Influences of Agricultural Activities, Forest Fires and Agro-industries on Air Quality in Thailand

Dissertation

Influences of Agricultural Activities, Forest Fires and Agro-industries on Air Quality in Thailand

Graduate School of Natural Science and Technology

Kanazawa University

Division of Environmental Science and Engineering

Student ID No: 1323142003

Name: Worradorn Phairuang

Chief advisor: Prof. Dr. Masami Furuuchi

8 January 2016

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Chapter 1

Introduction

1.1 Biomass Burning

Biomass burning refers to the burning of living and dead organisms, including crop residue and woodland. The air pollutant emission from vegetation burning contains a large amount of aerosol species (particulate matter; PM). Additionally, it contains toxic gases such as carbon monoxides (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and polycyclic aromatic hydrocarbon (PAHs) (Andreae and Merlet, 2001; Kim Oanh *et al*., 2011). The amount of pollutants emitted from biomass burning causes a haze problem in many countries (Levine *et al.,* 1995; Badarinath *et al*., 2006; Zhang *et al*., 2011). The main emitted pollutant from biomass combustion is PM; around 80-90% of mass concentration is made up of PM in accumulation mode ($D_p < 1$ μm). Moreover, the lower mass fraction approximately 10% has emitted the coarse mode particle (D_p 2.5-10 μm) and a minor fraction of coarse mode ash particles ($2< D_p < 20$ μm) (Raid *et al.,* 2005). On the other hand, the size distribution of PM depends on fuel type and moisture content, combustion procedure et cetera. The combustion process can be divided into a flaming and a smoldering phase, based on the combustion efficiency that it is the part of fuel actually burned by O_2 levels and CO/CO_2 ratio (Hays *et al*., 2005). Furthermore, emissions from biomass burning contains a large fraction of carbon elements, including organic carbon (OC) ~ 50-60% and black carbon (BC) ~5-10%. Smoke particles from biomass combustion affect global atmosphere through both absorption and reflectance of solar radiation (Watson *et al*., 2005).

Particulate matter (PM) emitted from biomass combustion processes affects the atmosphere by having both a direct and an indirect effect on atmospheric radiation. The direct impact of PM is absorbing and scattering solar radiation, which has an influence on the global climate change (Jacobson *et al*., 2001). Indirect effects are accumulating cloud condensation nuclei (CNN) that increase the cloud albedo (Cattani *et al*., 2006). Furthermore, the PM from biomass burning has serious effects on human health, including respiratory symptoms and cardiovascular morbidity, as well as adult mortality in high-risk groups (Balduzzi, 2003; Wiwanitkit, 2008).

1.2 Agro-industry and Energy supply

In developing countries, the agricultural sector plays a major role in the economy. A large amount of fruit and vegetable are produced and need to be processed before being marketed. Agro-industry involves converting products originating from agriculture, forestry and aquaculture. (Wilkinson and Rocha, 2009). The agro-processing industry can be divided into an upstream and a downstream process. Upstream industries mainly focus on initial agro-products, for instance rice milling, palm oil extraction and fish canning. Downstream industries, on the other hand, operate under manufacturing sectors, for example, para rubber products manufacturing, garment, and textile enterprises (Marsden and Garzia, 1998). Agro-industry is essential to generate income and work opportunities in developing countries (Reardonand Barrett, 2000).

However, agro-industry is still a traditional process in many countries. Production processes are associated with large amount of energy consumption and organic waste generation. It is a common method to recycle waste from the production process for energy supply (Schievano *et al.,* 2009). After processing, the biomass is turned into an energy source as feedstock for boilers. (Pippo *et al.,* 2007; Sumathi *et al.,* 2008). In the agro-industry sector, biomass is one of the primary sources of energy for agro-processing. For domestic industries, many types of highly efficient biomass boilers have been introduced to renew or modify existing equipment. On the other hand, the energy consumption and related pollutant emission in the farming production process is considerable, i.e. agricultural waste burning and biomass fuel utilization as a direct combustion cause large amounts of NO_x and PM emissions, which are not controlled (Bhattacharya *et al.,* 2000).

1.3 Emission Inventory

Emission Inventory (EI) is a common method to report the total pollutants from all of the emission sources in a spatial and temporal distribution. (IPCC, 2006; Miller *et al*., 2006). The EI may be used to identify the emission source of each pollutant being released into the atmosphere. A comprehensive list of emissions can benefit air quality management by facilitating development of supply strategies and policies to control air emissions (Fig. 1.1). An Emission Inventory is a crucially valuable tool to understand actual emissions on both a local and a global scale. The EI can classify source types from natural and anthropogenic sources, including many sectors that contribute pollutants, e.g. transportation, households, industry and construction.

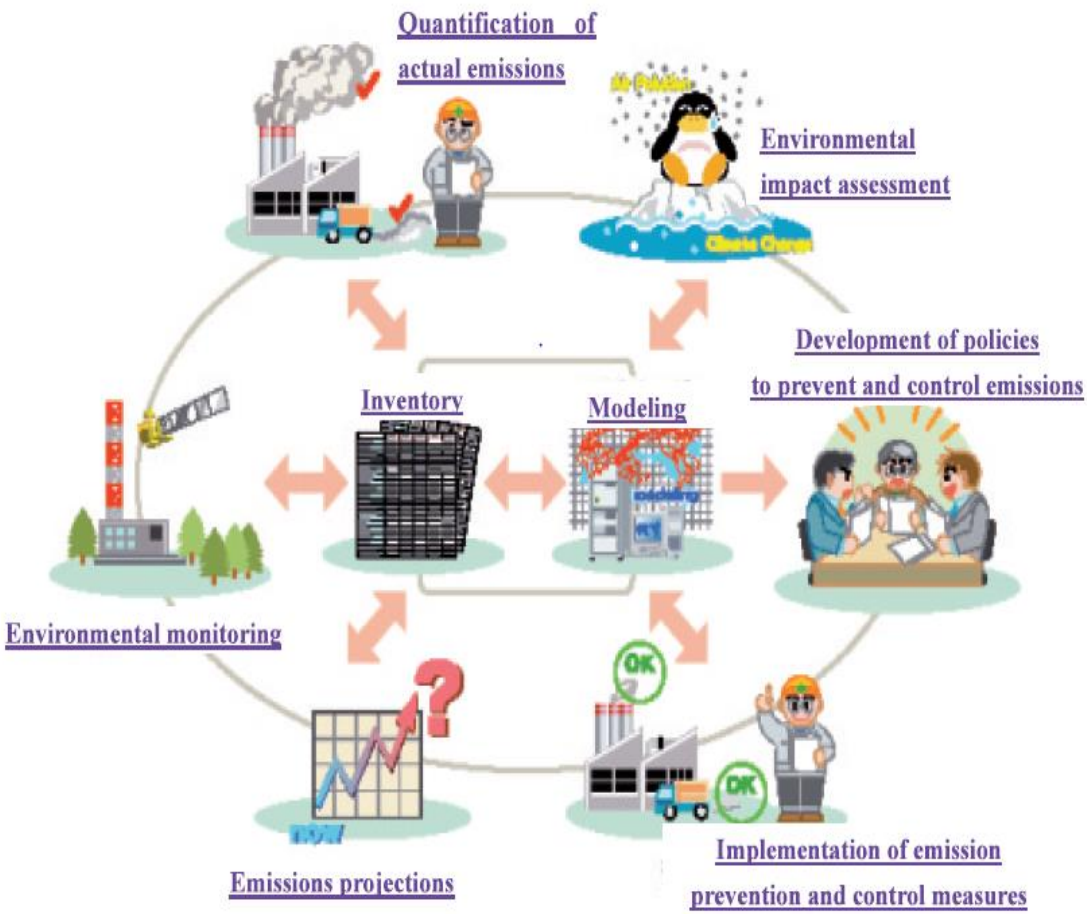


Fig. 1.1 Emission inventory strategies for air quality management
(Ministry of the Environment of Japan, 2007)

There are two main methods to develop an emission inventory: a top-down and a bottom-up approach. The top down approach is used when local data are not available and the budget does not allow collection of local information. Some examples of this method are Global Emission Inventory Activity (GEIA) (Graedel *et al*., 1993), Regional Emission Inventory in ASia (REAS) (Ohara *et al.,* 2007), and Global Fire Emission Database (GFED) (Van der waff *et al*., 2010). A rough emission estimate can be derived from regional or national data on population, fuel use and production. In contrast, the bottom-up approach is applied when domestic data are accessible. The data can be collected from individual activities and for specific data types (US-EPA, 2010).

One method for developing inventories of the particular types in one geographical area is the following equation:

$$\text{Emission} = \text{Emission Factors} \times \text{Activity data}$$

Where Emission Factors (EF) are the average emission rate in each pollutant per unit of activity data. The EFs from local data and particular types of fuel are best for estimating EI. Nonetheless, default values from the EI manual will be used when domestic data are unavailable. Activity data means information on the consumption of a quantity of any fuel use, e.g. biomass density, municipal solid waste amount, coal, petroleum fuel and so on.

1.4 Carbonaceous Aerosol

The largest portion of the particulate matter consists of carbon with various chemical and physical properties. The total carbon (TC) can be divided into organic carbon (OC) and black carbon (BC) or elemental carbon (EC). The term of BC and EC is often used interchangeably depending on the analytical method (Chow *et al*., 2010). The EC is applied when carbon fractions are measured with the thermal method, whereas BC is defined when the optical measurement method is used (Watson *et al*., 2005). Both BC and EC refer to light-absorbing carbon components. On the other hand, OC is the light-scattering carbon components (Vankatachari *et al*., 2006).

