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Bottom up Approach to Estimate Air Pollution of Rice Residue Open Burning in Thailand

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Abstract: Rice residue open burning is a farmer activity potentially contributes to global warming. This study was conducted with the objective of examining the spatial and temporal distribution of emissions from rice residue open burning in Thailand by using questionnaire survey and field experimentation. A sample of 1000 Thai farmers was interviewed in order to study the fire behaviours of farmers. One hundred and twenty rice sampling plots were selected for measuring rice residue characteristics. Of the farmer's fire behaviour, 45% of farmer regularly uses prescribed burning technique for land preparation activities. The amount of rice residue was approximately 117.7 Mt. Although nearly 60% of total residue was subjected to burning in the fields, only 15% of rice residue is actually burned in the fields because the residue and soil have high moisture content. The burning emissions are computed at 1.67 Mt of CO, 0.04 Mt of NO_x, 0.35 Mt of $PM_{2.5}$, 0.12 Mt of PM_{10}, and 0.01 Mt of BC. Approximately 30%, 26%, and 17% of all emissions are contributed by the lower-northern, central, and western regions of Thailand, respectively. Moreover, 31% and 30% of all emissions are annually emitted from December to January and April to May over one month periods following each harvesting season. The comparisons of rice residue burning emissions provided by this study and previous studies have found the emissions discovered in this study to range from one to five times higher than the finding of previous studies. This finding demonstrates the importance of the assessment of activity data specific to farming fire characteristics.

Key words: Emissions, greenhouse gas, biomass open burning, prescribed burning, questionnaire survey

1. Introduction

Biomass open burning is the burning of living or dead vegetation in the open air (Koppmann *et al*., 2005) which is a source of greenhouse gases, such as carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrous oxide (N_2O), and nitrogen oxide (NO_x). Furthermore, biomass open burning contributes pollutants to the atmosphere, including aerosols and hydrocarbons (Lemieux *et al*., 2004; Duan *et al*., 2004) due to the incomplete combustion process (IPCC, 2006) which contributes to global warming of the atmosphere (Crutzen *et al*., 1979). Biomass open burning is also the cause of lost nutrients and organic matter (Bossio *et al*., 1999; Jiaranaikul, 2004; Chandiramani *et al*., 2007).

Rice residue open burning is a part of biomass burning. It is a common method that is widely used in Thailand to remove residue, control weeds, and release nutrients for the next crop cycle (Jiaranaikul, 2004; Garivait *et al*., 2005; Gadde *et al*., 2009). This activity occurs annually because it saves time and cuts costs (GuoLiang *et al*., 2008; Suramaythangkoor and Gheewala, 2008; Yang *et al*., 2008; Gadde *et al*., 2009).

In Thailand, the burning of rice residue is a cause of trans-boundary emissions, impacts on ambient air quality and human health. Under the ASEAN agreement on trans-boundary haze, Thailand has set an agricultural residue open burning emission mitigation master plan. In this master plan, incorporation is promoted as an alternative management method to open burning (PCD, 2005).

A thorough examination of burning behaviour and the open burning situation will be useful in bringing about effective implementation of the agricultural emission control plan. This study is aimed at to quantifying the amount of air pollution from the open burning of rice residue through the study of rice cultivation behaviour and rice residue burning based on a bottom up approach by using a questionnaire survey and ground observation.

2. Material and method

a. Emission estimation

The amount of emission of a species, 'x', from the rice residues open burning used in this study was the product between the amount of burned rice residue as called activity data and emission factor (Crutzen *et al*., 1979) as shown in the Eq. (1). The activity data was assessed in terms of the burned area, biomass density and burning efficiency as seen in Eq. (2).

$$E_x = A \times EF_x \tag{1}$$

$$A = BA \times BD \times BE \tag{2}$$

Where: x is the emission type; E (g) is the amount of emission

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for each type; A (kg) is the activity data, EF (g kg^{-1}) is the emission factor; BA (km^2) is the burned area; BD (kg m^{-2}) is the biomass per surface unit; and BE (dimensionless) is the burning efficiency.

According to Eqs. (1)-(2), there are four related factors; *EF*, *BA*, *BD* and *BE*. The first factor was obtained from the literature review and the last three factors were obtained from the questionnaire survey (direct interviews).

EF depends on the fuel moisture content, burning characteristics (spread or pile), combustion efficiency, and weather conditions (Oanh *et al*., 2011). To quantify the *EF* that is the most specific for rice residues open burning in Thailand, this first priority screening is the fuel type (agricultural or rice residues), followed by burning area (Thailand), burning conditions (open or close burning), burning characteristics (spread or pile), data representation, and current data respectively. According to the literature review on *EF* for agricultural open burning, there are a few studies in which the value of *EF* is summarized as shown in Table 1.

According to Table 1, there were only two studies that developed *EF*s for rice residue burning in Thailand, i.e. the studies of Kanokkanjana and Garivait (2010) and Oanh *et al*. (2011). Kanokkanjana and Garivait (2010) developed the average of *EF* from field burning experiments in four provinces with varied patterns in cultivation, including major and minor rice in rain-fed and irrigated fields during 2007 to 2010, Thailand. Oanh *et al*. (2011) developed the average of *EF* from field burning experiments in Pathumthani Province during the major rice burning seasons between 2003 and 2006. The study of Kanokkanjana and Garivait (2010) offer more representative information. The selected *EF*s are detailed in Table 1.

b. Questionnaire survey design

The questionnaire survey was conducted with the objective to studying farming behaviour on rice cultivation practices, rice residue management and the characteristic of rice residue and area burning. The survey questions related to this study are shown in Table 2.

The questionnaires were collected during the rice planting season from 2008 to 2009 in the following 20 provinces (Fig. 1): 2 provinces in the upper northern region: Lampang and Chiengmai; 3 provinces in the lower northern region: Nakornsawan, Petchchabun, and Pitchsanulok; 3 provinces in the upper northeastern region: Khnongkai, Mahasarakam, and Konkaen; 3 provinces in the lower northeastern region: Surin, Buriram, and Nakornratchasrima; 1 province in the central region: Chainat; 3 provinces in the western region: Petchburi, Ratchaburi,

Table 1. Value of emission factors in each trace gas.

