

Spatial and Temporal Distribution of Forest Fire PM₁₀ Emission Estimation by Using Remote Sensing Information

Junpen A., Garivait S., Bonnet S., and Pongpullponsak A.

Abstract— This study aims to assess the PM₁₀ emission emitted and the spatial and temporal distribution of PM₁₀ emissions from forest fire during the 2005-2009 periods. The active fire product is known as fire hot spots (FHS) from MODerate-resolution Imaging Spectro-radiometer (MODIS) sensor were used to assess the forest fire areas in Thailand. During this period, Active fires was detected nearly 87,000 FHS with a highest significant in the deciduous forest, corresponding with a damaged forest area of about 78,200 km² and about 92% of it was burned habitually. The effecting of forest fire had resulted in a combusted surface fuel of approximately 22,388,000 tons dry matter and PM₁₀ emission was emitted at 187,331 tons. The obtained results have been used occasionally as reference to develop risk area map of PM₁₀. Risk area map is often use as a reference for many decision-making policies.

Index Terms—Forest fire, Emissions, Remote Sensing, MODIS.

I. INTRODUCTION

Thailand has been experiencing the usual hazy weather which effects on the human health and obscure visibility. It occurs every year as the dry season kicks off and farmers continue to use slash and burn techniques. Fire has been set by villagers who believe that the burning and subsequent ash will stimulate wild mushroom growth [1]. The urban population was severely affected by the particulate matter from forest fire. Measurements from monitoring station in the northern of Thailand show that the PM₁₀ concentrations were ranked between 120-360 µg/m³ which exceed about 2 to 3 times of PM₁₀ standard [2]. The particulate matter is made up of a combination of air pollutants that can compromise human health, harm the environment, and

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even cause property damage. It causes health problem such as asthma, emphysema, chronic bronchitis and other respiratory problems as well as eye irritation and reduced resistance to colds and lung infections.

To control the PM₁₀ concentration under the standard level, we have to know the quantity of the particulate matter emitted and the spatial and temporal distribution of PM₁₀ emission from forest fire. The estimation of PM₁₀ emissions emitted from forest fire depends on 4 main factors, included burned area (*BA*), biomass density or fuel combusted (*BD*), burning efficiency (*BC*), and emission factor (*EF*) [3].

For this study, the MODIS algorithm known as MOD 14 developed by NASA for global detection of fires and suitable for day time detection, when peak fire activity exists to estimate burned area (*BA*) [4]. This study used the version 4.3.2 of MOD 14.

For the other activity data as biomass density (*BD*) and burning efficiency (*BC*), these data are received by taken part within many Forest Fire Control Division National Park Organizations in Chiangmai (The Northern part of Thailand) to do the site survey in the deciduous dipterocarp forest and mixed deciduous forest which has the maximum of forest fire occurred in Thailand [5]. The actual burning experiment had let to know the forest fire behavior in Thailand which was a different from forest fire occurred in the tropical forest in the Southeast Asia such as the type of fuel consumed, the combustion rate, and the combustion efficiency. There lacks of research on emission factor of forest fire, so this study used default value, reported by Andrea and Merlet [6].

This study intended to assess the PM₁₀ emission emitted and the spatial and temporal variation of PM₁₀ emissions from forest fire during the 2005 to 2009 periods. Finally, the result of spatial and temporal distribution of forest fire area was presented in the grid map (size of grid 10 km × 10 km). The result shows the affected areas from the PM₁₀ emissions of forest fire and the forest areas that fire occurred frequently as well as the risk areas. The assessment results have been assisting many decision-making policies and planning and controlling of forest fire management.

