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Influence of agricultural activities, forest fires and agro-industries on air quality in Thailand

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ABSTRACT

Annual and monthly-based emission inventories in northern, central and north-eastern provinces in Thailand, where agriculture and related agro-industries are very intensive, were estimated to evaluate the contribution of agricultural activity, including crop residue burning, forest fires and related agro-industries on air quality monitored in corresponding provinces. The monthly-based emission inventories of air pollutants, or, particulate matter (PM), NOx and SO_2, for various agricultural crops were estimated based on information on the level of production of typical crops: rice, corn, sugarcane, cassava, soybeans and potatoes using emission factors and other parameters related to country-specific values taking into account crop type and the local residue burning period. The estimated monthly emission inventory was compared with air monitoring data obtained at monitoring stations operated by the Pollution Control Department, Thailand (PCD) for validating the estimated emission inventory. The agro-industry that has the greatest impact on the regions being evaluated, is the sugar processing industry, which uses sugarcane as a raw material and its residue as fuel for the boiler. The backward trajectory analysis of the air mass arriving at the PCD station was calculated to confirm this influence. For the provinces being evaluated which are located in the upper northern, lower northern and northeast in Thailand, agricultural activities and forest fires were shown to be closely correlated to the ambient PM concentration while their contribution to the production of gaseous pollutants is much less.

Introduction

Biomass burning refers to the burning of existing and dead vegetation including that in forests and agricultural areas. Biomass burning related to agricultural activities, such as crop residue burning represents an important source of air pollutants in many countries, especially in developing countries (Levine et al., 1995; Badarinath et al., 2006; Zhang et al., 2011). Biomass burning contributes to more than 50% of the global emission of black carbon into the atmosphere (Bond et al., 2004), e.g., and particulate matters (PMs) from biomass burning affect, not only the environment, but also human health. In developing countries, especially in the Southeast Asia, open biomass burning is a common protocol for handling crops before and after harvesting: for controlling of crop residues and weeds in the field after harvesting is completed (Garivait et al., 2004; Tipayarat and Sajor, 2012). Thailand is an agricultural-based country and generates massive amounts of agricultural waste and the economic contribution of agriculture promises to increase remarkably in the future because of the increasing population as well as growing trade and agro-industries (Kasem and Thapa, 2012).

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According to the Forest Fire Control Division (FFCD) (2014), the main reasons for forest fires are the collection of forest products by local residents, e.g., mushroom and bamboo (37%), incidents (12%), agricultural land clearing before the next crop cultivation (11%), hunting (11%), animal farming (4%), illegal logging (1%) and others (24%). Many of the recorded forest fires, therefore, are related to human activities, especially to agricultural ones. This promises to result in a serious situation regarding the ambient environment and health risks because a significant amount of air pollutants are emitted from open burning in fields in agriculture and related forest fires.

The emission from biomass burning related to agriculture is not only from open burning in fields but also from further processing by agro-industries. Sugarcane is a typical example in Thailand. In the central, northern and north-eastern parts of Thailand, sugarcane is the leading commercial crop, which is used in agro-industry as a raw material for producing sugar and the level of production has been rapidly increasing by more than 100% during the last 10 years (Office of the Cane and Sugar Board (OCSB), 2014). This can be attributed to the need for renewable energy such as bioethanol and gasohol that is promoted by the Thai government. Most of the sugarcane is processed in sugar factories to produce two main products, namely, sugar and molasses. Sugarcane residue, after the squeezing process, or, bagasse, is used as a fuel for boilers to produce the energy needed to operate a sugarcane plant. Since boiler emissions cannot be controlled in many cases and because emission control devices are often inadequate, a large amount of air pollutants may be released during the production of sugar. However, the issue of how it affects the status of the ambient pollutants has not been fully evaluated.

As a tool to evaluating the above described emission of air pollutants from biomass burning in agricultural activities, forest fires and agro-industries and their contribution to the status of the environment, the emission inventory (EI) is useful and is used as a standard method (Intergovernmental Panel on Climate Change (IPCC), 2006; Miller et al., 2006). Most of the EI has been developed for primary pollutants such as particulate matter ($PM_{2.5}$ and PM_{10}), carbon dioxide (CO_2), sulfur dioxide (SO_2) and nitrogen oxides (NO_x) (US EPA, 2010). There are several databases such as Global Emission Inventory Activity (Graedel et al., 1993), Transport and Chemical Evolution over the Pacific (TRACE-P) (Streets et al., 2003) and Regional Emission inventory in Asia (REAS) (Ohara et al., 2007). These databases can also be used for Thailand and EIs have been reported by governmental sectors such as the Pollution Control Department in Thailand (Pollution Control Department (PCD), 1994) as well as by researchers (Kim Oanh et al., 2011; Cheewaphongphan and Garivait, 2013). However, even when these available databases are used, detailed information such as a monthly-based inventory is very base limited or quite uncertain. Such information is important in terms of evaluating the emission linked to agricultural activities that are actually related to the harvesting and open burning periods, which differ from province to province in Thailand. It is also important to determine the relation between the emission inventory and status of the ambient environment such as the monthly averaged concentration of air pollutants.

In this study, annual and monthly-based emission inventories in northern, central and north-eastern provinces in Thailand, where agriculture and related agro-industries are quite intensive, were estimated, in order to evaluate the contribution of agricultural activity including crop residue burning, forest fires and related agro-industries to the air quality monitored in the corresponding provinces. The monthly-based emission inventories of air pollutants, or, PM, NO_x and SO_2, for various agricultural crops were estimated based on information supplied from various provinces on the amounts of typical crops: rice, corn, sugarcane, cassava, soybean and potato that are produced using emission factors and other parameters of country-specific values taking into account crop type and the period for burning local residues. The estimated monthly emission inventory was compared with air monitoring data obtained at monitoring stations operated by PCD, Thailand for the validation of estimated emission inventory. As the most influential agro-industry in the regions of interest, the emission inventory related to a sugar factory which uses sugarcane as the raw material and its residue as boiler fuel was estimated in order to evaluate their contribution. This was done, in order to verify the contribution of crop residue burning and forest fires from the distribution of crops and transportation by air mass flow, the 24-hr backward trajectory of air mass arriving at an elevation of 50 m from the average ground level at the PCD station corresponding to monitored data was calculated for selected periods.

1. Methods

1.1. Estimation of the amount of pollutants emitted

1.1.1. Crop residue burning

The amount of emissions from agricultural open burning was estimated for each crop based on literature values (Table 1). Emissions of air pollutants from crop residue burning were calculated from the following equation (Streets et al., 2003).

$$E = \Sigma_{\mathrm{crop}}(M \cdot \mathrm{EF}) \tag{1}$$

where E (g) is the emission of each pollutant, M (kg) is the total amount of burned biomass, EF (g/$\mathrm{kg_{dry\ mass}}$) is the emission factor of each air pollutant emitted from crop residue burning obtained from the country-specific value and available reported data (Table 2). M is defined as the amount of burned crop based on total crop production data:

$$M = P \cdot N \cdot D \cdot \beta \cdot F \tag{2}$$

where, P (kg) is the annual crop production, which was obtained from the Office of Agricultural Economics in Thailand (OAE) and available for each province in Thailand (Office of Agricultural Economics (OAE), 2015). N is the residue to crop ratio, D is the fraction of dry matter, β is the fraction burned in the field, and F is the crop-specific burn efficiency ratio, where these values from literature shown in Table 1 were used in the flowing discussion.