The primary source of carbonaceous aerosols is the burning of carbon contained fuel, including biomass and fossil fuel. Biomass burning is the largest emission source of EC. In a global emission data report, Bond *et al*., 2004 found that the highest emissions of OC and BC came from open biomass burning, followed by in-situ biomass burning and fossil fuel. Open biomass burning (forest, savanna, and agricultural residue) accounted for up to 73.68% of total OC emissions. Also, a considerable part of EC emissions (41.27%) came from open burning (Table 1.1). Fraction carbon profiles usually refer to EC rather than BC; the EC determined by the thermal method can use the OC/EC to identify the main sources of carbon. Biomass burning, coal combustion and motor vehicle exhaust gases have different levels of ratio. The higher ratio comes from biomass burning, while fossil and petroleum combustions result in a lower ratio of OC/EC (Cao *et al*., 2005; Plaza *et al*., 2006). However, the OC/EC is also influenced by other factors. The original primary source, deposition rate, and secondary organic aerosol (SOA) affect OC/EC values.

In the same way, EC can be divided into Char-EC as well as Soot-EC. Char-EC is generated in low combustion processes and contains the original source material. On the other hand, Soot-EC mainly originates from the high-temperature gas phase of the condensation of hydrocarbons (Han *et al*., 2007). The ratio of Char-EC and Soot-EC is distinct for different primary sources (Table 1.2).

Table 1.1 Global sectors of carbonaceous aerosols emission inventory (Bond *et al*., 2004)

Fuel/Sector	OC	BC	TC	%OC	%BC
			Gg/year		
Open burning					
Forest	11,239	1,238	12,477	33.19	15.57
Savanna	12,147	1,715	13,862	35.87	21.57
Crop residue	1567	328	1,895	4.63	4.13
Contained combustion					
Coal power	5	7	12	0.01	0.09
Diesel on-road	292	792	1,084	0.86	9.96
Wood residential	3,506	880	4,386	10.35	11.07
Crop waste residential	1,492	393	1,885	4.41	4.94
Animal waste residential	750	208	958	2.21	2.62
Coal industrial	450	642	1,092	1.33	8.08
Diesel residential	28	85	113	0.08	1.07
Coal residential	422	480	902	1.25	6.04
Diesel off-road	288	579	867	0.85	7.28
Gasoline	904	125	1,029	2.67	1.57
Other	776	478	1,254	2.29	6.01
Total	33,866	7,950	41,816		

Table 1.2 Source identification with OC/EC and Char-EC/Soot-EC ratios

Sources	OC/EC	Char-EC/Soot-EC
Diesel exhaust	<1.0 (Allen et al., 2001)	1.0-2.0 (Chow et al., 2004)
Gasoline exhaust	2.0-2.4 (Liu et al., 2006)	1.0-2.0 (Chow et al., 2004)
Biomass combustion	7.0-8.0 (Zhang et al., 2007)	2.0-5.0 (Chen et al., 2007)
Wood combustion	16.8-40.0 (Schauer et al., 2002)	/
Residential coal combustion	2.5-10.5 (Chen et al., 2006)	1.5-3.0 (Cao et al., 2005)
Residential cooking produced	32.9-81.9 (He et al., 2004)	2.0-6.0 (Chow et al., 2004)

1.5 Contents of this Research

This research composes of 3 parts, namely chapter 2; Influence of biomass burning on air quality in Thailand, chapter 3; Environmental impact from agro-industries on air quality in Thailand and chapter 4; Carbon components in size-segregated distribution of particulate matter in Thailand.

1.5.1 Influence of Biomass Burning on Air Quality in Thailand by Emission Inventory Analysis

Air pollutant emissions from open biomass burning in Thailand, including forest fire and agricultural residue burning, were investigated for reporting to Emission Inventory (EI) in Thailand year 2014. The emission inventory analysis method was integrated with satellite, government and review literature data for the best emission estimate. Moreover, the leading agro-industry for consuming biomass residues was investigated to complete the EI. The pollutants were studied during a one year period and include particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen oxides (NO_x) and sulfur dioxide (SO_2). Emitted amounts from forest fires and crop residue burning was examined, including rice, sugarcane, cassava, corn, soybean, and potato. All selected crops are subject to burning in the field before and after harvesting. The Emission Factors (EFs) and other parameters were mostly derived from country-specific values for Thailand and nearby regions. Monthly emission amounts were compared with data from air monitoring stations representative to the air quality in Thailand.

1.5.2 Environmental Impact from Agro-industries on Air Quality in Thailand

Biomass solid fuel is commonly used in agricultural-based countries. Many agricultural solid wastes are utilized for producing energy and electricity for product processing. In Thailand, the economy is shifting from the agricultural sector to the industrial and service sectors. The biomass energy consumption in the agricultural production process may produce a considerable amount of air pollutions such as particulate matter and toxic gases. The environmental impact on the atmosphere of residues, including bagasse, palm oil trash, rice husk, rubber wood and so on, was estimated by emission inventory analysis. The complete results were added to the total biomass burning in Thailand for integrated emission source from biomass burning.

1.5.3 Carbon Components in Size-segregated Distribution of Particulate Matter in Thailand

Carbonaceous aerosols are largely distributed from biomass burning. To understand the effect of particulate matter on the environment as well as human health, it is crucial to identify the chemical composition in each particle size. In this research, the author used a Nano-sampler that consists of a five stage impactor to separate particulate matter according to size and analyze chemical composition from 2 station sites in Thailand, namely Bangkok (Central) and Chiang Mai (Northern). This study aims to reach a better understanding of the major carbon components (OC and EC) in PM. Moreover, these results may confirm the particle sources and identify potential sources from spatial and temporal EI.

Chapter 2

Influence of Biomass Burning on Air Quality in Thailand by Emission Inventory Analysis

Chapter 2 examines the influence of open biomass burning, including forest fires and agricultural residue burning as well as agro-industry (sugar residues) on the air quality in Thailand. The year 2014 was selected to estimate air pollutants. The aim of investigating air pollutants from biomass burning activities was to assess the impact of both spatial and temporal distribution of pollutant emissions from biomass burning. Measured pollutants include particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen oxides (NO_x) and sulfur dioxide (SO_2). Emission rates by time and location was compared with air monitoring data from corresponding provinces in Thailand. Emission inventory data was used to supplement other data for recommending air quality management measures in Thailand.

2.1 Emission Inventory Analysis from Biomass Burning in Thailand

Emission Inventory (EI) is a standard technique to evaluate total source emissions of air pollutants and greenhouse gases in a geographical area (IPCC, 2006; Miller *et al*., 2006). Also, EI can be distributed spatially and temporally to support quality management of air pollutions (U.S. EPA, 2010). Most of the emission inventories were developed for primary pollutants, for instance carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur dioxide (SO_2) and particulate matter ($PM_{2.5}$, $PM_{10,}$ and TSP). On a global and continental scale, several well-known EIs that include Thailand are using top-down approaches, which are used when local data are not available and the budget does not allow collection of local information. Some examples of this method are Global Emission Inventory Activity (GEIA) (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). In contrast, the bottom-up approach is applied when domestic data are available. It should be noted that there are only a limited amount of indigenous EIs in Thailand produced by bottom-up approaches. The first total emission list was produced by Pollution Control Department, Thailand (PCD, 1994). The main study area was Bangkok Metropolitan Region (BMR). Additionally, an emission inventory is available from rice residue

open burning, rice being the major crop in Thailand. (Kim Oanh *et al*., 2011; Cheewapnongphan and Garivait, 2013).

One object of this chapter is to understand the relationship between the total amount of biomass burning emissions and air quality in Thailand. Firstly, by examining emission data from biomass burning year 2014, including forest fires and crop residue burnings of the most important crops in Thailand, namely rice, corn, sugarcane, cassava, soybean and potato. Secondly, by comp lementing agro-industry (sugar residues) activities to reach a total emitted amount. The Emission Factors and other factors are mostly derived from country-specific values for Thailand and neighboring regions. Finally, by monitoring data from typical provinces in Thailand and use these results to compare emission sources with emission estimations. Air monitoring stations used in this study was Chiang Mai in the upper north, Nakhon Sawan in the lower north, and Khon Kaen and Nakhon Ratchasima in the northeast of Thailand. Particulate matter with a diameter of 10 micrometers or less (PM_{10}) in each station and particulate matter with a diameter of 2.5 micrometers or less ($PM_{2.5}$) in Chiang Mai and Khon Kaen stations were investigated to reach an emission estimate.

2.2 Methodology

2.2.1 Forest Fire Emissions

Forest fire emission rates were estimated according to the Global Atmospheric Pollution Forum Air Pollutant Emission Inventory Manual (GAPF) version 5.0. Emissions from forest fires in Thailand were calculated using the following equations (Giglio *et al*., 2006):

(1) $E = \Sigma M \, x \, EF$

Where E = The emission of each pollutant (g) from a forest fire.

M = Total amount of biomass consumption.

EF = Emission factor of different pollutants ($g/kg_{dry\ mass}$)

EF was taken from national data in Thailand by Chaiyo and Garivait, 2014 (Table 2.1)

(2) $M = A \, x \, B \, x \, C$

Where A = Burned area (km^2),

B = Biomass density ($kg_{dry\ mass}/km^2$) in the forest area in Thailand

C = Combustion efficiency

Forest types in Thailand classified as tropical forest can be divided into tropical evergreen forest and deciduous forest (Thawatchai, 2012). For this reason, the authors selected available information on default biomass consumption and emission factors from primary tropical/subtropical forest fires from a domestic source. Concerning the estimation of the burned area, the authors used Moderate Resolution Imaging Spectroradiometer or MODIS active fire product (MOD14), Aqua and Terra developed by NASA to evaluate burned areas. The resolution 1 km x 1 km in each pixel can represent to burned area. The validity of this hotspot detection in Thailand was monitored and confirmed by Tanpipat et al., 2009, who found that MODIS hotspot validation over Thailand was highly accurate for the fire seasons from 2007 to 2009 with a 95.64% accuracy. The authors used data directly from Forest Fire Control Division in Thailand (FFCD), available online at http://www.forest.go.th/wildfire/hotspot/hotspot_report.php. However, for data validation, the author only used hotspot data for nominal-confidence fires (30%-80%) and high-confidence fires (81%-100%) to calculate the burned area. In 2014, fire hotspot data from forest areas were observed in approximately 96.57% of the nominal and high confidence fires. This means that fire hotspots from MODIS are very useful for providing forest fire burning data, including spatial and temporal distribution in Thailand (Junpen *et al*., 2011; Kim Oanh and Leelasakultum, 2011).