II. METHODOLOGY

A. PM₁₀ Emission Estimation

The PM₁₀ emission of forest fire is estimated based on (1).

$$E = A \times EF \quad (1)$$

Where *E* is the PM₁₀ emission (tonns) from fuel combustion, *A* is activity data of biomass burning as burned area and combusted fuel load, *EF* is the emission factor of

PM_{10} (ton/unit of activity data). The activity data (A) depends on three factors; burned area (BA), biomass density (BD), and burning efficiency (BC) as shown in (2).

$$E = BA \times BD \times BC \times EF \quad (2)$$

Where BA (km^2) is size of forest fire area, BD (tonns/ km^2) is the density of fuel load per area, BC (dimensionless) is combustion factor, and EF (g/kg dry matter burned) is emission factor of biomass burning.

B. Burned Area (BA) Estimation

The forest fire area is estimated from the data of the MODIS Active Fire Product (MOD 14). The MODIS has flid onboard the polar orbiting satellites of Terra and Aqua, a part of the NASA Earth Observing System since 2005. The orbit of them overpasses daily on Thailand, 4 times per day. The overpass time is about 5 minutes. The overpass period varies on 1.00 am to 2.00 am, and 10.00 am to 11.30 am, 1.00 pm to 2.30 pm, and 10.00 pm to 11.00 pm [7]. These studies used 2 sources of FHS data included Georeference position from Information for resource management system, University of Maryland during 2005 to 2006 and Geoinformatics center, Asia institute of technology during 2007 to 2009 [7].

The type of FHS was classified by using Geographic Information System (GIS) program. The type of fire included agricultural fire, forest fire, and other fire. The FHS was categorized by overlay between the FHS data and land use map in 2007 which was developed by Land Development Department, Thailand [8]. The resolution 1 km \times 1 km of pixel was used as a representative of one spot of burned area. The combustion efficiency of burned area in pixel, which is a measure of how efficiently a device consumes fuel, was about 0.9 [9].

Finally, the results of spatial and temporal distribution of forest fire area were presented in the grid map (size of grid 10 km \times 10 km) which covered the period of 2005 to 2009.

C. Biomass Density (BD) Estimation

The surface fuel load in the dipterocarp forest and the mixed deciduous forest were collected during 2009. This study focuses only on surface fuel because the forest fire in Thailand is surface fire that specifically combusted fuel on surface area of forest [10].

There are 2 types of surface fuel, classified by size; fine fuel and coarse fuel. Fine fuel included dead leaf and grass. Course fuel included twig and undergrowth [10]. The experimental size is 1 m \times 1 m, 60 sample plots per month.

The data shows the density of surface fuel classified by fuel component.

D. Burning Efficiency (BC) Estimation

The burning experiment was set in the mix deciduous and deciduous dipterocarp forests. The difference between the density of fuel load before burning and after burning was calculated by (3). The results represent the ratio of actual fuel load combusted by forest fire.

$$BC = (M_{BB} - M_{AB}) / M_{BB} \quad (3)$$

Where BC is burning efficiency of surface fuel, M_{BB} (g/m^2) is mass of dried surface fuel before burning, and M_{AB} (g/m^2) is mass of dried surface fuel left after burning.

The experimental result is combustion factor. Moreover, it can be used to study behavior of forest fire. It is used to estimate the combustion rate of forest fire in term of burned area per time.

For experiment, this study sets an experiment line in the forest area, as shown in Fig 1. There are 8 lines. Each line has 30 m length and 45° between lines equally. The experiment is plotted in 4 area slopes as 0-14%, 15-24%, 25-35%, and >35% by testing in 2 forest types as the mix deciduous forest and the deciduous dipterocarp forest. The experiment is done every month between January and May in 2009. So, the overall sample is about 40 plots.

After set the sample plot, the 8 random plots, plot size 1 m \times 1 m, around the experimental area is collected and weighted. The component of surface fuel is dead leaf, grass, twig, and undergrowth. The result shows in term of dry matter of fuel load per area classified by size of fuel; fine fuel (dead leaf and grass) and coarse fuel (twig and undergrowth).

Further experiment, start to fire at the center of the circle line and records the distance of fire in each line for every 2 minutes until once of line is burned to 30 m and stops the experiment. In this trail, data collections include: surface fuel weight after burning, combustion time, and burned area.