Table 1 – Summary of the specific of each coefficient used for the emission inventory in agricultural residue burning.

Parameter	Agricultural crop					
	Rice	Corn	Cassava	Sugarcane	Soybean	Potato
Productions, 2001 (Gg)	28.03	4.49	18.39	49.56	0.26	0.09
Productions, 2012 (Gg)	38.00	4.94	29.84	98.40	0.06	0.13
Productions, 2013 (Gg)	36.83	4.87	30.22	100.09	0.05	0.10
Productions, 2014 (Gg)	33.80	4.80	30.02	103.69	0.05	0.09
Residue to crop ratio (*N*)	1.19[a]	0.89[a]	0.12[a]	0.37[b]	1.50[c]	0.50[c]
Dry matter to crop residue ratio (*D*)	0.85[d]	0.40[d]	0.71[d]	0.71[d]	0.71[d]	0.45[e]
Fraction burned in field (β)	0.48[f]	0.61[g]	0.41[g]	0.55[g]	0.76[h]	≤1.0
Burn efficiency ratio (*F*)	0.87[i]	0.92[d]	0.68[d]	0.64[b]	0.68[d]	0.90[h]

Gg = Giga-gram; *N*, *D*, β and *F* values represent to the fraction. [a] Department of Alternative Energy Development and Efficiency (DEDE) (2007); [b] Sornpoon et al. (2014); [c] Yang et al. (2008); [d] Streets et al. (2003); [e] Intergovernmental Panel on Climate Change (IPCC) (2006); [f] Department of Alternative Energy Development and Efficiency (DEDE) (2003); [g] Energy for Environment Foundation (EFE) (2009); [h] Sajjakulnukit et al. (2005); [i] Pollution Control Department (PCD) (2005).

1.1.2. Forest fires

Particulate matter and gases emitted from forest fires were estimated using the Global Atmospheric Pollution Forum Air Pollutant Emission Inventory Manual (GAPF) version 5.0 and emissions from forest fires in Thailand were calculated from the following equation (Giglio et al., 2006).

$$E = \Sigma(M \cdot \mathrm{EF}) \tag{3}$$

where, *E* (g) is the emission of each pollutantfrom the forest area and *M* (kg) is the total amount of burned wood. EF ($\mathrm{g/kg_{dry\ mass}}$) is the emission factor of different pollutants emitted from vegetation fires available from Thai national data (Chaiyo and Garivait, 2014) (Table 2). *M* for the forest fire is defined as the mass of biomass combusted of vegetation as follows:

$$M = A \cdot B \cdot C \tag{4}$$

where *A* ($\mathrm{km^2}$) is the burned area, *B* ($\mathrm{kg_{dry\ mass}/km^2}$) is the wood density in the forest area in Thailand, and *C* is the combustion efficiency. Generally, forest types in Thailand are classified as tropical forests consisting of tropical evergreen and deciduous forests (Thawatchai, 2012) so that default biomass consumption and emission factors for tropical/subtropical forest burning were selected from a domestic data source. Values from the literature (Junpen et al., 2011), or, $B = 3.76 \times 10^5\ \mathrm{kg_{dry\text{-}mass}/km^2}$ and $C = 0.79$ in the forest area, which are averaged values for Thailand, were used in the following calculation.

1.1.3. Agro-industry

Taking into account the dominant contribution of the sugar processing industry compared to other agro-industries, the emission from the sugar production process using agricultural residue as a fuel for the power generation was evaluated. The rate of sugarcane production was obtained from the Office of the Cane and Sugar Board (OCSB) in Thailand (OCSB, 2012). According to OCSB, there are 47 sugar mills distributed mainly in the lower northern and northeastern regions of Thailand (OCSB, 2012). The consumption of agricultural residue fuel, or bagasse, in a sugarcane factory was calculated by the following equation:

$$\frac{\mathrm{W_{fuel}}}{\mathrm{year}} \times \frac{J}{\mathrm{W_{fuel}}} \times \frac{\mathrm{W}}{J} = \frac{\mathrm{W}}{\mathrm{year}} \tag{5}$$

where $\mathrm{W_{fuel}}$/year (Mg/year) is the total agricultural residue consumption in the sugar factory, which is provided by the OCSB. $J/\mathrm{W_{fuel}}$ (7600 kJ/kg) is the average lower heating value of bagasse (Jenjariyakosoln et al., 2014). *W/J* is the emission factor of different pollutants emitted from the boiler in the agro-industry provided by GAPF version 5.0 (GAPF, 2012).

The emission rate estimated for the industrial sector depends on the production rate and the performance of a pollution control device used in each factory and can be described by a following equation:

$$E = \mathrm{EF_{uncontrolled}} \cdot (1 - \mathrm{ER}) \cdot A = \mathrm{EF_{controlled}} \cdot A \tag{6}$$

Table 2 – Summary of emission factors for each pollutant (unit: $\mathrm{g/kg_{dry\ mass}}$).

Pollutants	Rice	Corn	Cassava	Sugarcane	Soybean	Potato	Forest
PM_{10}	9.10[a]	8.72[b]	3.90[c]	5.65[d]	3.90[c]	3.90[c]	26.19[e]
$PM_{2.5}$	8.30[a]	8.72[b]	3.90[c]	4.12[d]	3.90[c]	3.90[c]	26.19[e]
SO_2	0.48[f]	0.40[c]	0.40[c]	0.40[c]	0.40[c]	0.40[c]	0.57[c]
NO_x	3.43[g]	3.05[g]	1.70[h]	2.60[i]	1.70[h]	1.70[h]	2.45[c]

[a] Kim Oanh et al. (2011); [b] Kanokkanjana (2010); [c] Andreae and Merlet (2001); [d] Zhang et al. (2013); [e] Chaiyo and Garivait (2014); [f] Streets et al. (2003); [g] Cao et al. (2008); [h] Sahai et al. (2007); [i] Dennis et al. (2002).

where E (mass per time) is the emission rate, $EF_{uncontrolled}$ and $EF_{controlled}$ are the emission factors respectively without and with pollution control devices. ER is the efficiency of removal of a pollution control device, which is different with agro-industry types. A is the emission rate (activity unit per time). Note that $EF_{uncontrolled}$ is equivalent to $EF_{controlled}$ when $ER = 0$.

Emission control devices used in sugar factories were reviewed in the Environmental Impact Assessment Reports and all of the sugar factories use multi-cyclones to remove particulate matter before releasing smoke produced by the burning of the residue (bagasse) into the atmosphere, where the dust removal efficiency is estimated as 60%. Because of that, very few sugar factories use emission control facilities for NO_x and SO_2 and hence there is a lack of reliable data (Office of Natural Resource and Environment Policy and Planning (ONEP), 2015), these gaseous pollutants were assumed to be freely emitted. Sugar mills use bagasse every day during the sugar season and the number of operating days varies between 120 and 240 days (140 days on average). In provinces of concern, the sugar mills operated during December–April (OCSB, 2014).

1.2. Estimation of monthly-based emission inventory and their spatial distribution

As shown in Table 3, the monthly-based emission from agricultural activities was estimated according to data related to the amount of material produced and the harvesting procedure used for each crop. Data for the amount of corn, cassava potato, and soybean that are produced, were obtained from a calendar prepared by (Office of Agricultural Economics (OAE), 2015). The monthly emission of pollutants originating from these crops was directly calculated by Eq. (1) with the monthly-based production amount of M for each crop taking into consideration that these crops are burned just after harvest (Kanokkanjana and Garivait, 2010; Kanabkaew and Kim Oanh, 2011).