Trace gases	Emission Factor, EF_x (g of trace gases kg^{-1} dry matter burned)	Remark
CO_2	1460.00[a], 1515.00[b], **1185.00**[c], and 1147.00[d]	This study uses 1185 g CO_2 kg^{-1} dm which is more currently specific for rice residue and burned area of Thailand.
CO	26.00[a], 92.00[b], **133.20**[c], and 97.00[d]	This study uses 133.20 g CO kg^{-1} dm which is more currently specific for rice residue and burned area of Thailand.
CH_4	**2.70**[b]	This *EF* is for agricultural burning. No data available for rice residue burning in Thailand. This study uses 2.70 g CH_4 kg^{-1} dm reported by Andrea and Merlet (2001).
N_2O	**0.07**[b]	This *EF* is for agricultural burning. No data available for rice residue burning in Thailand. This study uses 0.07 g N_2O kg^{-1} dm reported by Andrea and Merlet (2001).
NO_x	**3.10**[a], 2.50[b]	This study uses 3.1 g NO_x kg^{-1} dm which is more currently specific for rice residue and burned area of Thailand.
$PM_{2.5}$	2.70[a], 3.90[b], **27.63**[c], 8.3[d], and 12.95[e]	This study uses 27.63 g$PM_{2.5}$ kg^{-1} dm which is more currently specific for rice residue and burned area of Thailand.
PM_{10}	2.86[a], **13.00**[b], and 9.4[d]	This study uses 9.4 gPM_{10} kg^{-1} dm which is more currently specific for rice residue and burned area of Thailand.
BC	**0.69**[b]	This *EF* is for agricultural burning. No data available for rice residue burning in Thailand. This study uses 0.69 g BC kg^{-1} dm reported by Andrea and Merlet (2001).

Sources:
[a]Jenkis and Bharnagar (1991) determined an average value of *EF* as CO_2, CO, NO_x, $PM_{2.5}$, PM_{10}, and etc. for rice residue with 8.4-10.8% moisture content by wind tunnel simulation (spreading and pile fires). Other 7 types of fuel (barley, wheat, corn, almond, walnut, Douglas fir, and Ponderosa pine) were reported in this study. Kadam *et al*. (2000) had mentioned this study to estimate rice straw burning emission in California.
[b]Andrea and Merlet (2001) reported the value of *EF* as CO_2, CH_4, N_2O, NO_x, $PM_{2.5}$, PM_{10}, BC, and etc. for agricultural open burning by extrapolation from the best value.
[c]Kanokkanjana and Garivait, (2010) developed the value of *EF* of CO_2, CO, and $PM_{2.5}$ for rice residue with 4.71 ± 0.82% moisture content by field experiment during 2007 to 2010 in Ratchaburi, Nakhonsawan, Samutsakhon, and Petchaburi provinces, Thailand.
[d]Oanh *et al*. (2011) proposed the value of *EF* of CO, CO_2, and PM for rice straw with 26 ± 5% average moisture content using site experiments during 2003 to 2006 in Pathumthani province, Thailand.
[e]Hays *et al*. (2005) proposed the value of *EF* of $PM_{2.5}$ for rice residues with 8.6% moisture content by simulated agricultural fires.

Table 2. Part of the questions in the questionnaire survey used in this study.

1. What is the size of your paddy field?
2. How many times do you usually plant rice in your area per year?
3. What is the rice variety that you planted?
4. What is your cultivated method?
5. What is your harvest method?
6. Do you use the rice stubble for any purpose? If yes, how much does it used?
7. Do you use the rice straw for any purpose? If yes, how much does it used?
8. Do you burn your paddy field? If yes, do you control your fire?
9. What is the purpose of the burning? When and how much does it burned
10. How much of the rice residue combusted by fire (1-25%, 26-50%, 51-75%, 76-100%)?
11. How much of the area combusted by fire (1-25%, 26-50%, 51-75%, 76-100%)?

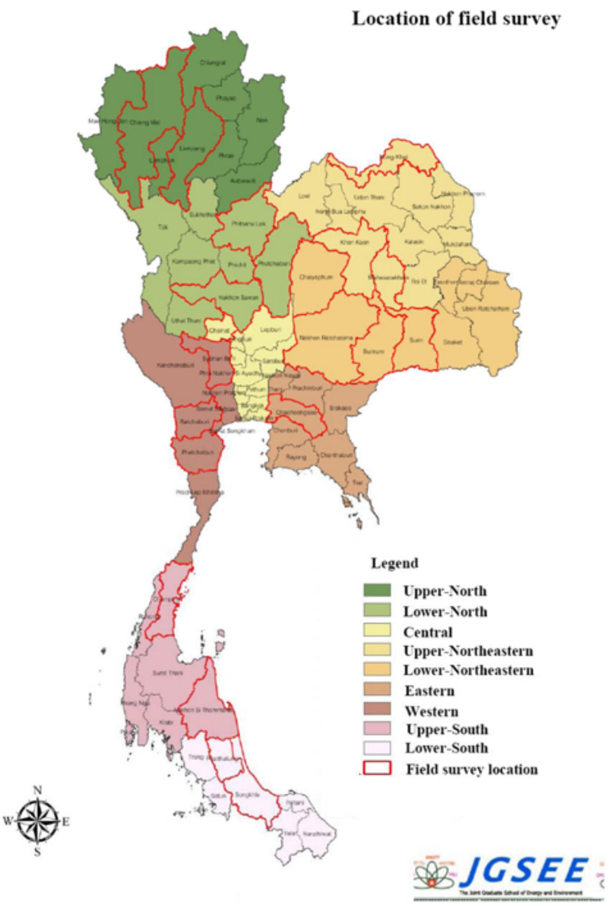

Fig. 1. Questionnaire survey location based on the FHS detected on paddy field interpretation.

and Suphanburi; 1 province in the eastern region: Chachoengsao, 2 provinces in the upper southern region: Chumporn and Nakornsrithammarat; and 2 provinces in the lower southern region: Pattalung and Songkla. The sampling provinces varied in terms of the intensity of farmers using the prescribed burning technique which was considered in terms of the density of fire hot spot (FHS) detected on the paddy fields for each province (Garivait *et al*., 2005). This study combined the FHS at 70% confidence detected by a Moderate-resolution imaging spectroradiometer (MODIS) sensor aboard the Terra and Aqua satellites (Giglio *et al*., 2003) and a land use map in 2007 (LDD, 2011).