After burning process, the mass of unburned fuel in 8 plots, 1 m \times 1 m is measured, then estimate the combustion factor from the relationship between before and after burned of surface fuel as shown in (3).

E. Emission Factor (EF)

The emission factor (EF) for tropical forest was reported by Andrea and Merlet (2001). In this study, EF was nearly 11.3 g/kg of dry matter burned.

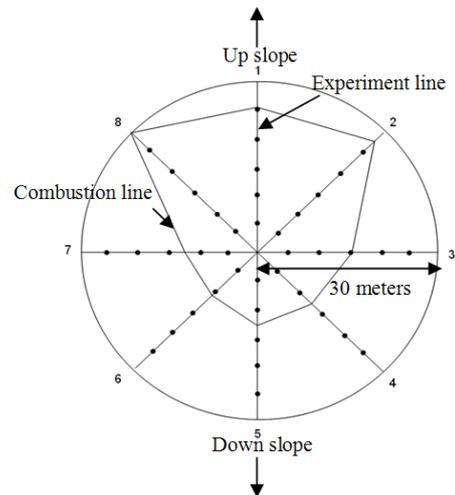


Figure 1. 1 The experimental plot

III. RESULTS AND DISCUSSION

A. Burned Area (BA) Assessment

From the satellite data during 2005 to 2009, the active fire was found about 86,877 FHS which damaged forest area was about 78,189 km^2 . The maximum of active fire occurred

in 2007 which was about 22,924 FHS or forest fire area 20,632 km² (Table 1).

TABLE I. THE NUMBER OF ACTIVE FIRE AND FOREST FIRE AREA

Year	Number of Active Fire (FHS)	Burned Area (km ²)
2005	16,657	14,991
2006	16,909	15,218
2007	22,924	20,632
2008	14,621	13,159
2009	15,766	14,189
Total	86,877	78,189

Considering on the temporal distribution of forest fire (Fig.2), it was found annually the peak period of forest fire was between January and April which maximum in March. This period is the dry season in Thailand. The surface fuel is rather dry. It is easily combusted.

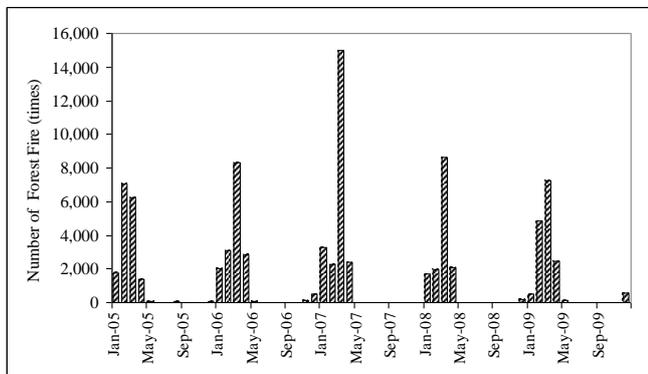


Figure 2. The temporal distribution of forest fire, 2005-2009.