Monthly sugarcane production in each province was obtained from the OCSB in Thailand, where the OCSB reports the daily amount of sugarcane both that burned in the field and unburned directly sent to sugar factories during the sugar season (December–early April)(OCSB, 2014). Sugarcane residues are burned both in the field and by the agro-industries. Sugarcane is usually burned before the harvest to remove sharp foliage, insects, and snakes so that stems are more easy collected by workers (Kanokkanjana and Garivait, 2012). According to a previous report (Sornpoon, 2013), pre-harvest burning accounts for 82% while post-harvest burning in the agro-industry as a boiler fuel contributes the remaining 18%. Hence, the pre-harvest burning of sugarcane was accounted for as the open burning during the harvesting period from December to April. The emission from post-harvest burning, which is mainly from provincial sugar factories, was estimated as described in the agro-industry section.

Unlike other crops, rice is cultivated year round and consists of two different periods of cultivation, or, major and second rice: the major rice is mainly cultivated in the wet season between May and October and harvested in the dry season from November to February. The second rice is grown from November to April in the following year and harvested in the rainy season from May to October. As a result, rice residue is burned throughout the year. However, the burning period for rice residues is different region by region. Because of this, the period of rice residue burning was based on a questionnaire survey (see Fig. 1) (Cheewaphongphan and Garivait, 2013) was used to calculate the amount of pollutants emitted.

Hotspot data from the Moderate Resolution Imaging Spectroradiometer (MODIS) active fire product (MOD14), provided for Thailand by the Forest Fire Control Division in Thailand (FFCD), were used to calculate the area that is burned by forest fires. These data were obtained by on board NASA's Aqua and Terra satellites with a resolution of 1 km × 1 km (NASA/University of Maryland, 2002). In the present study, the hotspot data designated as nominal-confidence fire (30%–80%) and high-confidence fire (81%–100%) were used (Forest Fire Control Division (FFCD), 2014). In 2014, fire hotspot data in the forest area were categorized as 96.57% for nominal and high confidence fire so that the fire hotspot from MODIS can be used to describe spatial and temporal forest fire hot spots in Thailand (Junpen et al., 2011; Kim Oanh and Leelasakultum, 2011).

1.3. Monitoring data of air pollutants

For a comparison between the estimated monthly-based emission inventory and air pollutant data monitored at the corresponding locations, air pollutant data available from the Pollution Control Department (PCD) of Thailand were used. There are 66 air quality monitoring (AQM) stations operated by the PCD in Thailand, nearly half of which, or, 28 stations are located in the Bangkok metropolitan region (PCD, 2014). The AQM stations selected in each area are listed in Table 4 and their locations are shown in Fig. 2: two stations in Chiang

Table 3 – Monthly crop residue burning in Thailand.

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Corn	4.42	2.82	2.15	1.69	0.34	0.92	2.52	15.11	23.25	18.24	16.39	13.81
Cassava	18.72	18.09	15.06	6.86	3.02	2.00	2.79	3.12	3.85	3.87	7.00	14.48
Sugarcane	27.47	24.42	21.32	4.76	0.28						1.84	19.91
Soybean	0.16	1.55	35.09	34.95	0.37		0.53	7.33	5.67	4.84	6.31	1.94
Potato	10.61	25.76	33.00	10.31	0.80		2.06	8.78	1.67	1.22	2.75	3.05

Monthly crop production in percent (%); blank cell mean no crop production in this month.

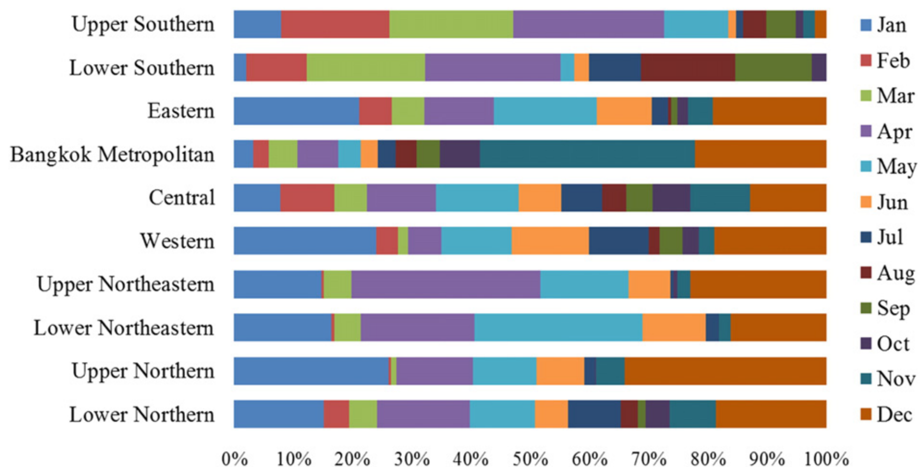

Fig. 1 – Percentage of rice residue burning by burning period in each region in Thailand.

Mai (upper northern Thailand), one station in Nakhon Sawan (lower northern Thailand), one station each in Khon Kaen and Nakhon Ratchasima (northeastern of Thailand). Because of the limited number of stations in each province, they may not be sufficient to permit the detailed characteristics of pollutant behavior to be determined. However, it should not be far from the averaged or background behavior except the case where the influences of local emission sources are extremely large such as at road side stations in Bangkok, where the emission from traffic significantly affects the monitoring data. Since all of the above mentioned PCD stations are located in nearly residential locations, the PCD monitoring data can be reasonably used for the present purpose, as described below.

1.4. *Air mass trajectories to monitoring location*

In order to verify the contribution of crop residue burning and forest fires from the distribution of crops and forests, which are linked to the transportation by air mass flow, the 24-hr backward trajectory of air mass arriving at an elevation of 50 m from average ground level at the monitored PCD station was calculated for the selected periods using the Hybrid Single-Particle Langrangian Integrated Trajectory Model version 4 (HYSPLIT4) (Air Resource Laboratory (ALR), 2016).

2. Results and discussion

2.1. *Total emission from agricultural open burning*

Fig. 3 shows the agricultural land utilization for Thailand in 2013 (Land Development Department (LDD), 2016). In the north-eastern region, the main cultivated crop is rain-fed lowland rice (Bridhikitti and Overcamp, 2012). The amount of rice production is very large so that the open burning of rice residues would be expected to generate a considerable amount of air pollutants. Sugarcane is also cultivated in the lower northern, central (except Bangkok metropolitan region) and north-eastern regions and is a crucially important crop. To the contrary, in southern Thailand, the dominant agricultural plants are para-rubber trees and oil palms (LDD, 2016). Many of the residues from these plants are used as the main fuel not only in the agro-industry for producing materials such as rubber sheets and palm oil but also in other industries.

The total annual production of the above main crops is 172.45 Gigagram (Gg)/year (Office of Agricultural Economics (OAE), 2015). The largest crop production is sugarcane at 103.69 Gg followed by rice (total of two different cultivation periods) at 33.80 Gg, cassava at 30.02 Gg and the minor

Table 4 – List of air monitoring stations in typical provinces in Thailand.