The population comprised farmers in 20 provinces for a total of approximately 1530000 farmers (OAE, 2010). The sample size of the farmers was calculated based on the rank set sampling method at 10% proportional error and 90% confidence level. The rank set sampling is a statistical technique which is a two-phase sampling process that reduces the number of sample requirements. According to the calculation, the sampling of farmers came to approximately 1000 farmers.

The results from the questionnaire survey were estimated for the population, population mean, variance, and standard deviation by using Eqs. (3)-(6), respectively as follows:

$$X = \bar{X}_{rss}N \tag{3}$$

$$\bar{X}_{rss} = \frac{1}{n}\sum_{i=1}^{n} X_{(i:n)} \tag{4}$$

$$Var(\bar{X}_{rss}) = \frac{1}{n^2}\sum_{i=1}^{n} \sigma^2_{(i:n)} \tag{5}$$

$$SD(\bar{X}_{rss}) = \sqrt{Var(\bar{X}_{rss})} \tag{6}$$

Where: X is the population; N is the number of the population; $\bar{X}_{rss}$ is the population mean; X is the random sample, n is the sample size; i is the order static from the sample size n ($i = 1,2, \ldots, n$); $Var(\bar{X}_{rss})$ is the variance of the population; $\sigma^2_{(i:n)}$ is the variance of the sample and $SD(\bar{X}_{rss})$ is the standard deviation of the population.

c. Ground observation design

The ground observation was conducted with the objective of studying the characteristics of rice residue after the harvesting process and assessing the density of rice residue in each area. In fact, the generated rice residue is composted of stubble and straw. Rice stubble and rice straw are the part of the rice stalks separated by harvest. The density of the stubble and straw depends on the rice variety, cultivation method, and harvesting method used for each field. In order words, rice varieties differ in height (from less than a meter for minor rice varieties to over than a meter for major rice varieties); amount of seed varies with planting methods (seed is applied at approximately 9.4-1.5 tons km^{-2} for broadcast and 2.5-4.4 tons km^{-2} for transplanted planting (RTM, 2010)). The cutting level varies with harvest method, i.e. the cutting level (measuring above ground level) of machinery harvests (30 cm) is lower than manual harvest (90 cm). The amounts of stubble and straw are strongly affected by cutting height (Kadam *et al.*, 2000; Summer *et al.*, 2003). Cutting rice stalks at ground level gives maximum straw. To obtain an accurate rice residue density assessment, the measurement should be made randomly in the field covering all factors influencing rice residue density. Therefore, a total of 120 plots were measured for density, including 30 plots of transplanted-major rice fields, 30 plots of broadcast-major rice fields, 30 plots of transplanted-minor rice fields, and 30 plots of broadcast-minor rice fields. Thirty samples are the minimum sample number acceptable for statistical methods. The processes of rice density measurement were carried out as follows:

(1) Sampling collection: The rice in the sample plots sized 1 m^2 was harvested at ground level. Then grain and stem were separated and measured for weight of grain and stem.

(2) Weighing rice botanical weight: A clump of rice was selected from each sample plot and measured for net weight. A part of the grain was separated from the stem. The stems were then divided into 10 cm sections, and each section was weighed.

(3) Dried weight estimation: The moisture content of the stems was determined by oven heating at 105°C Celsius for 24 hours (in accordance with the ASAE standard 358-1); after oven, the stems were weighed for dried weight.

(4) Rice residue density assessment: The dried weight of stems was interpolated to the density of the residue based on the weight of rice in the unit area (result from Step 1).

The data from the measurement was used to develop the rice residue determination model which was applied to assess the spatial distribution of stubble and straw. The data in Step 4 were used to analyzed and obtain the mean value and the relationship between the density of the residue at each level. Then the stem level was analyzed by using curve estimation regression.

d. Activity data calculation

(1) Burned area (*BA*)

The burned paddy area was estimated from the production between the harvested area and the fraction of the burned area as shown in Eq. (7).

$$BA = HA \times \%BA \quad (7)$$

Where: *HA* (km^2) is the harvested area; and *% BA* (percentage) is the percentage of burned area per harvested area.

The value of the harvested area (as shown in Table 3) was obtained from the report of the OAE (2010) which reports the amount of paddy fields and harvested fields annually. The percentage of the burned area was obtained from the questionnaire survey data.

(2) Biomass per surface unit (*BD*)

The biomass per surface unit is the amount of unused stubble and straw left in the fields and was estimated from the production between the amount of stubble and straw in the unit area and the fraction of unused residue as shown in Eq. (8).

Table 3. Rice harvesting area by region.

Region	Harvested area, *HA* (10^3 km^2)
Lower Northern	19.29
Upper Northern	7.12
Lower Northeastern	26.87
Upper Northeastern	24.88
Western	7.88
Central	12.42
Eastern	5.63
Lower Southern	2.18
Upper Southern	1.23
Total	107.48

Source: OAE (2010)

$$BD = BD_{Ti} \times (1 - U) \quad (8)$$

Where: *BD* (kg m^{-2}) is the amount of unused rice residue per surface unit; BD_T (kg m^{-2}) is the amount of generated rice residue per surface unit; *U* (dimensionless) is the fraction of utilized rice residue per generated rice residue; and *i* is type of residue (stubble/straw).

The density of the generated rice residue was obtained from ground observation. The fraction of utilized rice residue per generated rice residue was obtained from the questionnaire survey data.