Table 2.1 Summary of Emission Factors for each pollutant

Pollutants	Rice	Corn	Cassava	Sugar cane	Soybean	Potato	Forest
PM_{10}	9.1[a]	8.72[b]	3.9[c]	5.65[d]	3.9[c]	3.9[c]	26.19[e]
$PM_{2.5}$	8.3[a]	8.72[b]	3.9[c]	4.12[d]	3.9[c]	3.9[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) Field burning of rice straw in Thailand

[b] Kanokkanjana (2010) Carbonaceous Aerosols from Agricultural Open Burning in Thailand

[c] Andreae and Merlet (2001) Values are the best guess for any combination of crop residue

[d] Zhang et al. (2013) Biomass burning of agricultural residue in China

[e] Chaiyo and Garivait (2014) Black carbon emissions from a forest fire in Thailand

[f] Street et al. (2003) Data were likely obtained from various area sources

[g] Cao et al. (2008) Average emission factors from crop residues in China

[h] Sahai et al. (2007) Data from crop residue burning in India

[i] Dennis et al. (2002) Emission factor study developed in the USA

2.2.2 Agricultural Residue Burning

Emissions from agricultural residue burning were calculated using the following equations (Streets *et al*.,2003):

(1) $E = \Sigma_{crop} M \times EF$

When E = Emission of each pollutant (g)

M = The total amount of biomass burning

EF = Emission factor of different pollutants (g/kg $_{\text{dry mass}}$)

Emitted values from crop residue burning type were derived from country-specific values or available data (Table 2.1).

(2) $M = P \times N \times D \times B \times F$

When P = Annual crop production (kg)

N = Residue to crop ratio

D = Dry matter fraction

B = Fraction burned in the field

F = Fraction of residue oxidized

The annual crop production was obtained from the Office of Agricultural Economics in Thailand (OAE), 2014. This information is accurate for each of the provinces in Thailand. The other parameters are derived from review literature described by many researchers (Table 2.2).

Table 2.2 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, 2014 (Mtons)	36.85	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 (B)	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]

[a] DEDE (2007) Biomass potential for energy production in Thailand

[b] Sornpoon et al. (2014) Estimation of emission from sugarcane field burning in Thailand

[c] Yang et al. (2008) Primary data on crop residue burning in China

[d] Street et al. (2003) Data were likely obtained from various area sources

[e] IPCC (1996) Default value from IPCC EI manual

[f] DEDE (2003) Non-exploited rice straw in Thailand

[g] EFE (2009) Non-exploited crop residues in Thailand

[h] Sajjakulnukit et al. (2005) Surplus availability of crop residues in Thailand

[i] PCD (2005) National master plan for open burning control in Thailand

2.2.3 Spatial and Temporal Distribution

Monthly emissions for each emission source from open biomass burning were estimated from various data. For forest fires, the data was collected from satellite data that were made available and validated by the Forest Fire Control Division (FFCD) in Thailand. Moderate Resolution Imaging Spectroradiometer or MODIS active fire product (MOD14), Aqua and Terra developed by NASA provided monthly data for forest fires. However, crop residue burning that calculate emission from annual production data provide monthly production (Table 2.3).

Table 2.3 Monthly crop residue burning in Thailand

Crop	Monthly crop residue burning in Thailand											
	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

During the burning period, data from the OAE in Thailand shows that corn, cassava, soybean and potato residues were burnt continuously, since these crops can be burnt in the field immediately after harvesting. Sugarcane data is taken from the Office of the Cane and Sugar Board (OCSB) in Thailand. OCSB reports daily of burnt and unburnt sugarcane sent directly to sugar mills during the sugar season (November- April).

On the other hand, the monthly distribution of rice residue burnings were different from other crops. Rice is cultivated all year round in Thailand, and subjected to different burning patterns in each region. The high peak of rice straw and stubble burning is the dry season, especially in December and January. The temporal distribution of rice burning was studied by Cheewapnongphan and Garivait, 2013 (Fig 2.1).

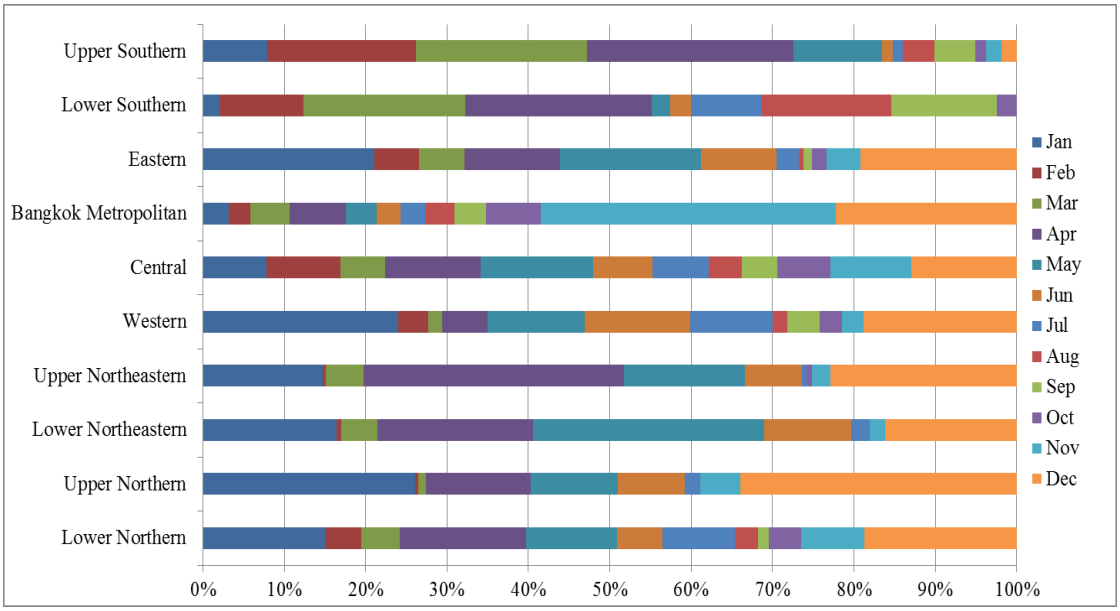


Fig. 2.1 Percentage of rice residue burning by burning period in each region in Thailand

2.2.4 Comparing Emission Inventory with Air Monitoring Data

The inventory of biomass burning in Thailand at a specific time, namely 2014, was compared with ambient air pollutants. Each pollutant was monitored at Air Quality Monitoring (AQM) stations in Thailand, established by the Pollution Control Department (PCD) of Thailand. The results from the emission inventory in Thailand was compared with air quality data from AQM stations in the northern and northeastern part of Thailand. The AQM stations were carefully chosen to be representative for each area in this study, and included two stations in Chiang Mai, upper northern Thailand, and one station each in Nakhon Sawan, lower northern part, Khon Kaen and Nakhon Ratchasima in northeastern of Thailand (Fig 2.2 and Table 2.4). In this study, the authors excluded pollutant emissions from the Bangkok Metropolitan Region. Thailand Environment Monitor, 2002 indicates that air pollutants emissions in Bangkok mainly come from the Transport, Industry, and Energy sectors. Consequently, the authors compared the effect of biomass burning on air quality between the different regions.