Province	Station code	Latitude	Longitude	Altitude (m a.s.l)	Pollutants monitoring
Chiang Mai (suburban)	T35_CM1	18° 83′ 77″ N	98° 97′ 29″ E	324	PM_{10}, NO_2, SO_2, CO, O_3
Chiang Mai (urban)	T36_CM2	18° 78′ 83″ N	98° 99′ 32″ E	314	PM_{10}, $PM_{2.5}$, NO_2, SO_2, CO, O_3
Nakhon Sawan	T41_NS	15° 70′ 78″ N	100° 13′ 19″ E	31	PM_{10}, NO_2, SO_2, CO, O_3
Khon Kaen	T46_KK	16° 44′ 53″ N	102° 83′ 52″ E	165	PM_{10}, $PM_{2.5}$, NO_2, SO_2, CO, O_3
Nakhon Ratchasima	T47_NR	14° 97′ 67″ N	102° 10′ 21″ E	189	PM_{10}, NO_2, SO_2, CO, O_3

m a.s.l = Meter above mean sea level.

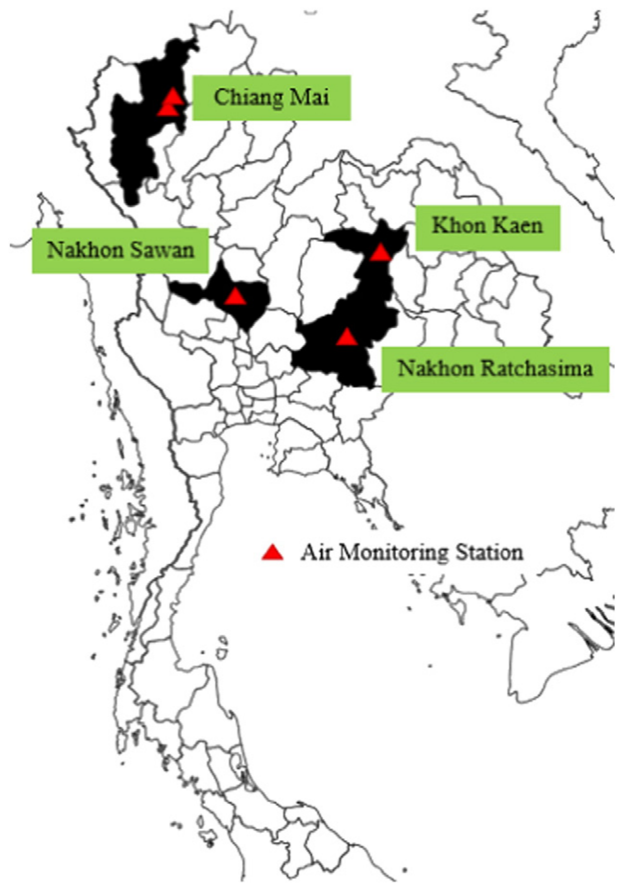

Fig. 2 – Location of typical province and monitoring stations in Thailand.

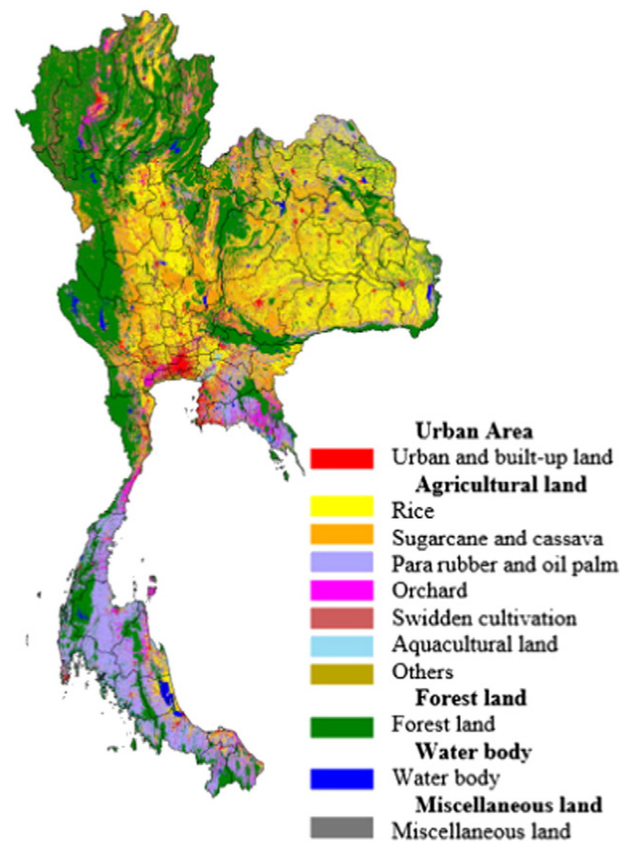

Fig. 3 – Land use map in Thailand in 2013 (LDD, 2016).

production of corn, soybean and potato (4.94 Gg) (see Table 1). The annual emissions of air pollutants in 2014 from forest fires and open burning of crop residues were estimated as shown in Table 5. The open burning of rice residues is the largest contributor to pollution, followed by the burning of the sugarcane and cassava residues. Other crops such as corn, soybeans and potatoes are almost negligible compared to the main crops. The emission from forest fires is an especially important source in the northern part, where more than 70% of the forest area is subjected to the risk of forest fire (Forest Fire Control Division (FFCD), 2014). Spatial distributions of the amount of PM_{10}, $PM_{2.5}$, NO_x and SO_2 emitted from the total open biomass burning in each province are shown in Fig. 4, where total emission inventories of crop residue burning and forest fires were evaluated by using Eq. (1) with EF listed in Table 2 and Eq. (3) with the hotspot data, respectively. The total amount of air pollutants emitted as the result of the burning of agriculture residues is significant in north-eastern and northern areas followed by the central and southern areas. This indicates the importance of the present discussion focusing on the north-eastern and northern areas in Thailand, although a recent transboundary haze event in the southern provinces caused by the transportation of air pollutants from forest fires in Indonesia is receiving increasing attention (Chisholm et al., 2016).

2.2. Correlation between emission inventory and monitored pollutants

2.2.1. Particulate matters

Fig. 5 shows the estimated monthly emission inventories of crop residue burning and forest fire along with the monthly averaged PM_{10} concentration, respectively at Chiang Mai-1, Chiang Mai-2, Nakhon Sawan, Khon Kaen and Nakhon Ratchasima. The emission inventory from agricultural residues was evaluated for the main crops, or, rice, corn, cassava and sugarcane, taking into account the reported residue burning periods, as described in Section 1.2. In the Chiang Mai province, forest fires are the primary source of air

Table 5 – Emissions of air pollutants from forest fires and the burning of each crop residue in Thailand for the year 2014 (unit: Mg/year).