(3) Burning efficiency (*BE*)

The burning efficiency (*BE*) is the proportion of the rice field residue and the area consumed by fire. This study used the *BE* of the actual farmer's fire with some difficulty in obtaining this value with a consistent value for each field because this value depends on moisture content, soil humidity, and burning behaviour (controlled or uncontrolled fires by farmers). To obtain a consistent value, this study classified the fraction of burned rice residue and area into 4 groups as shown in Figs. 2 and 3 respectively: 1) minimally burning (1-25%) 2) nearly half burned (26-50%) 3) more than a half burned (51-75%) and 4) nearly all burned (76-100%).

3. Results and discussions

a. Questionnaire survey analysis

Rice cultivation in Thailand can be classified by season into two types: major rice, which is cultivated in the rainy season and minor rice, which is cultivated in the dry season. According to the questionnaire survey data, the following conclusion can be drawn:

(1) Rice cultivation practice

The information related to rice cultivation practice in Thailand is summarized as shown in Table 4 with the following con-

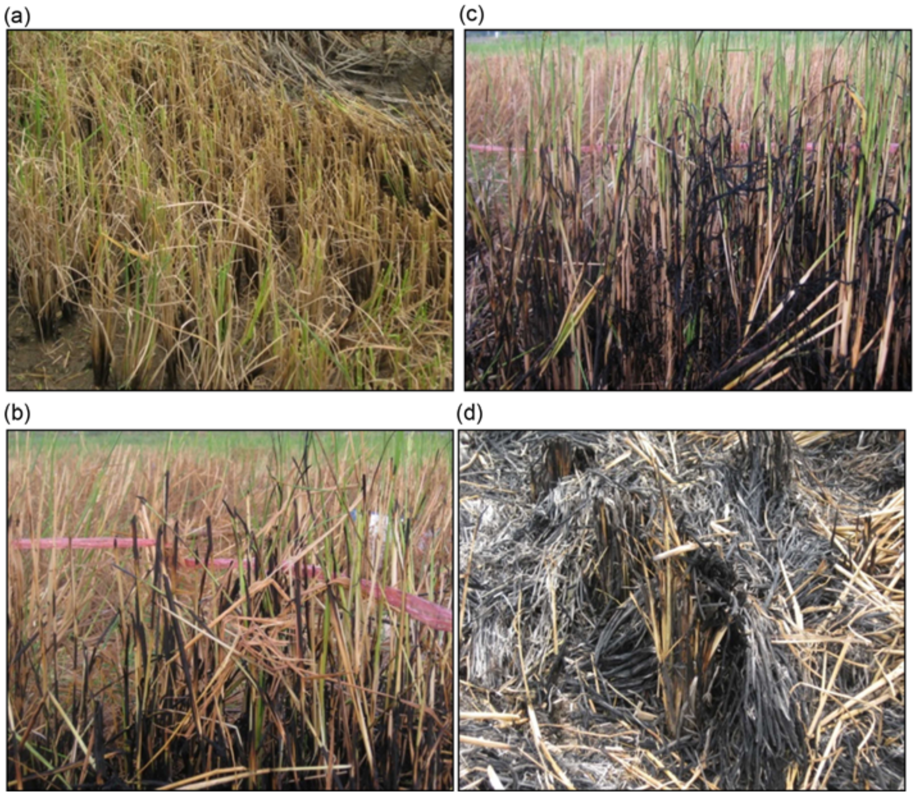

Fig. 2. 4-categories of rice residues characteristic after burning for (a) 1-25% residue combustion, (b) 26-50% residue combustion, (c) 51-75% residue combustion, and (d) 76-100% residue combustion.

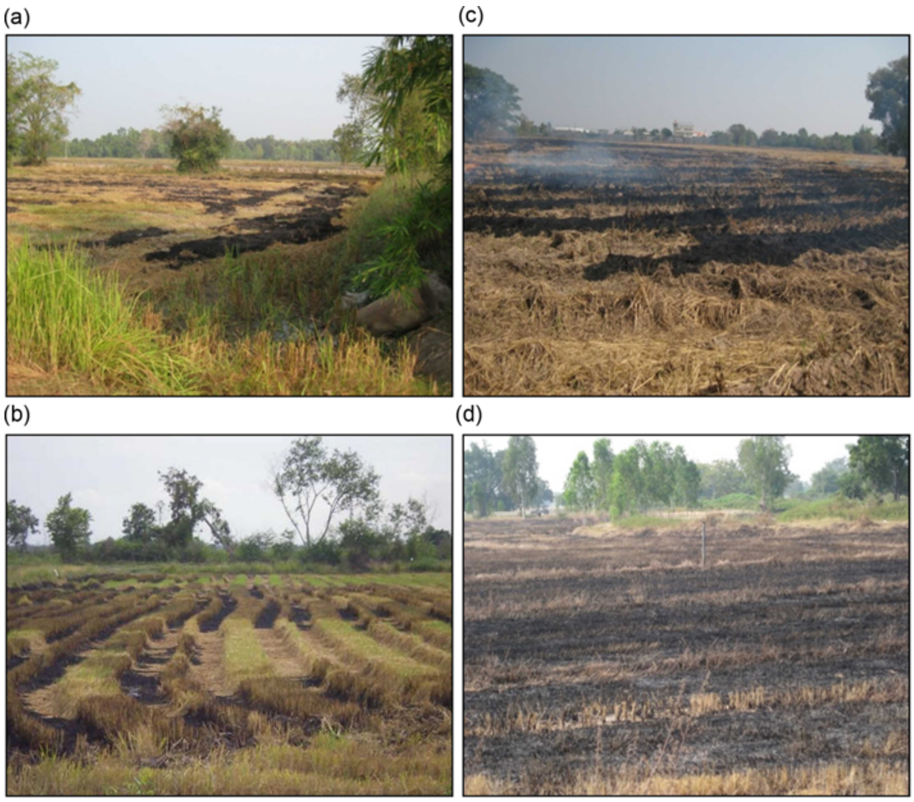

Fig. 3. 4-categories of area characteristic after burning for (a) 1-25% area combustion, (b) 26-50% area combustion, (c) 51-75% area combustion, and (d) 76-100% area combustion.

Table 4. Rice cultivation practice data.