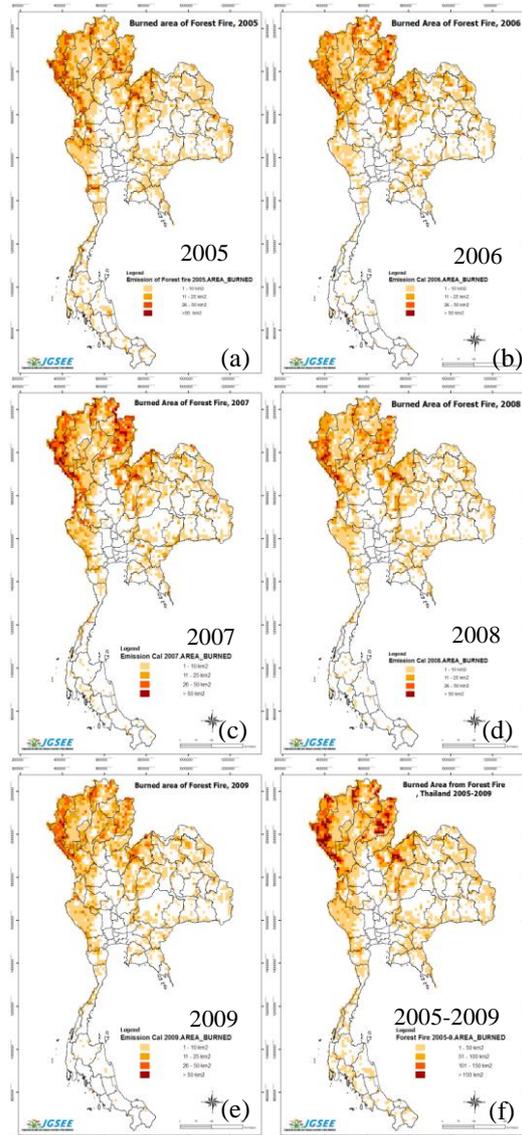
Taking into consideration on the spatial distribution of forest fire area between 2005 and 2009 (Fig.3), it was found the high density of forest fire area (burned area ≥ 26 km² per grid as shown in the dark grid) occurred in the mixed deciduous forest and the deciduous dipterocarp forest especially in the Western, the Upper-Northern, and the Upper-Northeastern part of Thailand. For the general density of forest fire area (burned area ≤ 25 km² per grid as shown in the light grid), it occurred in the evergreen forest, the mixed deciduous forest, the deciduous dipterocarp forest and the pine forest which were near the forest fire control center. The fire-starting were controlled immediately by fire control officer.

The accumulation forest fire area during 2005 to 2009, it was found the high density of forest fire area (burned area ≥ 100 km² per grid) was about 34% of the actual forest fire map. We had found that the high density emerged in the mix deciduous forest and deciduous dipterocarp forest at The Upper-Northern, the Western, and the Upper-Northeastern of Thailand.

B. Biomass Density (BD) Assessment

The 4 components of fuel load are collected monthly in 2009. From the data analysis on the temporal variation of 4 components of fuel load, it was found the fuel load has increased in the forest fire season (January-May) especially fine fuel as dead leaf because of the leave is shredded from the tree. In the rainy season, grass and undergrowth has a

high growth rate. The temporal variation of fuel load is shown in the Fig 4.



Legend of (a) to (e) 1-10 km²/grid, 11-25 km²/grid, 26-50 km²/grid, > 50 km²/grid
 Legend of (f): 1-50 km²/grid, 51-100 km²/grid, 101-150 km²/grid, > 150

Figure 3. The spatial distribution of forest fire area, 2005-2009.

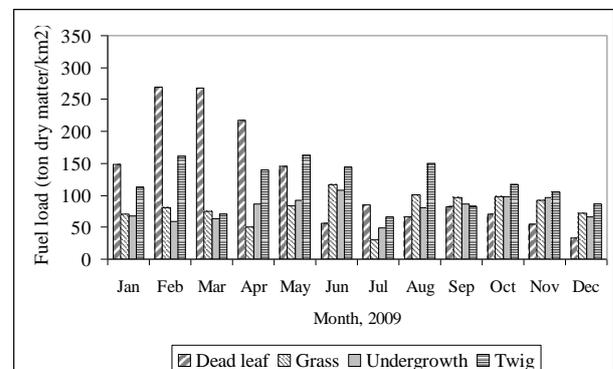


Figure 4. The temporal distribution of biomass density classified by fuel component

This study estimates the forest fire emission through the amount of fuel load in the forest fire season (January-May).