Type	PM_{10}	$PM_{2.5}$	NO_x	SO_2
Rice	88,541	80,757	54,625	7644
Corn	7734	7734	2928	461
Sugarcane	54,177	39,506	19,274	4603
Soybean	166	166	101	29
Potato	78	78	34	10
Cassava	2781	2781	1212	342
Forest fire	69,640	69,640	7312	1516
All Type	223,117	200,662	85,486	14,605

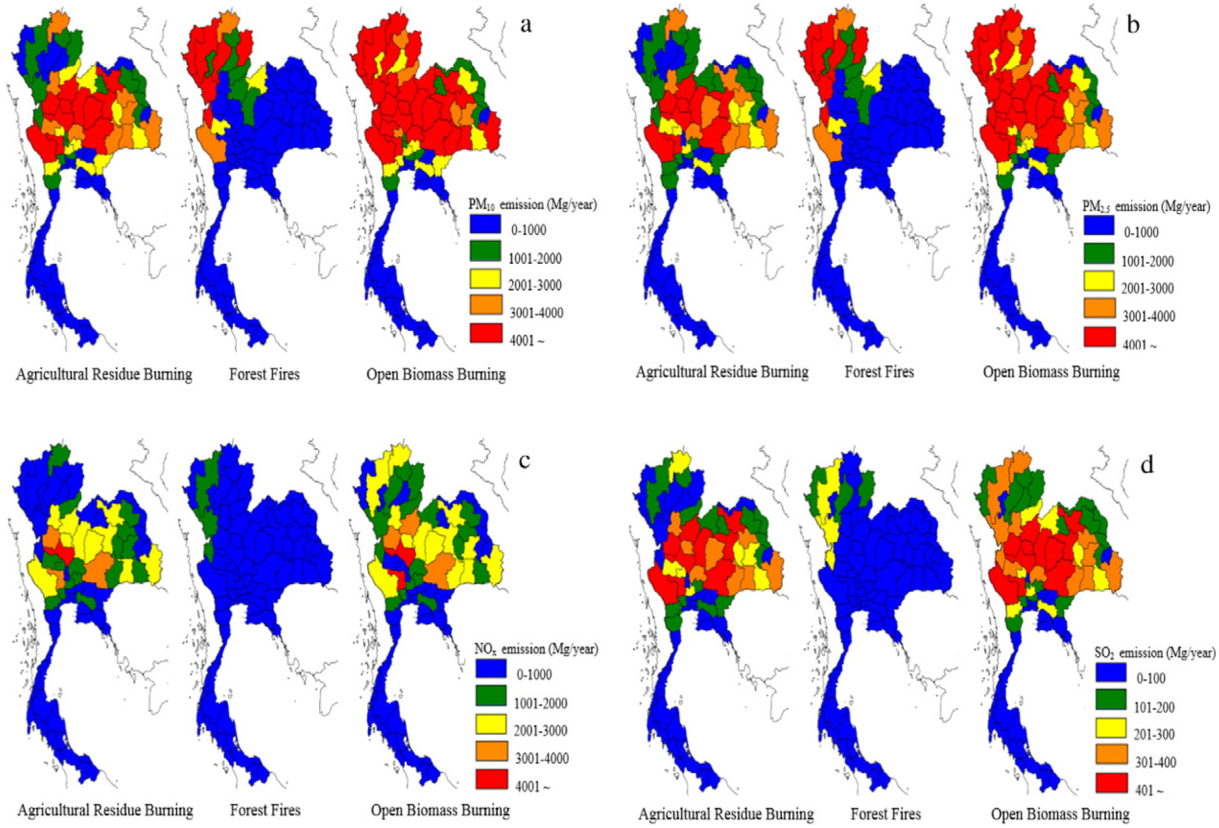

Fig. 4 – Distribution of each pollutant by province in Thailand, 2014, (a) PM_{10}, (b) $PM_{2.5}$, (c) NO_x and (d)SO_2.

pollutants, especially during the dry season from February to April. The contribution from rice and the burning of other residues reaches a maximum in December although it is still much lower than that from forest fires in the dry season. However, this is not the case in other provinces (Fig. 5c–e). In these provinces, crop residue burning makes the largest contribution and the emission from the sugar-industry assumes importance during the sugarcane harvesting season while forest fires have a slight influence. The behavior of PM_{10} concentration appears to be associated with the total emission inventory.

As shown in Fig. 6, there are clear correlations between the total emission inventory and the monthly averaged PM_{10} in every province. This is the same for $PM_{2.5}$ as shown in Fig. 7 for Chiang Mai and Khon Kaen, where $PM_{2.5}$ has also been monitored. The tendency in PM_{10} is consistent with those in 2012 and 2013, as shown in Fig. 8a–b, indicating that the emission from agricultural activities including the agro-industry and forest fires dominates the behavior of ambient particulate matter and other sources have much less influence. This may be similar in other provinces where intensive agricultural activities are ongoing, while being of much less influence of agricultural activities than traffic and industries in Bangkok.

2.2.2. NO_x and SO_2

Fig. 9a shows the correlation between the monthly averaged NO_2 concentration monitored at the PCD station in Khon Kaen and the emission inventory from biomass burning from agriculture, agro-industry and forest fires. The correlation is not so clear as the corresponding values for particulate matter and these results were similar in other provinces. This may be so because other sources such as motor vehicles and oil burning industries make comparable or even larger contributions. Fig. 9b shows monitored SO_2 concentration in relation to its emission inventory for Khon Kean. The correlation is very poor compared to PMs since major sources of SO_2 are oil burning industries (Vongmahadlek et al., 2008).

The above results refer to the fact that particulate matter is the most influential air pollutant emitted from biomass burning in agricultural activities and forest fires, and it has a significant effect on air quality in Thailand, especially in the case of forest fires.

2.3. Air mass trajectories

As described above, the number of monitoring stations may not be sufficient to permit a detailed evaluation of the influence of emission sources. As a result, the distribution of sources may have an effect in some cases. This may be the case regarding forest fires in Chiang Mai province since many of the hotspots of forest fires were located west and southwest of the PCD stations at a distance in March 2014 as shown in Fig. 10 (Royal Forest Department, 2014). As can be seen from Fig. 11, air mass movement reaching the corresponding PCD station from the southwest direction that passed over a dense hot spot area was significant. This may explain the transportation of smoke particles from the forest