Region	Frequency (round yr^{-1})	Fraction area by planted method (dimensionless)		Fraction area by harvest method (dimensionless)	
		Broadcast	Transplant	Human	Machine
Lower Northern	2.0 ± 0.00	0.75	0.25	0.17	0.83
Upper Northern	2.0 ± 0.31	0.51	0.49	0.45	0.55
Lower Northeastern	1.4 ± 0.48	0.65	0.35	0.37	0.63
Upper Northeastern	1.8 ± 0.37	0.57	0.43	0.59	0.41
Western	1.6 ± 0.48	1.00	0.00	0.00	1.00
Central	2.1 ± 0.60	1.00	0.00	0.00	1.00
Eastern	2.0 ± 0.00	1.00	0.00	0.00	1.00
Lower Southern	1.3 ± 0.46	0.97	0.03	0.11	0.89
Upper Southern	1.3 ± 0.47	0.71	0.29	0.29	0.71
Total	1.7 ± 0.35	0.79	0.21	0.22	0.78

Source: Questionnaire survey data

clusions:

· The average plantation frequency is approximately 1.0-2.1 round year^{-1} with the lowest frequency found in the lower and the upper northeastern regions.

· Different varieties are used for major and minor rice cultivation. A photosensitive variety is used for major rice cultivation whereas a non-photosensitive variety is used for minor rice cultivation. In the photosensitive variety, the height ranges from 130 to 180 cm, which is higher than the non-photosensitive variety which is only 103 to 130 cm in height.

· There are two general cultivation methods, including transplanting and direct seeding (broadcast). Transplanting is used mainly in the upper northeastern region, the lower northeastern region, and the upper northern region; direct seeding is used mainly in the remaining regions (lower northern, western, central, eastern, upper southern and lower southern regions).

· There are two harvesting methods, including manual and machinery methods. Manual harvesting is the traditional method used in the upper and lower northeastern regions, and the upper northern region. Machine harvesting is used in the remaining regions.

According to the above mentioned data, the most common rice cultivation practices generally found in Thailand are broadcast cultivation with machine harvests. A factor influencing rice cultivation practices is the frequency of rice cultivation as evident from the central, eastern, and western regions where farmers are able to plant more than once a year and there a need to use the rice cultivation practice requiring the shortest amount of time as broadcast-machinery harvesting practice.

(2) Rice residue management

The data related to rice residue management is summarized as shown in Table 5 with the following conclusions:

Table 5. Rice residues management data.

Region	Percentage of Residues by utilization, *%U*		Percentage of Area by burning Management, *%BA*
	Stubble	Straw	
Lower Northern	19 ± 1.8	45 ± 14.0	62 ± 9.9
Upper Northern	27 ± 2.8	48 ± 17.0	47 ± 18.4
Lower Northeastern	39 ± 7.1	69 ± 15.5	26 ± 1.4
Upper Northeastern	29 ± 5.0	75 ± 25.5	16 ± 8.5
Western	14 ± 2.2	40 ± 20.0	70 ± 27.6
Central	8 ± 1.3	37 ± 16.5	52 ± 0.0
Eastern	16 ± 3.5	42 ± 21.9	79 ± 22.6
Lower Southern	24 ± 2.1	50 ± 17.3	27 ± 4.9
Upper Southern	31 ± 1.4	60 ± 26.2	30 ± 7.8
Total	23 ± 3.0	52 ± 19.3	45 ± 11.2

Source: Questionnaire survey data

· Some rice residue is utilized, some is burned, and some is left in the fields depending upon the residue type and region.

· The regional percentage of utilization by residue type ranges from 8% to 39% of stubble and 37% to 75% of straw. The highest utilized fraction of stubble and straw is in the lower and upper part of the northeastern region. Regarding the report from the National Statistical Office (NSO), Thailand, the northeastern region (both upper and lower) is an area where cattle are raised; therefore, stubble and straw are mainly used as animal feed. The utilization of rice residue can be classified into two groups, namely, on-field and off-field utilization. In on-field utilization, rice residue is mainly used for incorporation followed by grazing animal. In off-field utilization, rice residue is mainly used for cattle feed, followed by mushroom plantation and fuel, respectively.

(3) Rice residue burning characteristic

The percentage of the burned area is approximately 45% of the paddy fields. The regional percentage of the burned area ranges from 16% to 62%. Moreover, the burning also varies in terms of time as shown in Table 6. There are two peaks for the largest part of burning. The first peak is during December to January of the following year and the second peak is during April to May. There are different times and reasons for the burning in each area, i.e., in the central and lower northern regions, the burning occurs year-round because these areas have high frequency of rice plantation. This burning aims at reducing the time spent in preparing the area for planting. In the lower northeastern and upper northeastern regions, the burning occurs mainly from April to May which is the pre-cultivation period for the major rice season. The cause of burning in these areas is to remove major-residue and weed from the fields. In the upper northern, eastern, and western regions, the burning occurs mainly from December to February of the following year, which is the post-harvesting period. Due

Table 6. Temporal variation of rice residue burning.

Region	Percentage of Burning of rice residue by burning period (%)											
	Year 2007								Year 2008			
	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Lower Northern	11.1	5.6	8.9	2.9	1.3	4.0	7.8	18.7	15.1	4.4	4.7	15.6
Upper Northern	10.7	8.2	1.8	0.0	0.0	0.1	4.9	34.0	26.1	0.4	0.9	12.9
Lower Northeastern	28.4	10.7	2.2	0.0	0.0	0.0	1.9	16.2	16.4	0.6	4.4	19.2
Upper Northeastern	14.9	7.0	0.6	0.0	0.0	0.6	2.3	22.9	14.7	0.4	4.7	32.0
Western	11.9	13.0	10.1	1.8	3.9	2.8	2.6	18.8	24.0	3.6	1.7	5.6
Central	13.9	7.2	7.0	4.0	4.4	6.5	10.0	12.9	7.8	9.1	5.5	11.7
Eastern	17.4	9.3	2.7	0.6	1.0	1.8	4.2	19.2	21.1	5.5	5.6	11.7
Lower Southern	2.3	2.5	8.7	15.9	13.0	2.4	0.0	0.0	2.0	10.3	19.9	22.9
Upper Southern	10.9	1.3	1.2	3.9	5.0	1.3	1.9	1.9	7.9	18.3	21.0	25.4
Total	13.5	7.2	4.8	3.2	3.2	2.2	4.0	16.1	15.0	5.8	7.6	17.4

Source: Analytical from questionnaire survey data

to the limitations of the water regime in these areas, most of these areas plant garlic, beans, shallots, onions, etc. (group of vegetables) in the fallow season (OAE, 2010). Therefore, the main reason for the burning is to clear the area for the other crops. In the lower and upper southern regions, the burning mainly occurs from February to April to remove major-residue from the fields.