Table 2.4 List of air monitoring stations in typical provinces in Thailand

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

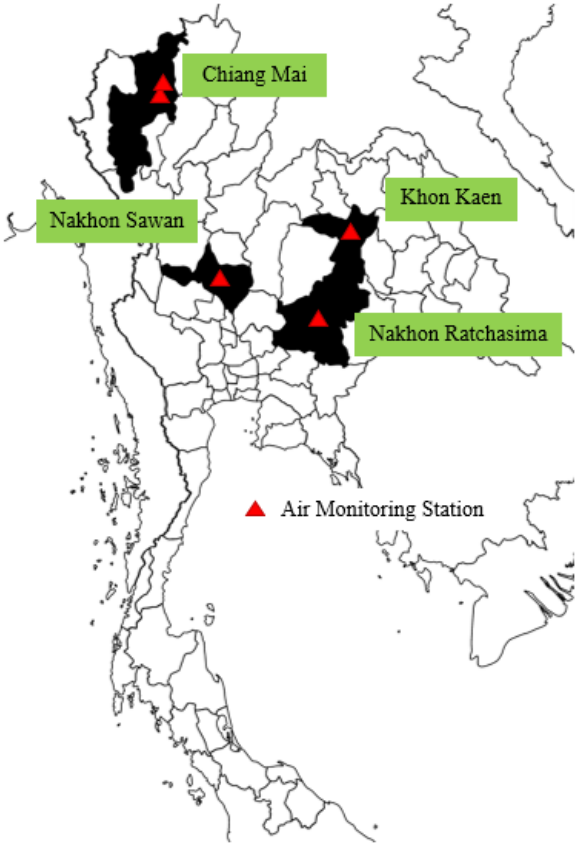


Fig. 2.2 Location of typical province and monitoring stations in Thailand

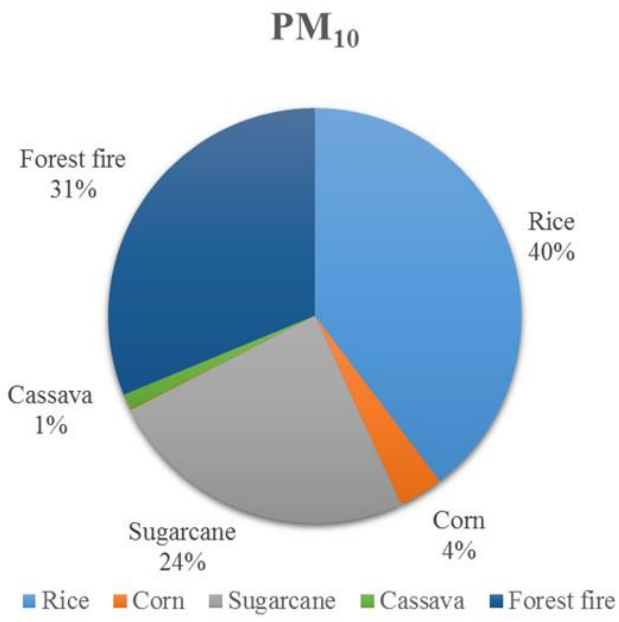
2.3 Results and Discussion

2.3.1 Annual Emissions

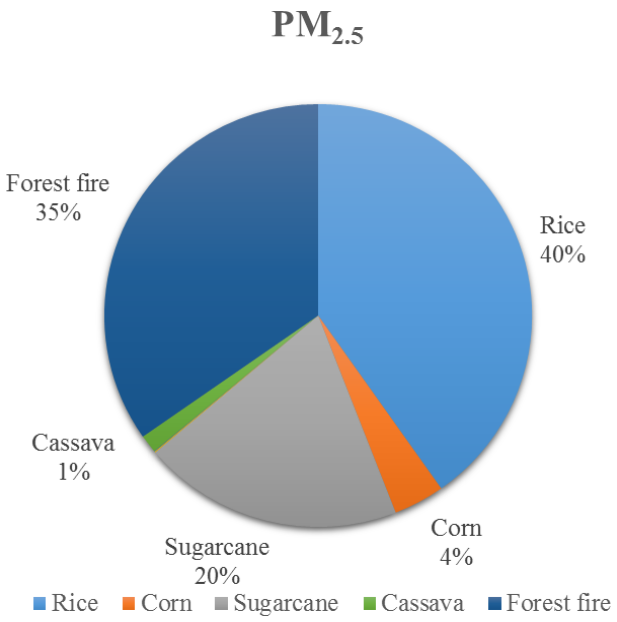
Table 2.5 shows the annual emissions for emission inventory analysis of open biomass burning for 2014. The emission estimates from forest fires and crop residue burning were as follows; PM_{10} 223,117 tons, $PM_{2.5}$, 200,662 tons, NO_X 85,486 tons and SO_2 14,605 tons. Fig. 2.3 displays the percentage of each type of air pollutant emission from open biomass burning for 2014. Rice is the largest contributor in all species: PM_{10} and $PM_{2.5}$ around 40%, NOx 64% and SO_2 52%. Overall, for most pollutants from agricultural residue burning, rice residue burning contributes the largest emissions, followed by sugarcane and cassava residue burning. Emissions from other plants, including corn, soybean and potato, are too small to be shown in this figure.

Table 2.5 Emissions of air pollutants from forest fires and the burning of each crop residue in Thailand for the year 2014 (unit: tons/year)

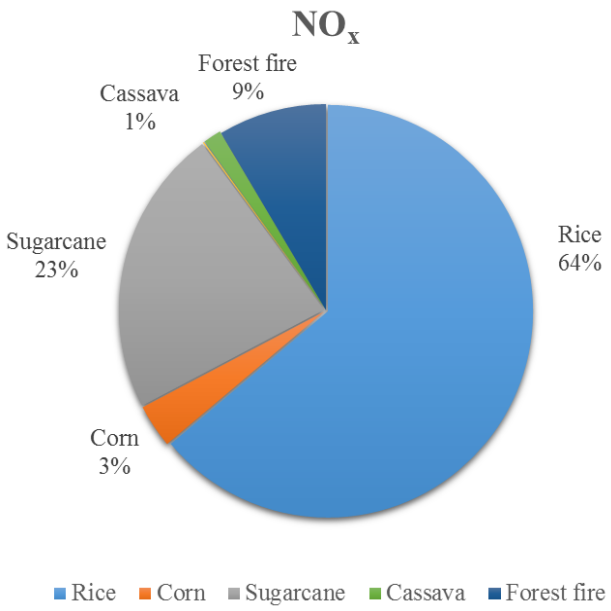
Type	PM_{10}	$PM_{2.5}$	NO_x	SO_2
Rice	88,541	80,757	54,625	7,644
Corn	7,734	7,734	2,928	461
Sugarcane	54,177	39,506	19,274	4,603
Soybean	166	166	101	29
Potato	78	78	34	10
Cassava	2,781	2,781	1,212	342
Forest fire	69,640	69,640	7,312	1,516
All Type	223,117	200,662	85,486	14,605



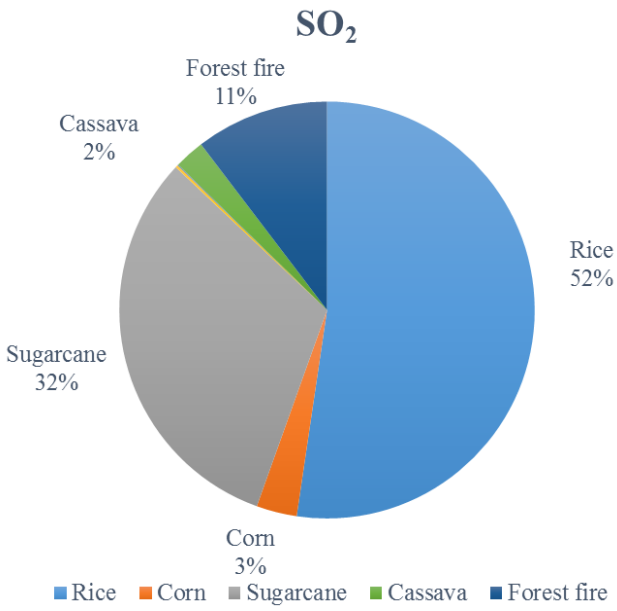
(a) PM_{10}



(b) $PM_{2.5}$



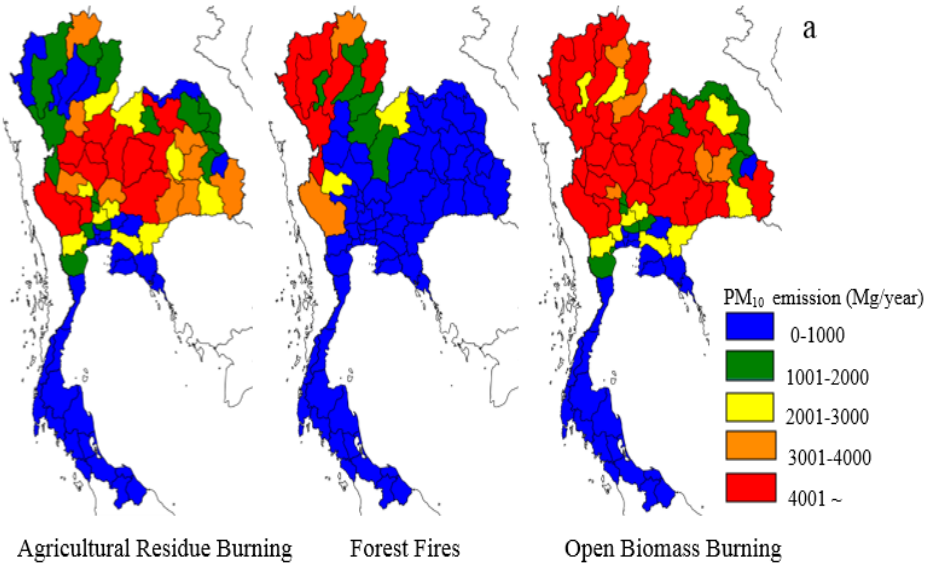
(c) NO_x



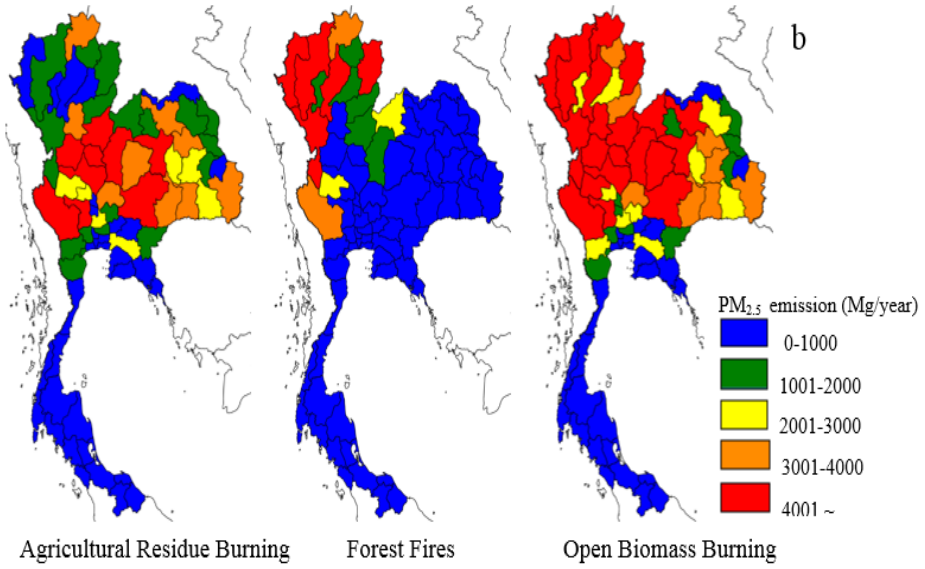
(d) SO_2

Fig. 2.3 Contribution of Air Pollutant Emission from Open Biomass Burning year 2014 (a) PM_{10}, (b) $PM_{2.5}$, (c) NO_x and (d) SO_2