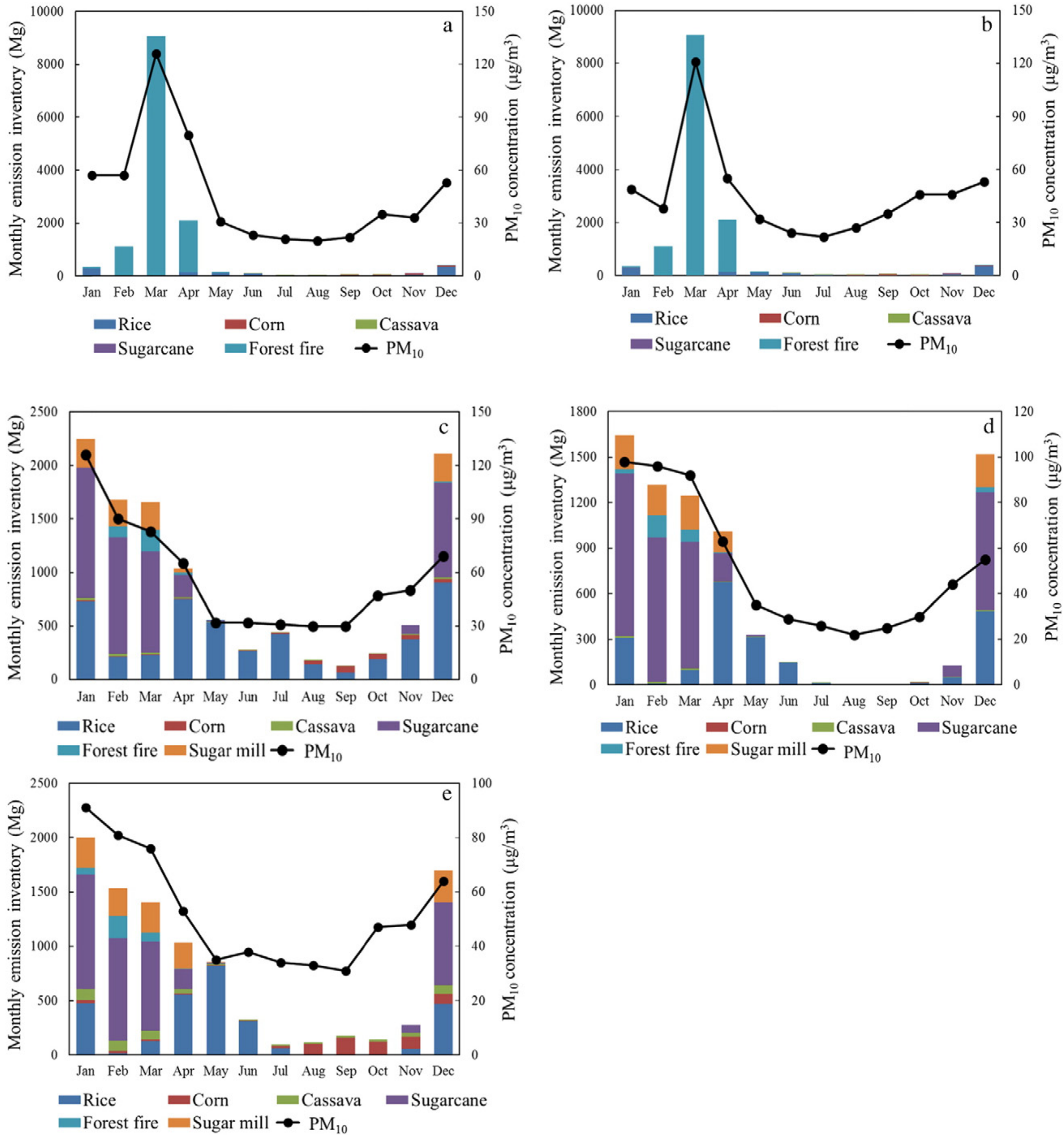

Fig. 5 – Monthlybased average PM_{10} and monthly emission inventory from crop residues and agro-industry in (a) Chiang Mai-1 (Suburban), 2014, (b) Chiang Mai-2 (Urban), 2014, c) Nakhon Sawan, 2014, (d) Khon Kaen, 2014 and (e) Nakhon Ratchasima, 2014.

area to Chiang Mai city area, leading to the largest concentration of PM in March, in spite of the fact that the PCD stations are located in Chiang Mai.

The influence of the long-range transportation of air pollutants emitted in surrounding countries such as Myanmar, Laos and China in northern Thailand, need to be considered for an accurate evaluation. These influences are not discussed here. This is mainly because of difficulties associated with obtaining information on the emission inventory and events in these countries. However, it is important to discuss not only the influences to Thailand but also those from Thailand to other countries. Therefore, this issue will be the subject of a future study.

3. Conclusions

Annual and monthly-based emission inventories were estimated to discuss the contribution of agricultural activity including crop residue burning, forest fires and related agro-

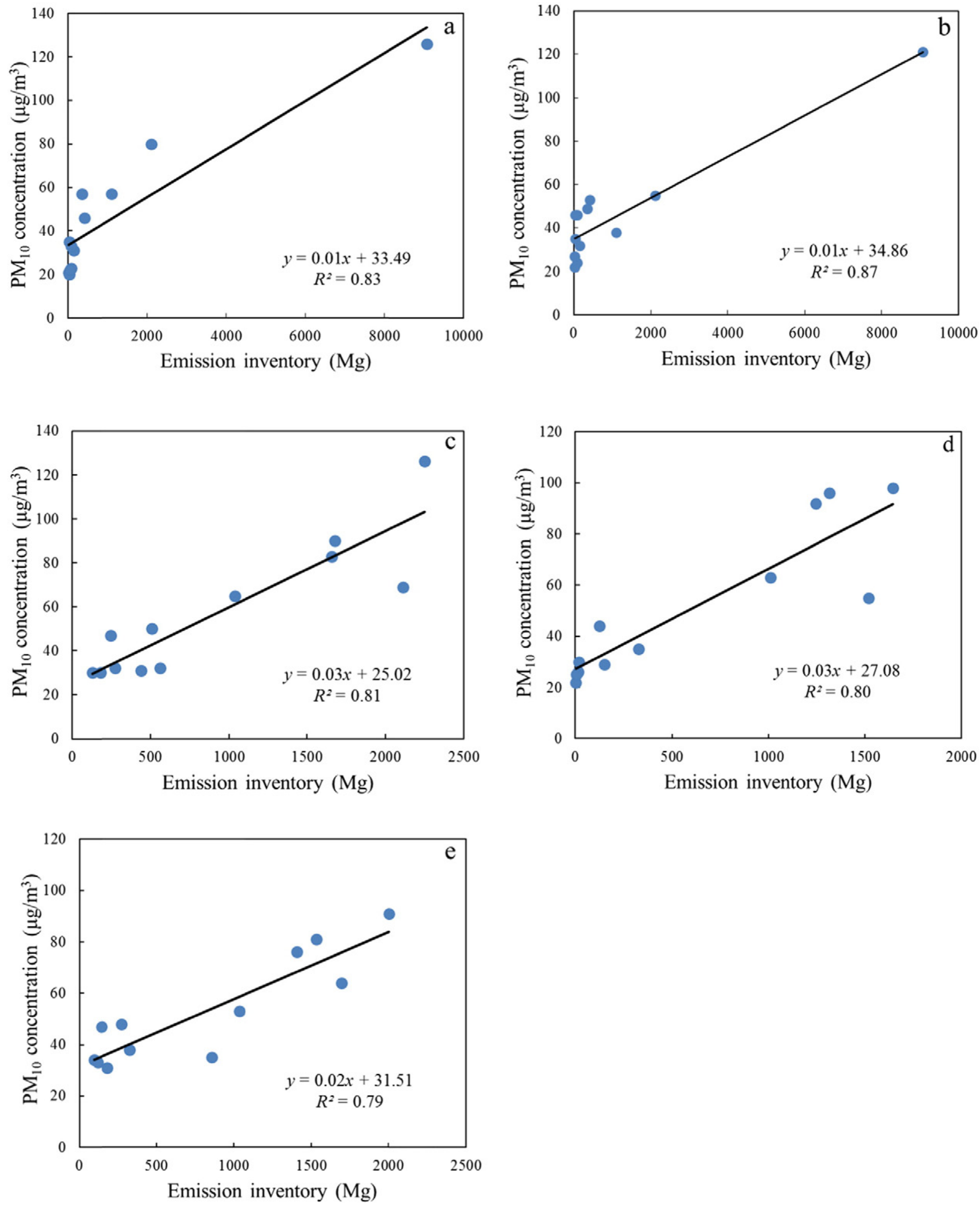

Fig. 6 – Correlation between the total emission inventory and monthly averaged PM_{10} concentration (a) Chiang Mai-1 (Sub-urban), 2014, (b) Chiang Mai-2 (Urban), 2014, (c) Nakhon Sawan, 2014, (d) Khon Kaen, 2014 and (e) Nakhon Ratchasima, 2014.