Garivait *et al*. (2005) assessed the burned areas of paddy fields by using the pixel burned area from the FHS with a pixel resolution 1 km × 1 km, based on MODIS Terra and Aqua satellites. This study reported approximately 4539 FHS associated to paddy fields, which represented 4539 km^2 of the burned area or approximately 4.5% of all paddy fields in 2005. The comparison of the percentage of the burned area was derived from Garivait *et al*. (2005) and this study found the percentage of the burned area from questionnaire survey to be approximately 10 times that of satellite data. One reason for the lower estimation of the satellite data is the lack of concurrence between the time of the satellite overpass and the time the paddy field burned were initiated (Garivait *et al.*, 2005; Smith *et al.*, 2007). Another reason is the limitation of the MODIS sensor for the detection of small agricultural fires (Smith *et al.*, 2007).

Table 7. Temporal variation of FHS detected on paddy field.

	No. of FHS, (FHS)
January	More than 1500
February	More than 1500
March	More than 1500
April	301-900
June	1-70
July	1-70
August	1-70
September	1-70
October	1-70
November	1-70
December	71-300

Source: Garivait *et al*. (2005)

When the temporal distribution (monthly) of the FHS detected on the paddy fields was considered as demonstrated in Table 7, the finding shows that the FHS detected on the paddy fields every month to be a different level. The large FHS (more than 1500 FHS) was detected on the paddy fields from January to March and a small FHS (less than 70 FHS) was detected from May to November. Hence, the main field burning occurred from January to March following the harvest of major rice (according to the questionnaire survey, the season for major rice harvesting is between December and April).

b. Ground observation analysis

The data from ground observation included moisture content and density of the residue, which was applied to develop the rice residue determination model.

(1) Moisture content

Stubble and straw were collected after the harvesting season and measured for moisture content as presented in Table 8. The measurement found the moisture content of the stubble in

Table 8. Moisture content of rice residue.

Region	Percentage of Moisture content (%)	
	Stubble	Straw
Lower Northern	42%	14%
Upper Northern	41%	17%
Lower Northeastern	69%	33%
Upper Northeastern	58%	23%
Western	60%	24%
Central	76%	31%
Eastern	78%	37%
Lower Southern	85%	41%
Upper Southern	73%	29%

Source: Field experiment

each area to range from 40% to 85% whereas the straw ranged from 14% to 37%. The residue in the upper and lower northern regions had the lowest moistness and the lower southern region had the highest moistness. The moisture content of the residue varied in terms of residue type and climate conditions which were confirmed by the report of the Revised IPCC (1996). Stubble had higher moisture content than straw due to the influence of soil humidity. The climate conditions vary from region to region. When the annual rainfall in the northern, northeastern, central, eastern, and southern regions as reported by the Thai Meteorological Department (TMD) were taken into consideration, the annual rainfall was found to be approximately 1375.7 mm, 1677.3 mm, 1478.2 mm, 1939.4, and 1999.7 mm, respectively (TMD, 2008). In area with high amounts of rainfall area, the environment is humid, so the residue has high moisture retention.

(2) Rice density

Rice density is the mass of rice in a unit area. The rice densities from four crop types were collected, including transplant-major, broadcast-major, transplant-minor, and broadcast-minor. The results show that the mass of rice stalks varies with height. Weight declined while the botanical height increases due to the physical characteristics of rice. This finding concurs with the findings of the study of Summer *et al*. (2003) who found the mass in each botanical fraction to vary with height. Based on four crop types, density differs for each crop with the highest density in broadcast-minor rice as seen in Table 9. When the rice is considered by cultivated method (broadcast and transplant) broadcast was found to have higher density than transplant due to the larger amount of rice seed used. Considering the rice by season (major and minor), minor rice was found to have higher density than major rice because the minor rice has short and fat characteristics providing a higher yield. For these characteristics, the area that produces the highest amount of rice residue is the area where minor rice is planted by using the broadcast cultivated method.

Table 9. Data from field survey.

Height (cm)	Cumulative Weight (g m^{-2})			
	Major rice		Minor rice	
	Transplant	Broadcast	Transplant	Broadcast
0-10 (above ground)	109.94	59.43	337.01	306.59
0-20	202.76	145.99	552.5	613.68
0-30	295.79	233.92	706.42	901.14
0-40	382.15	314.48	840.87	1,152.34
0-50	452.43	379.35	942.1	1408.40
0-60	524.45	444.36	1119.10	1611.51
0-70	589.13	510.4	1269.88	1812.51
0-80	648.8	574.78	1412.93	1987.99
0-90	707.04	630.82	1565.04	2058.58
0-100	753.32	684.99	1721.17	2132.56
0-110	807.76	775.2		
0-120	845.52	827.52		
0-130	909.71	902.15		

Table 10. Regression equations for determination of generated rice residue.

	Model [a]	R^2	SEE
Major-broadcast	$y = -0.007x^2 + 7.767x$	0.9996	11.583
Major-transplant	$y = -0.027x^2 + 10.341x$	0.9997	9.859
Minor-broadcast	$y = -0.070x^2 + 23.663x$	0.9962	70.061
Minor-transplant	$y = -0.128x^2 + 34.461x$	0.9996	28.457

[a]x (cm) is the height of rice; y (g m^{-2}) is the density of rice.