The amount of fuel load at surface area in the mixed deciduous forest is about 364.5 tonnes dry matter/km², which included 214.4 tonnes dry matter/km² of fine fuel and 150.2 tonnes dry matter/km² of coarse fuel. For the deciduous dipterocarp forest, the fuel load is about 371.4 tonnes dry matter/km², which included 218.3 tonnes dry matter/km² of fine fuel and 153.1 tonnes dry matter/km² of coarse fuel. The fuel load and standard deviation is used to estimate the emission (Table 2).

TABLE II. BIOMASS DENSITY FROM FIELD SURVEY, 2009

Forest type	Biomass Density (tonnes dry matter / km ²)		
	Fine fuel	Coarse fuel	Total fuel
Mixed deciduous forest	214.4	150.2	364.5
	SD = 57.5	SD = 45.5	SD = 68.5
Deciduous dipterocarp forest	218.3	153.1	371.4
	SD = 55.4	SD = 43.3	SD = 65.6

C. Burning Efficiency (BC) Assessment

From the simulation of real fire in the forest area found the fine fuel as dead leaf and grass is burned more than coarse fuel. In the mixed deciduous forest and the deciduous dipterocarp forest, the average of fuel burned is about 0.78. The fine fuel is burned about 0.98 and the coarse fuel is burned 0.49. The value and standard deviation of burning efficiency used for forest fire emission estimation is shown in table 3.

TABLE III. BURNING EFFICIENCY FROM BURNING EXPERIMENT, 2009

Forest type	Burning efficiency		
	Fine fuel	Coarse fuel	Average
Mixed deciduous forest	0.98	0.49	0.78
	SD = 0.16	SD = 0.22	SD = 0.13
Deciduous dipterocarp forest	0.98	0.49	0.78
	SD = 0.07	SD = 0.26	SD = 0.16

Considering on monthly burning efficiency in both forest types found dead leaf and grass has been completely burned since February. Twig, the dried fuel is unstable burned that the burning rate depends on the amount of twig in the area in each month. Undergrowth, the highest of moisture content, has burned increasing when the weather is drier. The result is shown in Fig.5.

For the combustion rate of forest fire found the mixed deciduous forest (MDF) and the deciduous dipterocarp forest (DDF) has the highest of combustion rate in March which is about 10.1×10^3 m²/hr and 11.5×10^3 m²/hr, respectively, followed by April about 5.8×10^3 m²/hr and 8.7×10^3 m²/hr respectively. The result of combustion rate represented the spread of forest fire is very useful for firefighter to set the firebreaks for reducing the ultimate area size of forest fire. The combustion rate of forest fire is shown in table 4.

D. PM₁₀ Emission Assessment

Forest fire during 2005-2009, the fuel load combusted was about 22,388,060 tonnes dry matter which included 16,577,930 tonnes dry matter of fine fuel and 5,810,130 tonnes dry matter of coarse fuel (Table 5). The PM₁₀ was emitted approximately 187,331 tonnes (Table 6).

For the yearly temporal variation of PM₁₀, it was found the trend of PM₁₀ between 2005 and 2009 was unstable. The PM₁₀ was increased during 2005-2007, and then dropped down during 2008-2009.