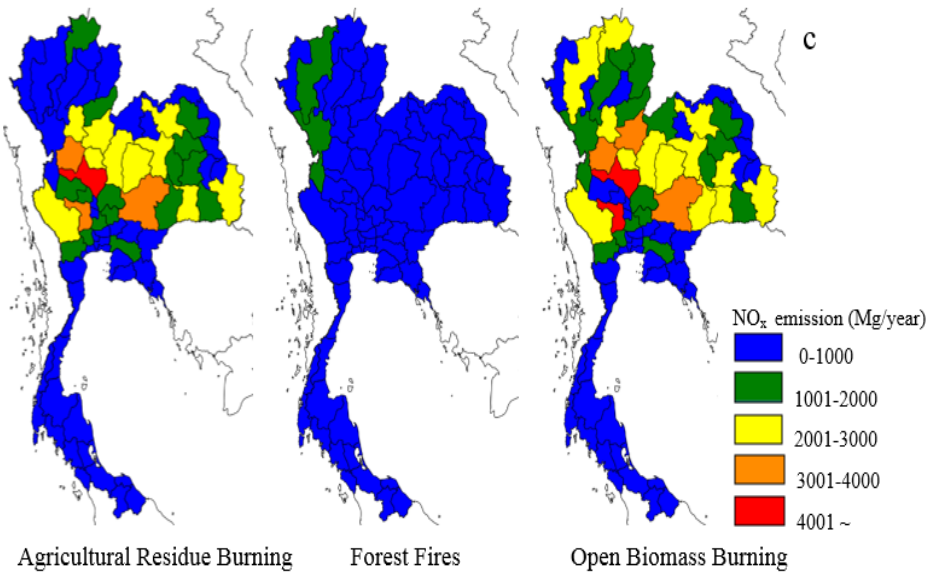
The spatial distribution of PM_{10}, $PM_{2.5}$, NO_X and SO_2 emissions from overall open biomass burning in each province is shown in Fig. 2.4. A major part of total air emissions from biomass activities in Thailand was released in the Northeastern and Northern part, followed by the Central and Southern region, respectively. Additionally, the spatial allocation of each plant is displayed by emission of PM_{10}, $PM_{2.5}$, NO_X and SO_2. Rice burning in paddies is more frequent in the Central and Northeastern region. Forest fire emissions are highest in the north of the country, as well as in certain provinces in the western part. There is a risk of fire in the highly dense forest area every year. Also, there were few forest fires occurring in the northeastern and southern part of Thailand.


a
PM10 emission (Mg/year)
0-1000
1001-2000
2001-3000
3001-4000
4001 ~
Agricultural Residue Burning
Forest Fires
Open Biomass Burning

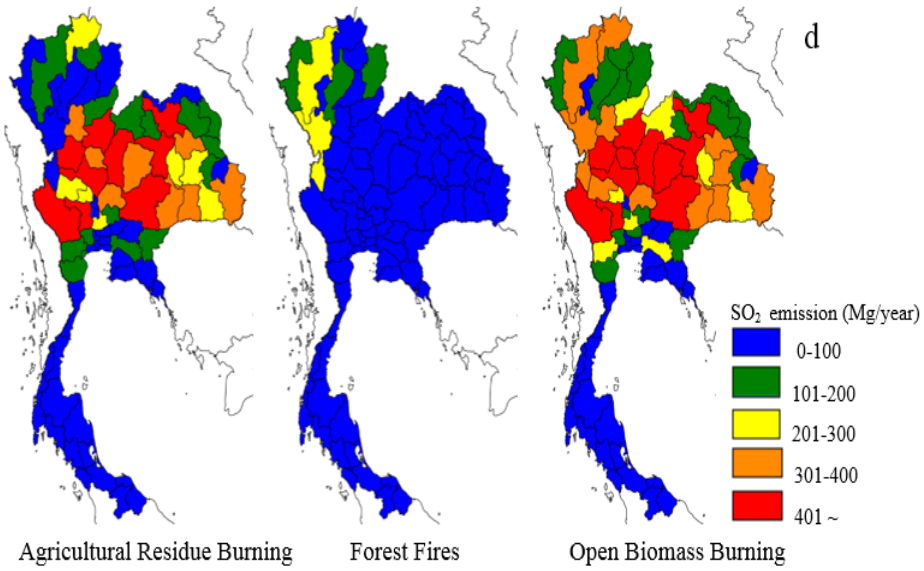
(a) PM_{10}


b
PM2.5 emission (Mg/year)
0-1000
1001-2000
2001-3000
3001-4000
4001 ~
Agricultural Residue Burning
Forest Fires
Open Biomass Burning

(b) $PM_{2.5}$



(c) NO_x



(d) SO_2

Fig. 2.4 Provincial distribution of each pollutant in Thailand, 2014 (a) PM_{10}, (b) $PM_{2.5}$, (c) NO_x, and (d) SO_2

2.3.2 Emission Inventory and Air Quality Data

Air quality is mainly affected by source emission intensity. The author compared the emission inventory of total biomass burning in Thailand with air quality data from air monitoring stations in Thailand. Fig. 2.5-2.9 present correlations between emission inventory and average PM_{10} concentration in the typical provinces of Thailand during a 1-year period (January-December, 2014). Fig. 2.5 Chiang Mai 1 (suburban) and Fig. 2.6 Chiang Mai 2 (urban), representing upper northern Thailand, show a high correlation between average PM_{10} concentration and the emission inventory. R^2 is equal to 0.8300 in Chiang Mai station 1 and 0.8692 in Chiang Mai station 2. In upper northern Thailand, forest fires are clearly the outstanding primary source of air pollutants. The figures show higher emission inventory values of open burning from woodlands during the dry season (January-April and November-December), and lower emission inventory values during the wet season (May-October). However, haze episodes where the PM_{10} exceeds Thailand's national standard occur in March every year. The correlation plot reveals that most of the particulate matter (up to 90%) came from forest fires, while approximately 10% originated from crop residue burning in Chiang Mai.

In contrast, results from Nakhon Sawan in lower northern part, and Khon Kaen and Nakhon Ratchasima in the Northeast of Thailand are presented in Fig. 2.7-2.9. For all three stations, the highest emissions come from burning of crop residues, with R^2 of correlation between PM_{10} concentration and emission inventory is 0.8119, 0.8053 and 0.7923, respectively. In Nakhon Sawan, the highest emission inventory values for open biomass burning were from agricultural trash burning in the dry season, with lower emission inventory values during the wet season. Also, January is the month with the highest emission inventory values from crop residue burning, including rice and sugarcane. Nakhon Sawan is a prominent cultivator of sugarcane, and a large quantity of sugarcane is processed in sugar mills for 5-6 months (from January-April, as well as November-December) every year. The air quality in Nakhon Sawan has deteriorated because of sugarcane residue burning, both of in field and in the factory. Conversely, rice residue burning from major rice harvests (referring to the rice grown during May and October) starts in November and December. It is interesting that crop residue burning after harvesting is delayed around one month from harvesting productions and high uncertainty to use them for others (PCD, 2005). Rice residue burning is significant year round, with elevated values in December and January as well

as in April. The difference from crop burning before harvesting is that air pollutant emissions can reliably be attributed to the harvesting process at the same time (OSCB, 2014)

Fig. 2.8 (Khon Kaen) and Fig. 2.9 (Nakhon Ratchasima) from stations in northeastern Thailand show the same patterns as Nakhon Sawan. Higher emission inventory values were detected in the dry season (from January-April and December), whereas lower emission inventory values were found during the wet season (May-October). In Khon Kaen, the highest emission inventory value is from rice, followed by sugarcane and bagasse burning, and small emission from other sources. Finally, Nakhon Ratchasima is mostly affected by emissions from rice, sugarcane, and cassava, respectively.

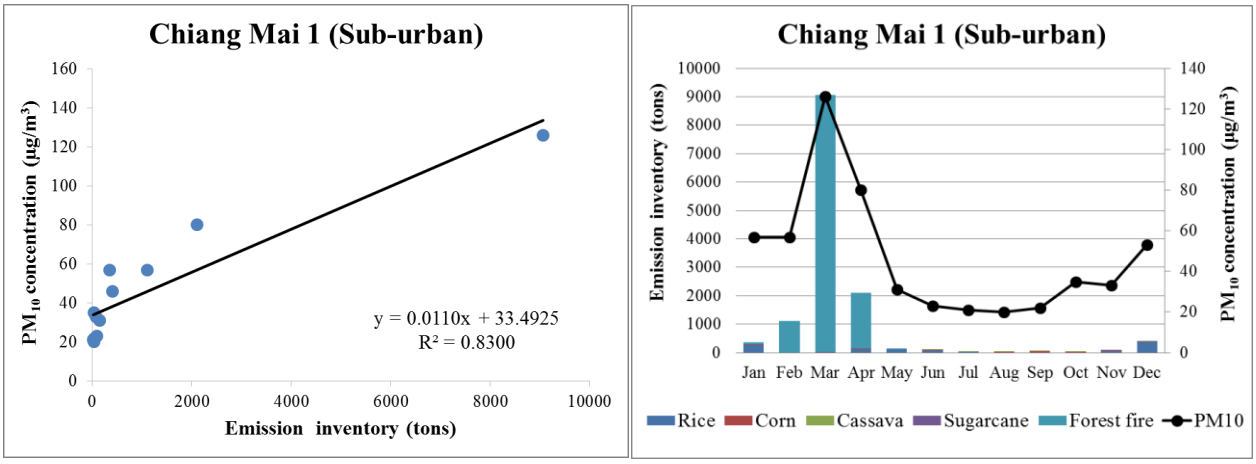


Fig. 2.5 Correlation of emission inventory and PM_{10} concentration in Chiang Mai 1