(3) Rice residue prediction equation development

The data from ground observation was analyzed by regression for the relationship between the height and weight in each section. The correlation analysis results of the four crop types are provided in Table 10. According to the findings the height is closely relate to the density with a polynomial relationship (R^2 is 0.99 for all crop types). The height describes weight at 99.9%, 99.97%, 99.62% and 99.96% confidence values. This relationship was applied to estimate the spatial amount of rice stubble and straw by applying the height of the rice and the harvest method of each area into the model.

The rice residue determination model was applied to assess the spatial density of the stubble and straw. When the height of the rice was applied to the model for each variety (140-154 cm represented the major rice varieties and 98-118 cm represented the minor rice varieties), the finding shows the density of the residue which ranged from 866 to 930 g m^{-2} for major rice residue and from 1896 to 2049 g m^{-2} for minor rice residue. When the height obtained from the harvest method was applied (90 cm represented for manual method and 30 cm represented for machine method) to the model, the findings show the density of the stubble which is approximately 677 and 256 g m^{-2} for major rice with manual and machine harvesting, respectively, and approximately 1812 and 782 g m^{-2} for minor rice with manual and machine harvesting, respectively. The difference between the density of the residue and the stubble is the density of the straw. The amount of major straw varies within a range from 189 to 674 g m^{-2}. The amount of minor straw varies within a range of 84 to 1267 g m^{-2}.

c. Activity data assessment

(1) Burned area (*BA*) assessment

From the amount of the paddy fields reported by of the National Statistic Office (NSO), Thailand (as shown in Table 3) and the fraction of the burned area (as shown in Table 5) approximately 44000 km^2 of the paddy field was found to be burned annually. The spatial amount of the burned area is tabulated in Table 11.

Table 11. Information from activity data for rice residue open burning emission estimation.

Region	Burned Area, *BA* (10^3 km^2)	Biomass per surface unit, *BD* (kg m^{-2})		Burning Efficiency, *BE* (dimensionless)	
		$BD_{stubble}$	BD_{straw}	$BE_{stubble}$	*BE* straw
Lower Northern	12.0 ± 0.9	0.596 ± 0.023	0.236 ± 0.145	0.21 ± 0.007	0.61 ± 0.099
Upper Northern	3.4 ± 0.2	0.598 ± 0.055	0.237 ± 0.115	0.10 ± 0.078	0.34 ± 0.141
Lower Northeastern	7.0 ± 0.5	0.274 ± 0.050	0.225 ± 0.112	0.17 ± 0.028	0.86 ± 0.099
Upper Northeastern	4.0 ± 0.4	0.276 ± 0.053	0.227 ± 0.130	0.33 ± 0.049	0.82 ± 0.156
Western	5.5 ± 0.3	0.691 ± 0.036	0.239 ± 0.171	0.02 ± 0.000	0.23 ± 0.184
Central	6.5 ± 0.6	0.692 ± 0.042	0.210 ± 0.107	0.06 ± 0.014	0.46 ± 0.141
Eastern	4.4 ± 0.3	0.697 ± 0.026	0.235 ± 0.177	0.04 ± 0.007	0.33 ± 0.325
Lower Southern	0.6 ± 0.1	0.447 ± 0.006	0.240 ± 0.113	0.10 ± 0.000	0.61 ± 0.205
Upper Southern	0.4 ± 0.05	0.452 ± 0.015	0.241 ± 0.167	0.10 ± 0.000	0.53 ± 0.042
Total	43.6 ± 3.4	0.525 ± 0.034	0.237 ± 0.157	0.18 ± 0.007	0.69 ± 0.049

(2) Biomass per surface unit (*BD*) assessment

According to the estimation of the amounts of stubble and straw by using the rice residue determination model (as described in Section 3.b.3) and the rice residue management (as described in Table 5) the density of the stubble and straw subjected to burning in the fields was found to be approximately 0.5 and 0.2 kg m^{-2}, respectively. The spatial density is shown in Table 11. In terms of weight, the total amount of rice residue subjected to open burning was found to be approximately 30.8 Mt, including 16.8 Mt of stubble and 14.0 Mt of straw. The stubble is left in the field and quite useless due to the difficulty of collection and limitation of time.

(3) Burning efficiency (*BE*) assessment

Based on the questionnaire survey related to rice residue burning characteristics (as shown in Section 3.a.3) the burning efficiency for stubble was found to be only 0.18 whereas the burning efficiency for straw was found to be 0.69. The burning efficiency is tabulated by residue type and region as shown in Table 11. These findings demonstrate that more straw is burned than stubble because of its lower moisture content. Moreover, in considering farmer behaviours, farmers always start fires with the driest straw, so straw is easier to ignite especially the upper part of straw.

d. Rice residue open burning emissions estimation

The amount of emissions from the open burning of rice residue was determined by the amount of open burning of rice residue and the emission factor. The global warming potential of CH_4 and N_2O for the agricultural sector over a 100 years life time is 25 and 298, respectively (IPCC, 2007). The amount of emissions from the burning of rice residue during the 2008 to 2009 seasons is shown in Table 12. The following conclusions have been drawn:

(1) The burning of 12.55 Mt of rice residue is the cause of contributing GHG emissions at 1.11 Mt of CO_2equivalent (Stand error (SE) 0.02; excluded neutral CO_2 caused by biomass burning).

Table 12. Emissions from open burning of agricultural residues for the 2008-2009 seasons.

Trace gases	Emission of a species x from rice residues open burning, E_i (Mt)
CO_2	14.87 ± 0.217
CH_4	0.03 ± 0.0005
N_2O	0.0009 ± 0.00001
CO	1.67 ± 0.024
NO_X	0.04 ± 0.0006
$PM_{2.5}$	0.35 ± 0.005
PM_{10}	0.12 ± 0.002
BC	0.01 ± 0.0001

(2) The burning of 12.55 Mt of rice residue is contributes to pollutants, such as CO, NO_x, $PM_{2.5}$, PM_{10}, and BC approximately 1.67 Mt of CO (SE 0.02), 0.04 Mt of NO_x (SE 0.0006), 0.35 Mt of $PM_{2.5}$ (SE 0.005), 0.12 Mt of PM_{10} (SE 0.002), and 0.01 Mt of BC (SE 0.0001), respectively.