industries to the air quality monitored in corresponding provinces in Thailand. The monthly-based emission inventories of air pollutants, or, particulate matter (PM), NOx and SO_2, for various crops were estimated based on information supplied from various provinces regarding the production amount of typical crops. The estimated monthly emission inventory was compared with air monitoring data obtained at monitoring stations operated by the Pollution Control

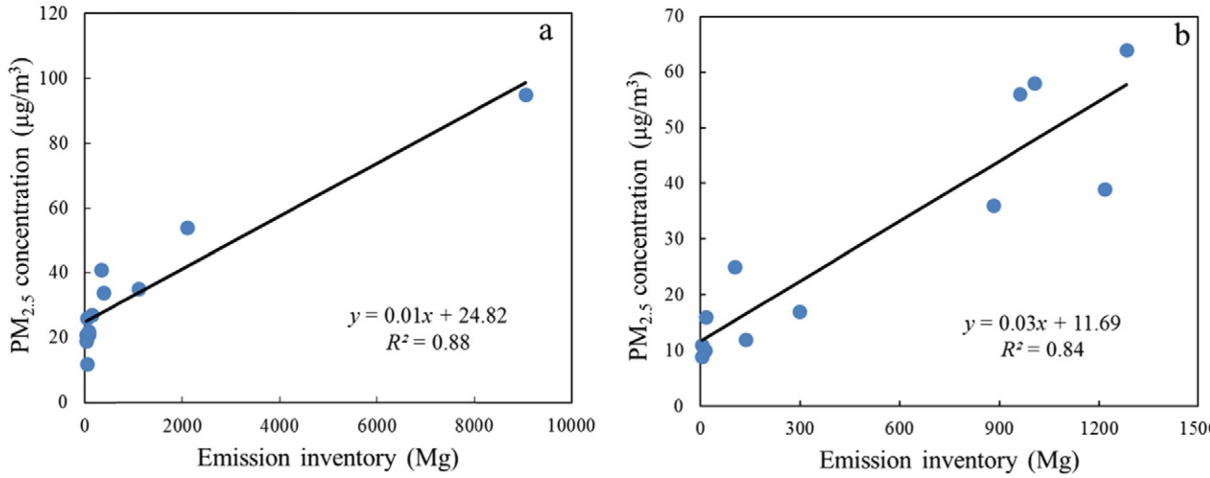

Fig. 7 – Correlation between the total emission inventory and monthly averaged $PM_{2.5}$ concentration (a) Chiang Mai-2 (Urban), 2014 and (b) Khon Kaen, 2014.

Department, Thailand (PCD) for the validation of estimated emission inventory. As the most influential agro-industry in the regions of interest, the emission inventory related to the sugar factories which use sugarcane as a raw material and its residue as fuel for producing energy was estimated in an attempt to assess the magnitude of the contribution. In the

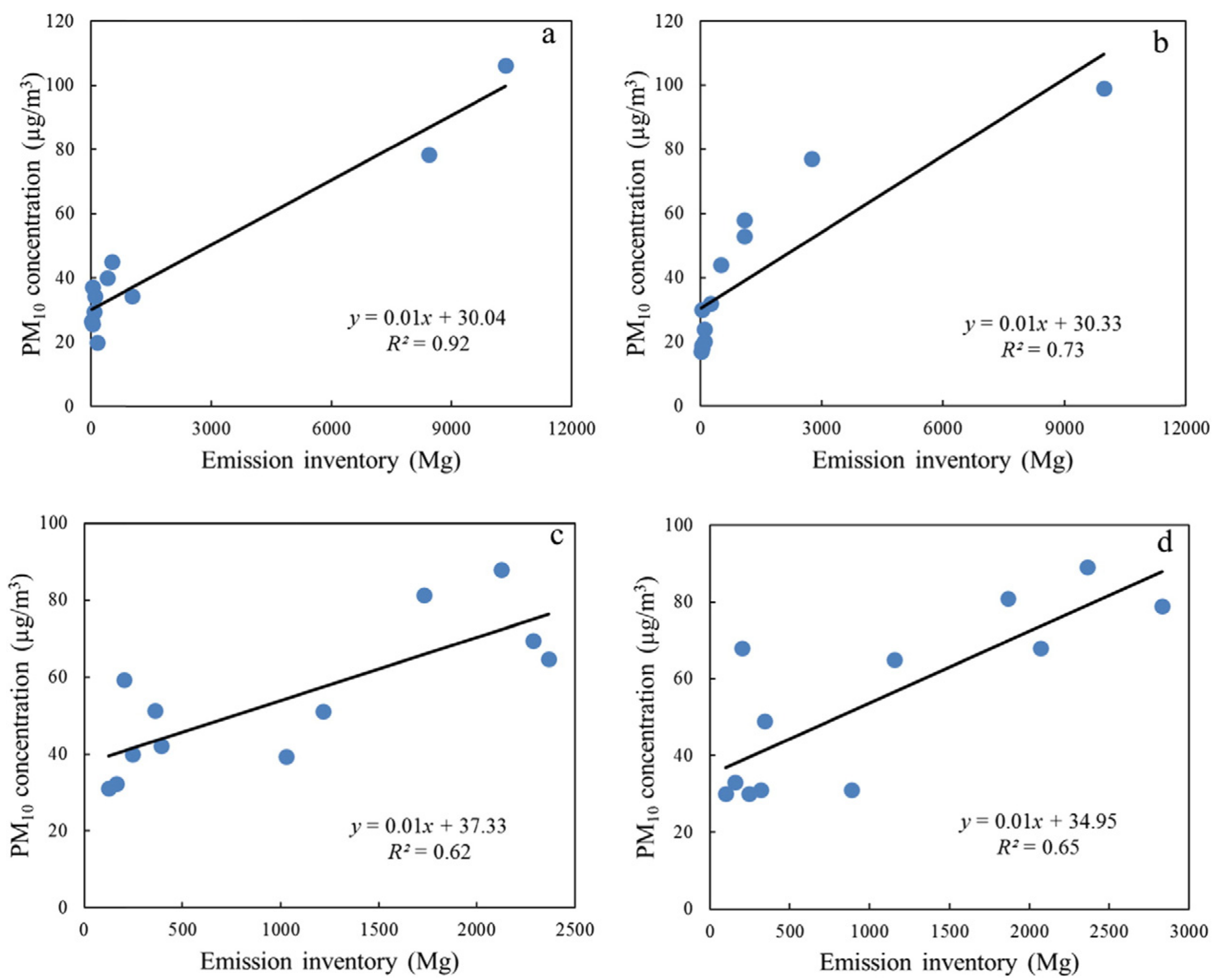

Fig. 8 – Correlation between the total emission inventory and monthly averaged PM_{10} concentration (a) Chiang Mai-1 (Sub-urban), 2012, (b) Chiang Mai-1 (Sub-urban), 2013, (c) Nakhon Ratchasima, 2012 (d) Nakhon Ratchasima, 2013.