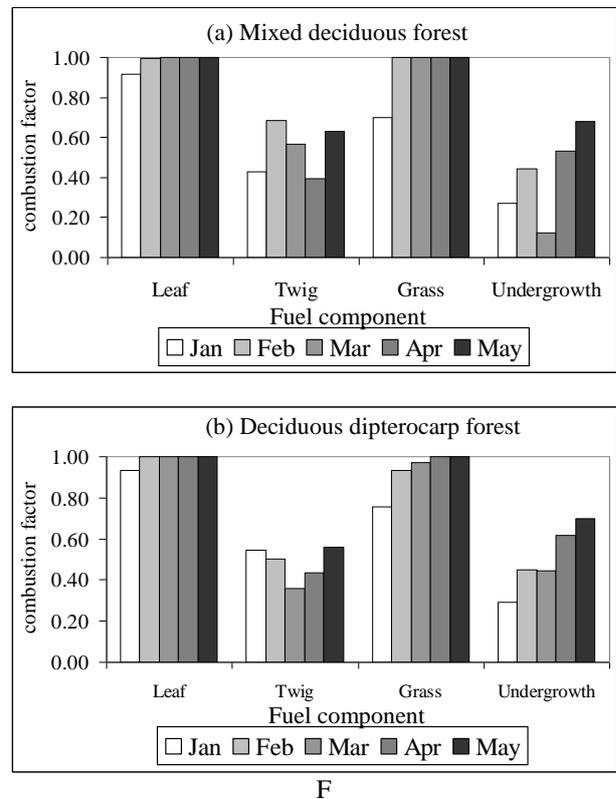


Figure 5. The temporal distribution of biomass efficiency classified by fuel component

TABLE IV. FUEL LOAD COMBUSTED FROM FOREST FIRE, 2005-2009

Year	Fuel Load Combusted (tonnes dry matter)		
	Fine Fuel	Coarse Fuel	Total
2005	3,178,500	1,113,981	4,292,481
2006	3,226,587	1,130,834	4,357,421
2007	4,374,374	1,533,103	5,907,477
2008	2,789,989	977,818	3,767,808
2009	3,008,479	1,054,393	4,062,872
Total	16,577,930	5,810,130	22,388,060

TABLE V. COMBUSTION FACTOR ESTIMATION

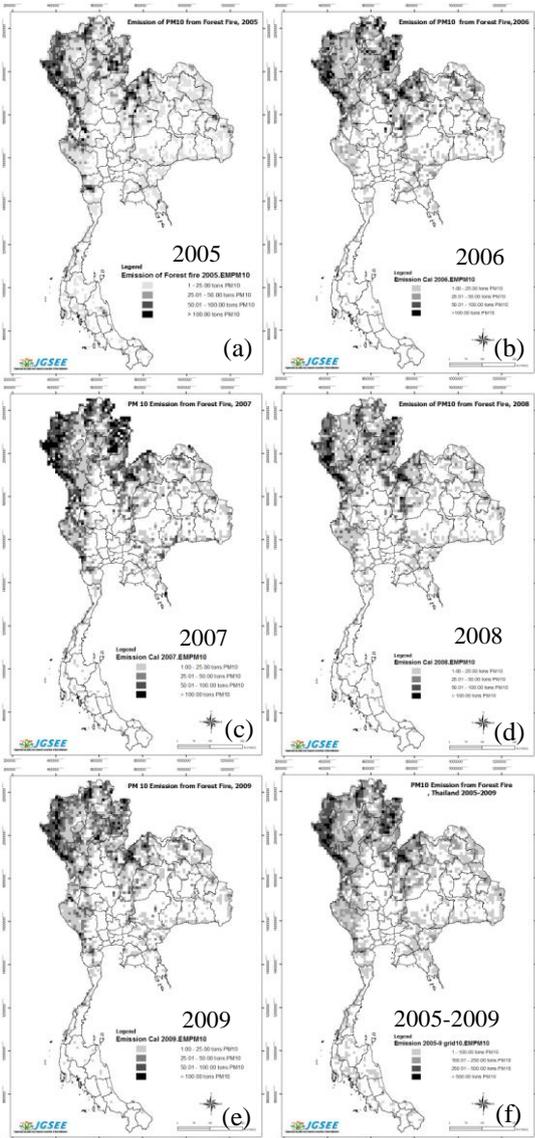
Year	PM ₁₀ Emission from Forest Fire (tonns)
2005	35,917
2006	36,460
2007	49,430
2008	31,527
2009	33,996
Total	187,331

In view of the spatial distribution of PM₁₀ (Fig.6), It was found that the higher PM₁₀ occurred in the higher of damaged forest fire area. In the high density of forest fire area (> 26 km² per grid) emitted more than 50 tonnes of PM₁₀ (as shown in the dark grid). In the low density of forest fire area (≤ 25 km² per grid) emitted 1-50 tonnes of PM₁₀. In case of observation, the

density of grid PM₁₀ was varied every year because of the difference of cumulative of fuel.