(3) Considering the spatial distribution of emissions from the open burning of rice residue, the lower northern region is the largest contributor of rice residue open burning emissions at approximately 30% of the emissions from open burning of rice residue, followed by the central region (26%) and the western region (17%).

(4) The temporal distribution of emissions from the open burning of rice residue as shown in Fig. 4 demonstrates approximately 0.09 Mt of CO_2 equivalent contributed monthly due to the open burning of rice residue. The period with the largest contribution of GHG emission is from December to January and from April to May (31% and 30% of all emissions from rice residue open burning, respectively).

(5) Taking into account the spatial distribution of annual emissions from open burning of rice residue as demonstrated in Fig. 5, the amount of emissions was found to vary with region and time. The area that facing the largest amount of emissions year-round is the central and lower northern regions. Other areas also facing large amounts of emissions, especially from December to February (of the following year) is the upper

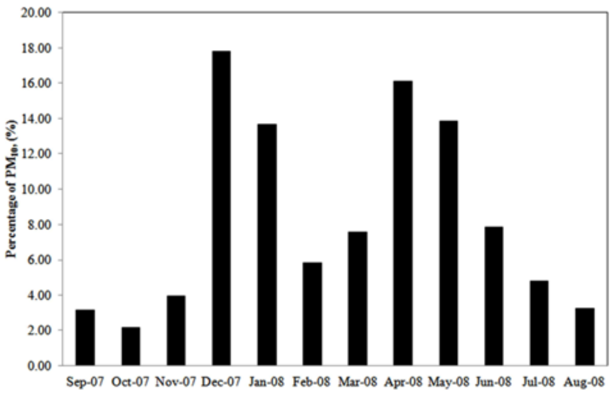

Fig. 4. Temporal distribution of PM_{10} from rice residues opens burning.

northern, eastern, and western regions. In the case of the lower and upper northeastern regions, the peak of emissions is during April to May. For the lower and upper southern regions, which have the lowest amounts of emissions, the peak is from February to April.

The comparison of rice residue burning emissions derived from Gadde *et al*. (2009) with findings of this study in 2009 is shown in Table 13. The estimated emissions from this study are approximately one to five times higher than the findings of Gadde *et al*. (2009). The reasons for the distinction are the methodology and the sources of the burning data. The emission estimation of Gadde *et al*. (2009) was based on the top-down approach using secondary data and only a single value as a representative for the whole country whereas this study was based on the bottom up approach using primary data.

4. Conclusion

This study demonstrates that the bottom up approach is very useful in assessing the spatial and temporal distributions of emissions from rice residue open burning. The findings show the affected areas where farmer always use prescribed burning to eliminate rice residue. The central and the lower northern regions of Thailand face the highest amount of air pollution from agricultural fires throughout the year.

The farmer survey provides three factors that related to estimated fire emissions as the fraction of burned area (*BA*), burning efficiency (*BE*), and rice residue density (*BD*). The values of these factors depend on the pattern and season of rice cultivation. These factors can be used to assess the amount of rice residue burning in the future as long as the same rice cultivation patterns are used. In the future, when the new agricultural technology is applied in Thailand, these factors should be readjusted by farmer surveys. This report also suggests that the results from the countries in the Greater Mekong Sub-region where agricultural open burning emissions are estimated using the top down method should be confirmed by comparing with a bottom up estimation.

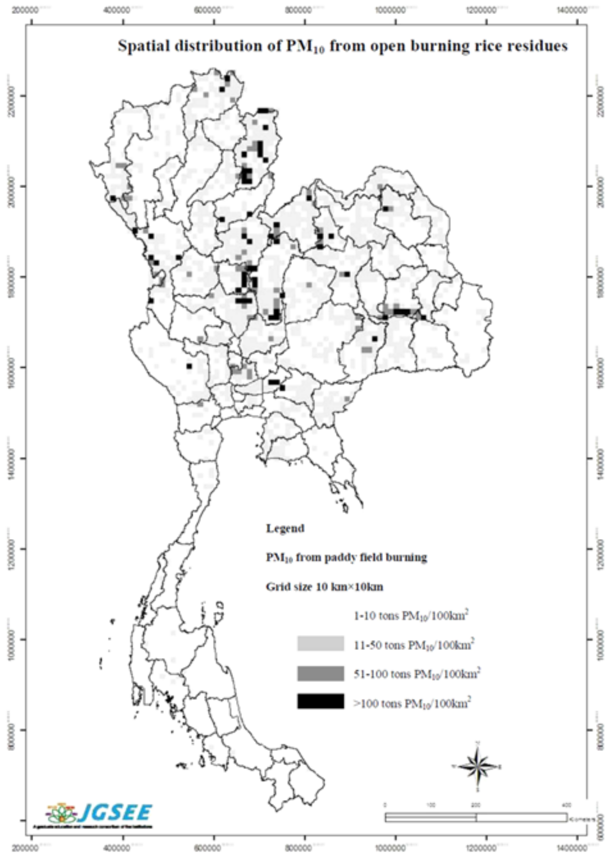

Fig. 5. Spatial distribution of annual PM_{10} from open burning of rice residue.

Table 13. Comparison of amounts of rice residue burned *(A)*, emission factor *(EF)*, and emission (*E*) between this study and previous study.

	Rice residue burned, *A* (Mt)		Emission factor, *EF* (g kg^{-1} dm)		Emission, *E* (Million tons)	
	This study	Gadde *et al*. (2009)	This study	Gadde *et al*. (2009)	This study	Gadde *et al*. (2009)
rice residue burned	11.25	8.36				
CO_2			1185.00	1460.00	14.87	12.21
CH_4			2.70	1.20	0.03	0.01
N_2O			0.07	0.07	0.001	0.001
CO			133.20	34.70	1.67	0.29
NO_X			3.10	3.10	0.04	0.03
$PM_{2.5}$			27.63	12.95	0.35	0.11
PM_{10}			9.40	3.70	0.16	0.03

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