burning emission derived from GFEDv3.1 in Thailand to this study in 2010.

	The total of open biomass burning emissions estimation (tons of trace gases) in year 2010					
Emissions	GFEDv3.1	GFEDv3.1	This study	This study	Ratio[a]	Ratio[b]
	Forest	Agricultural	Forest	Agricultural		
CO_2	38,301,000	6,732,000	730,671	330,968	52	20
CO	2,331,000	438,000	48,095	33,086	48	13
CH_4	140,790	40,470	3,145	715	45	57
N_2O	1,500	144	92	19	16	18
$PM_{2.5}$	213,030	38,340	4,208	1,032	51	37
BC	10,023	1,690	319	325	31	5

[a]Ratio is the fraction between forest burning emission derived by GFEDv3.1 and this study
[b]Ratio is the fraction between agriculttal burning emission derived by GFEDv3.1 and this study

with burned area data drivers from MODIS direct broadcast algorithm with a biogeochemical model known as the Global Fire Emissions Database, version 3 (GFED3). GEEDv3.1 is based on mapped MODIS burned area, and is aggregated from the native 500-meter spatial resolution to 0.5 degree and MCD45A1 emission estimated from this study [23-24]. The results of this study were found to be lower than GFEDv3.1 in forest burning with a range of 16 to 52 times, and in agricultural burning with a range of 5 to 57 times. The results are is show in Table 8.

4. Conclusions

In this study, emissions from open biomass burning in Thailand were estimated for three continuous years from 2009 to 2011. The results indicated that the burned area detected in forest areas and agricultural areas was approximately 887,778 ha. The most significant burning occurred in 2010 with a total approximate area of burning of 410,636 ha. The total burned biomass was computed at 26,539 tons dry matter, which included burned forest biomass at 15,460 tons dry matter and burned agricultural biomass at 11,078 tons dry matter. The open biomass burning emissions were computed to be approximately 2,150,077 tons of CO_2, 163,175 tons of CO, 7,704 tons of CH_4, 221 tons of N_2O and 2,841 tons of NO_X. They also emitted about 10,469 tons of $PM_{2.5}$, 16,571 tons of PM_{10} and 1,014 tons of BC. The results of our study found that, the size of burned area to be was the higher than FFCD burned area reported, and lower than the burned area reported by FHS. The biomass burning emissions from this study are lower than the results of GFEDv3.1 for forest burning, with a range of 16 and 52 times and for agricultural burning with a range of 5 and 57 times, for 2010. Using adjustment factors from our study, as derived from from ground validation, arenecessary to reduce the uncertainty of open biomass burning emission estimations in Thailand.

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