The accumulation PM₁₀ emission emitted during 2005 to 2009, the high density of PM₁₀ emission emitted (more than 250 tonnes per grid) was about 34% of the actual emission map. It was nearly occurred around the settlement in the upper Northern, the Western, and the upper North-eastern. The result shows the risk of city area which is near the high density PM₁₀ emissions emitted has occurred a high PM₁₀ concentrations.

Moreover, it was found 68% of forest fire was occurred five times in the same area, followed by 15% of forest fire was occurred four times in the same area (Fig.7). The result showed the occurrence of forest fires were repetitiously committed arson by human.



Legend of (a) to (e):
 1-25 tons/grid, 25.1-50 tons/grid
 50.01-100 tons/grid, > 100 tons/grid
 Legend of (f):
 1-100 tons/grid, 100.1-250 tons/grid

Figure 6. The spatial distribution of PM₁₀ emission, 2005-2009.

TABLE VI. COMBUSTION RATE OF FOREST FIRE, 2009

Forest type	Area slope	Combustion rate of forest fire (10 ³ x m ² /hr)				
		Jan	Feb	Mar	Apr	May
MDF	0-14%	0.9	1.4	6.8	1.8	0.9
	15-24%	1.3	2.9	6.9	3.1	2.5
	25-35%	2.7	4.9	10.6	5.9	4.3
	>35%	3.4	10.3	15.9	12.3	5.6
	Average	2.1	4.9	10.1	5.8	3.3
DDF	0-14%	1.4	5.4	7.8	6.6	3.2
	15-24%	3.3	5.5	9.3	5.0	4.6
	25-35%	4.6	6.9	11.2	11.0	6.5
	>35%	7.9	15.2	17.7	12.3	7.7
	Average	4.3	8.3	11.5	8.7	5.5
Grand average		3.2	6.6	10.8	7.2	4.4

TABLE VII. FUEL LOAD COMBUSTED FROM FOREST FIRE, 2005-2009

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	Fine Fuel	Coarse Fuel	Total
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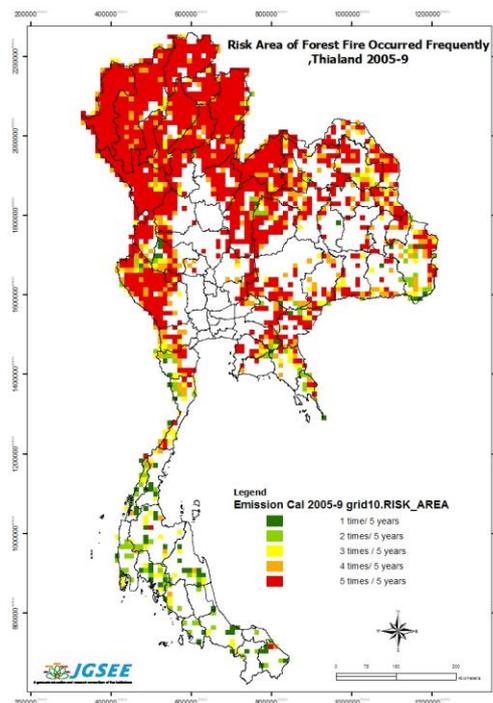


Figure 7. Frequency of Forest Fire Between 2005-2009

IV. CONCLUSION

This study demonstrates the satellite data is an essential tool for emission estimation of forest fire. MODIS sensor is suitable for monitoring on emission in national scale, because it enables to give efficient continuous data. It is also used to assess the spatial and temporal distribution of forest fire. Moreover, the simulation of forest fire contributes to understanding the tropical forest fire behavior for each region. The result will provide the more accuracy of forest fire emission estimation.

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