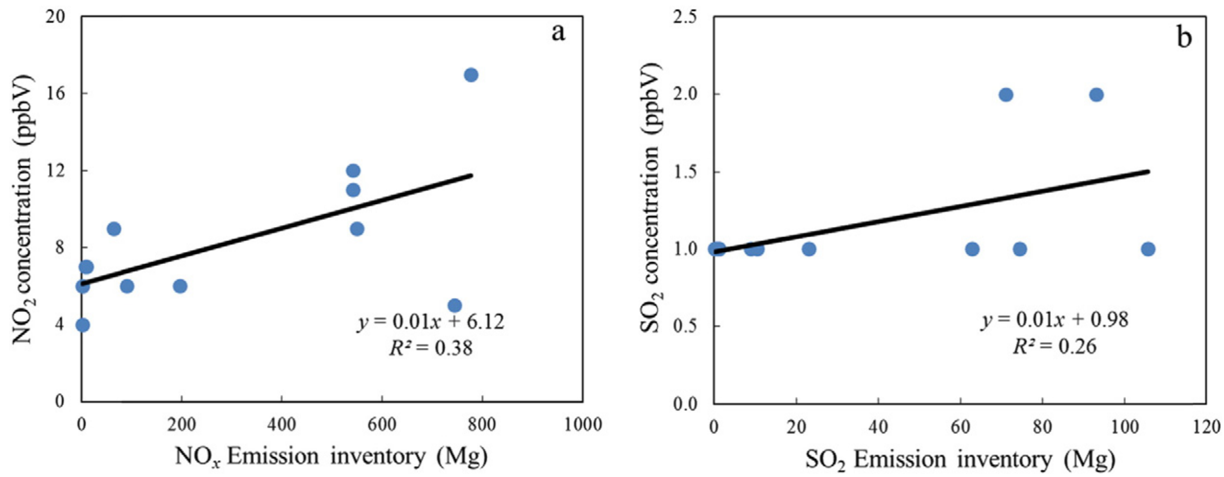

Fig. 9 – Correlation between the total emission inventory and monthly averaged gaseous pollutant production in Khon Kaen (a) NO*x* and (b) SO_2.

upper northern provinces (Chiang Mai), forest fires were found to be the largest contributor, while in the lower northern (Nakhon Sawan) and northeast (Khon Kaen and Nakhon Ratchasima) provinces, the open burning of rice residues and pre-harvest open burning of sugarcane as well as burning sugarcane residues in sugar industries were found to dominate the PM concentration. In Thailand, the emission inventory of agricultural activities including agro-industry as

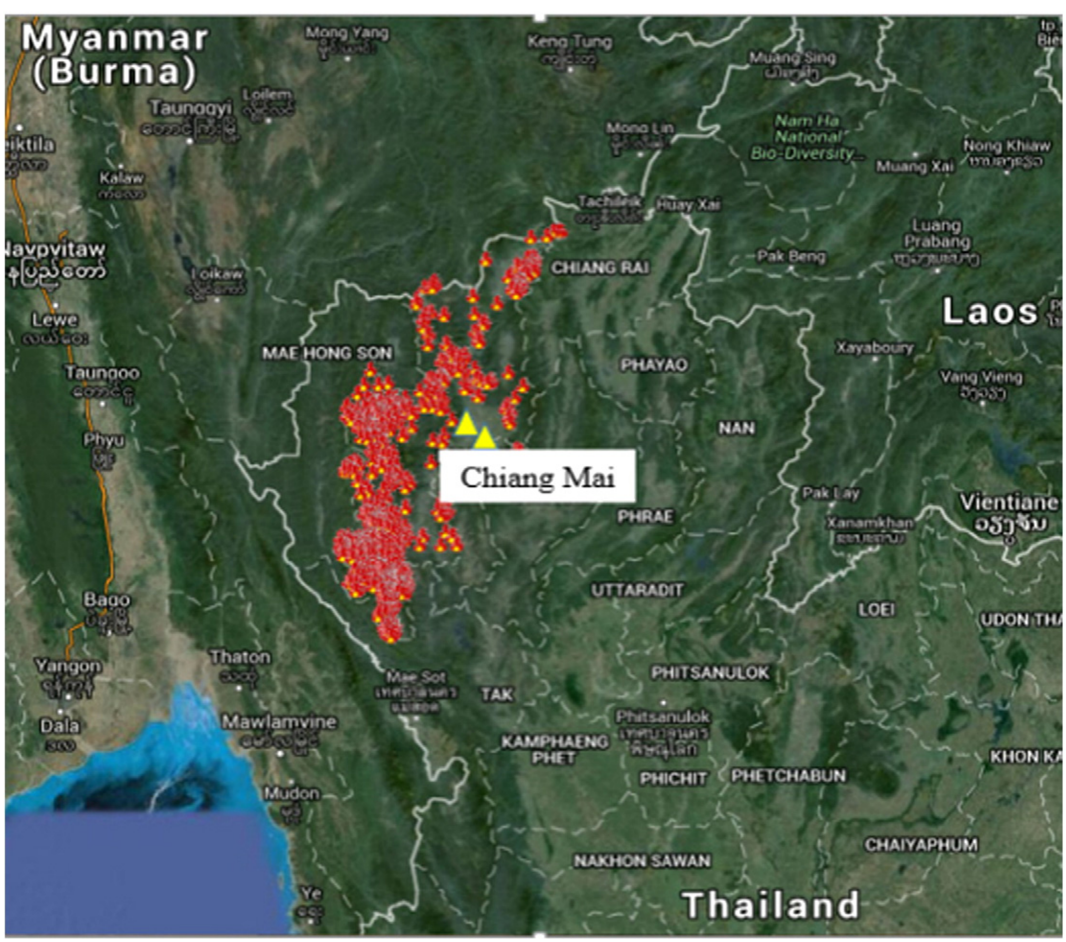

Fig. 10 – Hotspots in the Chiang Mai Forest Area, March, 2014 (available at: http://www.forest.go.th/wildfire/hotspot/Hotspot_index.php).

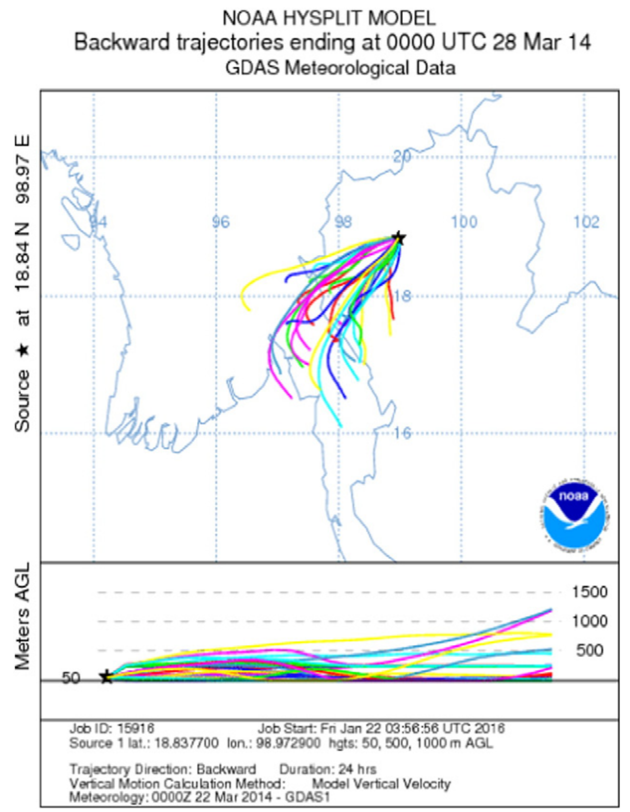

Fig. 11 – 24-hr backward trajectories in Chiang Mai, March 2014.

well as forest fires was shown to be closely correlated to the monthly averaged ambient PM concentration while this was not the case for gaseous pollutants.

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