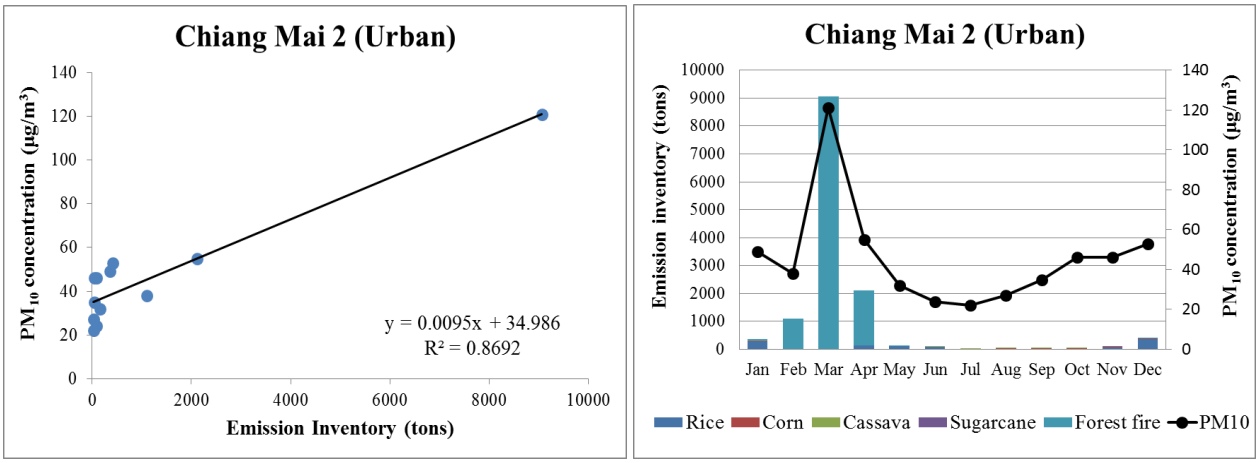
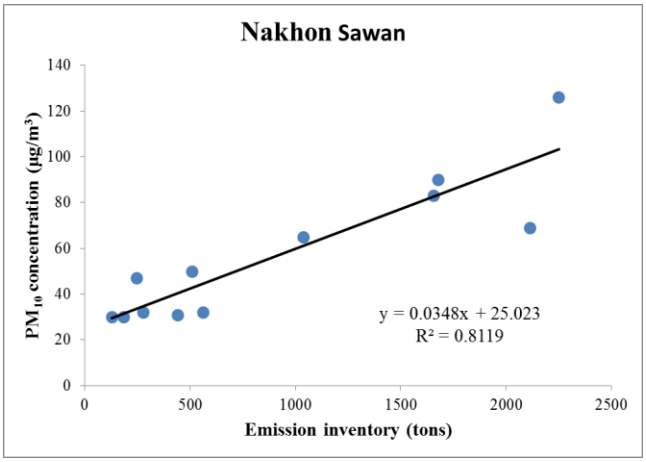


Fig 2.6 Correlation of emission inventory and PM_{10} concentration in Chiang Mai 2



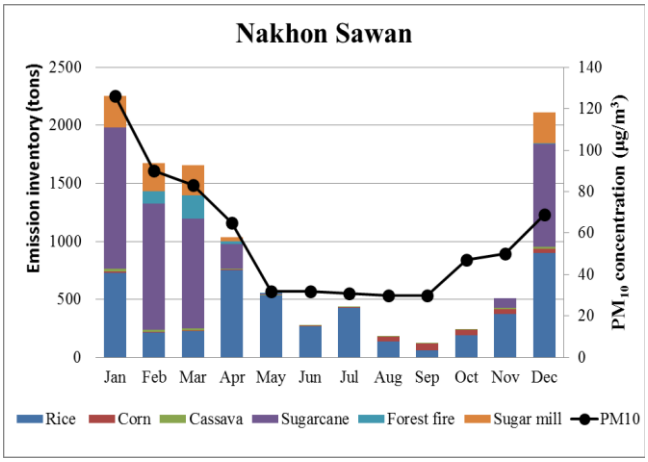
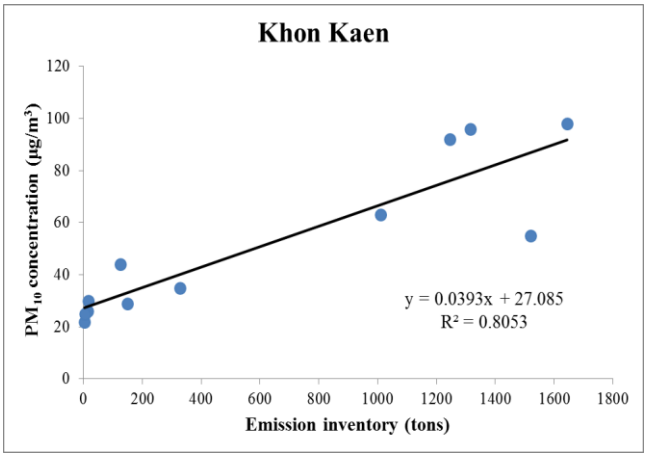


Fig. 2.7 Correlation of emission inventory and PM_{10} concentration in Nakhon Sawan



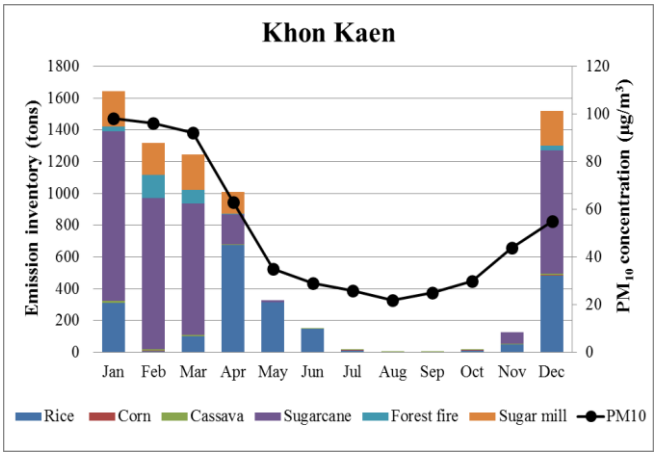
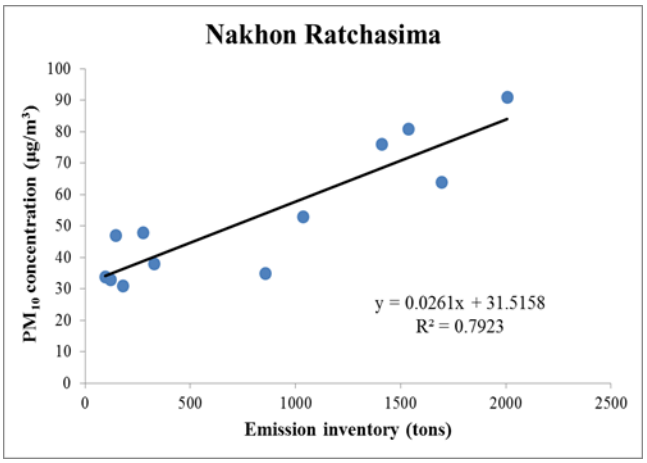


Fig. 2.8 Correlation of emission inventory and PM_{10} concentration in Khon Kaen



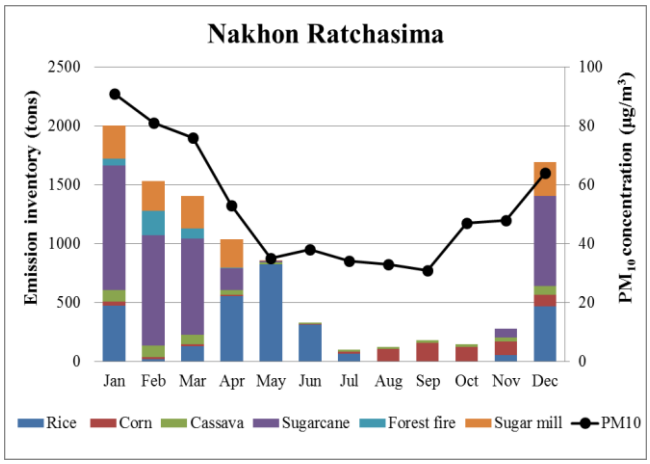


Fig. 2.9 Correlation of emission inventory and PM_{10} concentration in Nakhon Ratchasima

It is worth noting that two stations, namely Chiang Mai 2 (Urban) and Khon Kaen, showed a good correlation between the emission inventory and $PM_{2.5}$ concentration. In the case of Chiang Mai 2, R^2 was 0.8828, while in Khon Kaen R^2 for $PM_{2.5}$ was 0.8425 (Fig 2.10-2.11).

The good correlation between the emission inventory and monthly average PM_{10} concentrations in Thailand confirms that open biomass burning in the dry season is a significant emission source. However, there are considerable differences between the studied areas. Upper northern Thailand is extremely affected by forest fires. The lower north and north-east of Thailand are mainly affected by the agricultural activity in each region.

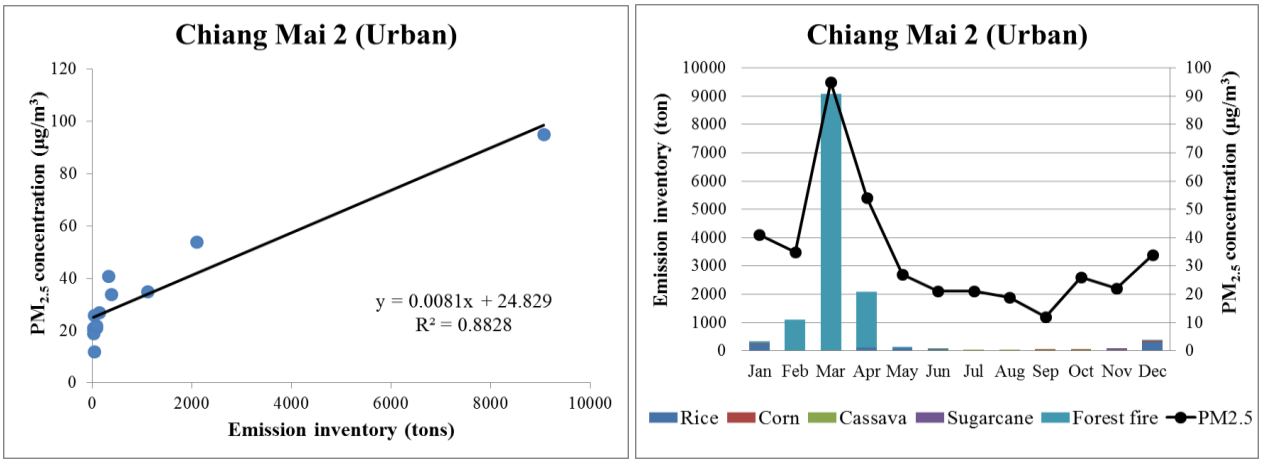


Fig. 2.10 Correlation of emission inventory and $PM_{2.5}$ concentration in Chiang Mai

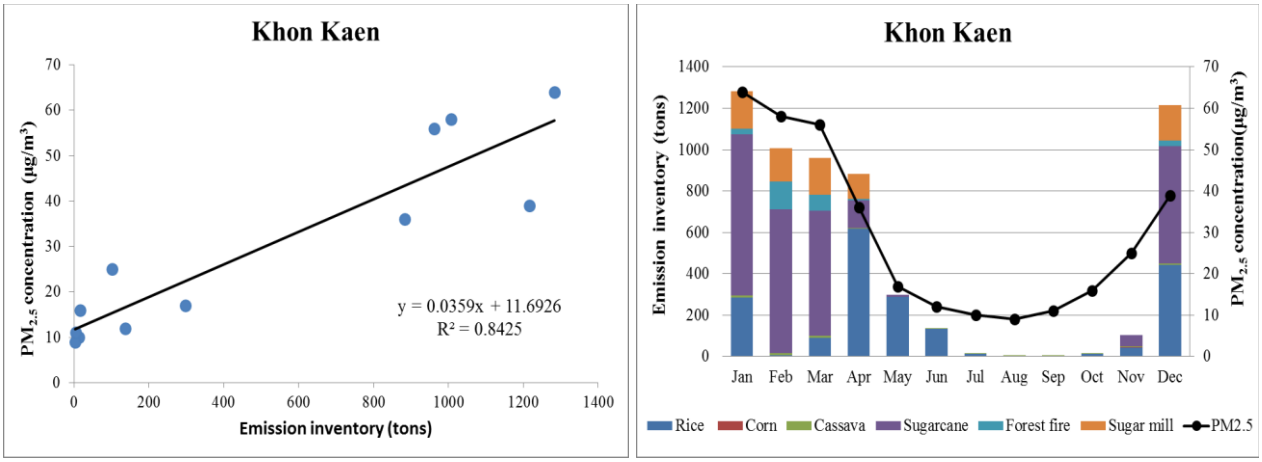


Fig. 2.11 Correlation of emission inventory and $PM_{2.5}$ concentration in Khon Kaen

Chapter 3

Environmental Impact from Agro-Industries in Thailand

3.1 Agro-industries in Thailand

Thailand is an agricultural-based country and has been producing high volumes of food and beverages in the last decade. Many agricultural products need to be processed before contributing to the domestic and international market. Agro-industrial sectors in Thailand still use traditional processes in Thailand (Dhamvithee *et al*., 2005). Several firms and enterprises use agricultural waste as a self-sufficient means to generate power and electricity. A large energy consumption means that a tremendous amount of pollutants are released into the environment. The industrial sector in Thailand can be classified into 9 manufacturing industrial subsectors (DIW, 2013). Energy consumption data for each category show that the food and beverages subsector has the largest energy consumption in Thailand. Also, biomass was the main energy resource in manufacturing in Thailand (Table 3.1). In total, biomass consumption accounted for approximately 29% of the total energy use in the industrial sector (Fig. 3.1).

Table 3.1 Energy consumption in the manufacturing sector by sub-sectors (2013)

unit (ktoe)*

Subsector	Lignite and Coal	Petroleum	Natural Gas	Electricity	Biomass	Total
Food and beverages	624	1,186	108	1,143	6,546	9,607
Textile	87	158	27	589	8	869
Wood and Furniture	0	154	13	161	18	346
Pulp and Paper	221	181	726	208	400	1,736
Chemical	516	514	604	930	255	2,819
Non-Metal	4,232	338	739	585	503	6,397
Basic Metal	116	424	280	606	0	1,426
Fabricated Metal	0	369	91	1,421	0	1,881
Others	151	1,576	41	81	0	1,849
Total	5,947	4,900	2,629	5,724	7,730	26,930

*thousand tons of oil equivalent (ktoe)

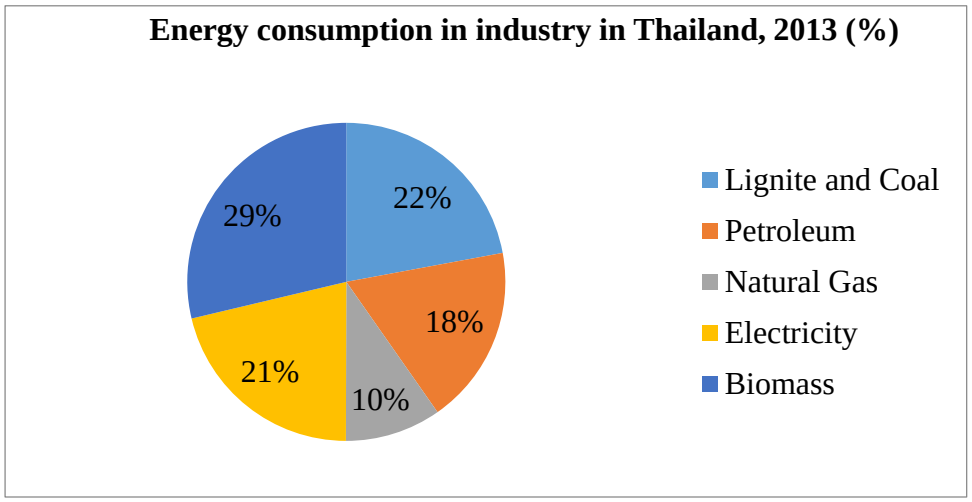


Fig. 3.1 The percentage of energy consumption types in industrial sector in Thailand

In 2013, the primary source of biomass fuel in Thailand in the industry sector was bagasse (sugarcane residue). Sugarcane was the highest production crop in Thailand. Biomass residues from sugarcane, both in and off the field, are burned every year. All sugar mills use residue from the sugarcane extraction process to supply the factories with energy. Biomass residue from sugarcane accounted for 51% of the total biomass waste consumption in Thailand (Fig. 3.2). Other important biomass residues were fuel wood (9%), rice husk (6%) and biogas (6%). The remaining 28% included palm oil waste and mixed biomass fuel used in boilers for energy production.

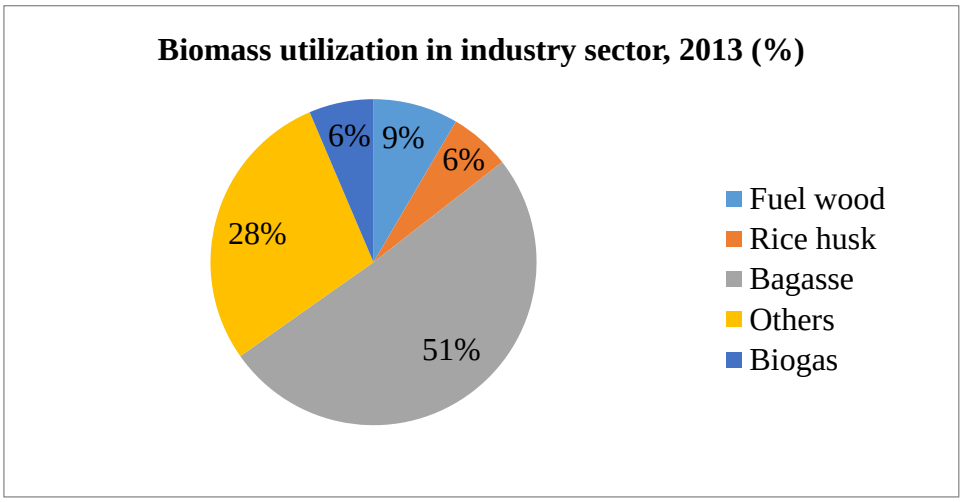


Fig. 3.2 The percentage of biomass utilization in industry in Thailand

This chapter aims to estimate the amount of emissions from the agro-industry in Thailand. An emission inventory of each pollutant, including PM_{10}, $PM_{2.5}$, NO_x, and SO_2, was performed to estimate the total annual amount and monthly average concentrations. Thereafter, biomass burning results from open burning and the agro-industry were integrated with the total biomass burning emissions in Thailand from chapter 2, and subsequently compared with air quality data.

3.2 Methodology

3.2.1 Agro-industry Emission

Emission estimates of fuel consumption in biomass boilers of agro-industry on a national level were multiplied with an Emission Factor.

(1) $$E = EFuncontrolled\ x\ (1 - ER)\ x\ A = EFcontrolled\ x\ A$$

Where, E = Emission of air pollutants

A = Fuel consumption rate by sub-category and fuel type (GJ/year or ton/year)

EF = Emission Factor by sub-category and fuel type (g/GJ or g/ton)

EF$uncontrolled$ = Emission Factor not under any pollution control device

ER = Emission control efficiency for each agro-industry type

EF$controlled$ = Emission Factor controlled by available technology

The Emission Factors (EF) for the biomass fuel in this study were taken from EMEP/EEA Emission Inventory Guidebook 2009. The EF of PM_{10}, $PM_{2.5}$, SO_2 and NO_x uses in term of solid biomass fuel.

(2) $$A = F\ x\ NCV$$

Where, A = Fuel consumption rate by sub-category and fuel type (TJ/year).

F = Fuel consumption rate by sub-category and fuel type (Gg/year)

NCV = Net Calorific Value: Net Calorific Value per weight (TJ/Gg)

NCV varies between different countries, depending on fuel production region and fuel standards of the country. Subsequently, country-specific NVC data should be used as much as possible. Table 3.2 shows residue production crops with Net Calorific Values (Heat content) and the available amount of each residue in the agricultural sector in Thailand.

Table 3.2 The potential of agricultural residues and Net Calorific Value (Heat content) in Thailand, 2014 (DEDE, 2011)

Crop	Production (10^3 tons)	Types of residue	Conversion factor			Residue amount
			Residue ratio	Surplus Available Factor	Heat Content (TJ/Gg)	(10^3 tons)
Sugarcane	103,697	Top and Leave	0.37	0.98	15.31	38,367.89
		*Bagasse	0.29	0.01	7.53	30,072.13
Rice	33,808	Stalk	0.45	0.78	13.80	15,213.6
		*Husk	0.23	0.45	14.40	7,775.84
Corn	4,805	Stalk	0.89	N/A	16.01	4,276.45
		*Cob	0.19	0.58	16.78	912.95
Cassava	30,022	Stalk	0.09	0.70	15.59	2,701.98
		*Rhizome	0.12	0.98	16.11	3,602.64
Oil palm	12,503	Empty Bunches	0.28	0.58	16.32	3,500.84
		*Fiber	0.12	0.13	17.25	1,500.36
		*Kernel Shell	0.08	0.04	18.53	1,000.24
		Frond	0.27	1.00	16.03	3,375.81
Coconut	1,000	*Husk	0.36	0.59	16.41	360.00
		Shell	0.16	0.38	18.26	160.00
		Bunches	0.05	0.84	15.43	50.00
Soybean	51	*Stalk, Leave, Shell	2.66	0.76	16.23	135.66
Fuelwood	4,432	*Para-rubber	0.38	N/A	15.99	1,684.16
Sawdust	NA	N/A	0.38	N/A	10.88	N/A

N/A = Not Available

*Used in biomass boilers in agro-industry

For emission control technology in agro-industry, Environmental Impact Assessment Reports (EIA reports) of sugar factories were reviewed for estimating reduction efficiency. In summary, all of them use multi-cyclones for controlling particulate matter before releasing flue gas into the atmosphere. A standard multi-cyclone used in connection with bagasse burning in a sugarcane mill has an estimated reduction efficiency of 60%. Nonetheless, for NO_x and SO_2 reduction efficiency, the Emission Factor not under any pollution control device was estimated owing to shortage of reliable data. Moreover, other biomass boilers were lacking up-to-date data for the pollution control device. The authors calculated for all types of pollutants with EFs not under any pollution control device. Also, data for pollution control devices for use of other types of biomass in boilers could not be accessed.

Table 3.3 Number of boilers using biomass in Thailand

Biomass type	No. of boilers	Total boilers capacity (ton/hr)	% capacity
Bagasse	174	15,878.0	46.42
Wood (Chip, dust, etc.)	1,589	10,416.8	30.45
Rice husk	618	3,355.0	9.81
Oil palm	215	3,080.3	9.01
Wood + oil palm shell	23	682.1	1.99
Wood + bagasse	8	472.0	1.38
Corn peel	32	102.3	0.30
Coconut shell	16	65.1	0.19
Wood + rice husk	1	50.0	0.15
Wood + corn cobs	5	38.3	0.11
Corn cobs	8	37.1	0.11
Coffee grounds	1	13.2	0.04
Wood + coconut shell	2	6.1	0.02
Soybean meal	2	5.6	0.02
Cotton shell	1	2.4	0.01
Banana peel	1	1.0	0.00
Total	2,696	34,205.3	100.00

The total number of biomass boilers in Thailand is approximately 2,696 boilers; bagasse burning by sugar factories account for nearly half (46%) the total boiler capacity, followed by fuel wood (30%), rice husk (~10%) and palm oil residues (9%). The four dominant types of biomass residue in the agro-industry occupy up to 96% in term of solid biomass fuel. The remaining biomass boilers using other crops and co-biomass fuel represent only around 4% of biomass boilers in Thailand. (Sattayawuthiphong, 2013)

3.2.2 Bottom-up approach of emission inventory from industry in Songkhla, southern Thailand

An emission inventory from industry sectors in Songkhla province in southern Thailand was estimated for the annual emission inventory, including PM_{10}, $PM_{2.5}$, NO_x, and SO_2. Activity data came from local level, specific to the fuel boilers used in the manufacturing sector. Industry in southern Thailand is mainly based on agriculture, including aquaculture, para rubber, and palm oil. Relating to emission control technology, local data on pollution control device use in Songkhla were unavailable in the different manufacturing sectors.

3.3 Results and Discussion

3.3.1 Annual Emissions

Table 3.4 shows annual emission estimates per biomass boiler type used in the agro-industry in Thailand. It is interesting to note that the highest emissions came from wood boilers. This is because of the enormous number of wood boilers in the agro-industry in Thailand. After wood, the highest emission were from bagasse, rice husk, oil palm, respectively. Other types of boiler fuel and mixed fuel only stand for a small portion of the total annual emissions. The highest pollutant was NO_x emissions with around 104,924 tons/year, followed by PM_{10} 84,748, $PM_{2.5}$ 84,183 and SO_2 26,944 tons, respectively.

Table 3.4 Total emission of air pollutants from biomass boilers in Thailand, 2014

Biomass type	PM_{10}	$PM_{2.5}$	NO_X	SO_2
	(tons/year)			
Bagasse	13,451	13,361	33,627	8,608
Wood (Chip, dust, etc.)	48,367	48,044	48,367	12,382
Rice husk	9,238	9,176	9,238	2,365
Oil palm	5,862	5,823	5,862	1,501
Wood + oil palm shell	4,069	4,042	4,069	1,042
Wood + bagasse	1,918	1,906	1,918	491
Corn peel	581	577	581	149
Coconut shell	411	408	411	105
Wood + rice husk	263	261	263	67
Wood + corn cobs	217	215	217	56
Corn cobs	215	214	215	55
Coffee grounds	73	72	73	19
Wood + coconut shell	36	36	36	92
Soybean meal	31	31	31	8
Cotton shell	12	12	12	3
Banana peel	5	5	5	1
Total	84,748	84,183	104,924	26,944

PM_{10}, $PM_{2.5}$ and NO_x emissions were comparatively equivalent between different boiler types, relying on EFs that are quite similar for estimating emissions in industrial boilers. However, PM emissions from bagasse boilers were slightly lower compared to NO_x. The main reason is that all sugar mills in Thailand already use installed multi-cyclones before releasing dust into the atmosphere. There were lacking data on collection efficiency for NO_x and SO_2 as well as PM from other biomass boilers (except bagasse). Sugar factories make up such a large part of the food and beverage industry in Thailand that the enormous emissions from the production process had to be controlled, which is why the mills were equipped with pollution control devices.

3.3.2 Emission Inventory from Agro-industry in Songkhla

Agro-industry in Songkhla province mainly consumed biomass energy for the production process. Total PM_{10} and $PM_{2.5}$ emissions from biomass fuel were 2,674 and 2,859 tons/year, respectively (Table 3.5). Regarding types of solid biomass energy used, wood was the main fuel in the process and accounted for up to 93% of total PM emissions from the agro-industry sector (Fig 3.3). On the other hand, the percentage of NO_x and SO_2 emitted from agro-industry is different from PM. The amount of NO_x from biomass boilers is quite similar to the PM amount, around 2,625 tons/year, but only represent 61% of total NO_x emissions. NO_x from other fuel types, including diesel and C grade fuel oil, account for approximately 1,710 tons (39%) of the emissions. Also, SO_2 is widely released from fossil fuel types, with emissions up to 8,691 tons (92%), while a much smaller amount is emitted from solid biomass fuel; 731 tons (8%). Regarding energy sources used in agro-industry, fuel wood is largely used in the southern region of Thailand. Biomass fuel releases an enormous amount of PM in the atmosphere. There is a lack of reliable data for an emission control device for controlling particles from the industry processes that is subject to causing considerable air pollution in this area.

Table 3.5 Emission of air pollutants from industry in Songkhla, Thailand, 2014

Types	Emission (tons/year)			
	PM_{10}	$PM_{2.5}$	NO_x	SO_2
Emission by biomass fuel	2,674	2,656	2,625	731
Emission except biomass	203	203	1,710	7,960
Emission by industry	2,877	2,859	4,335	8,691

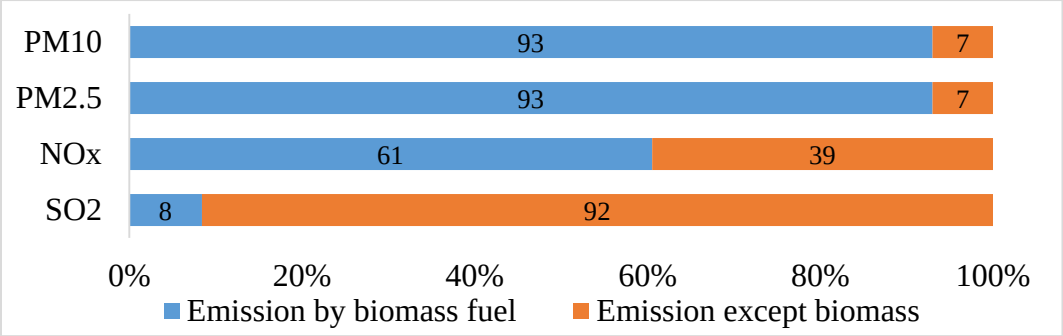
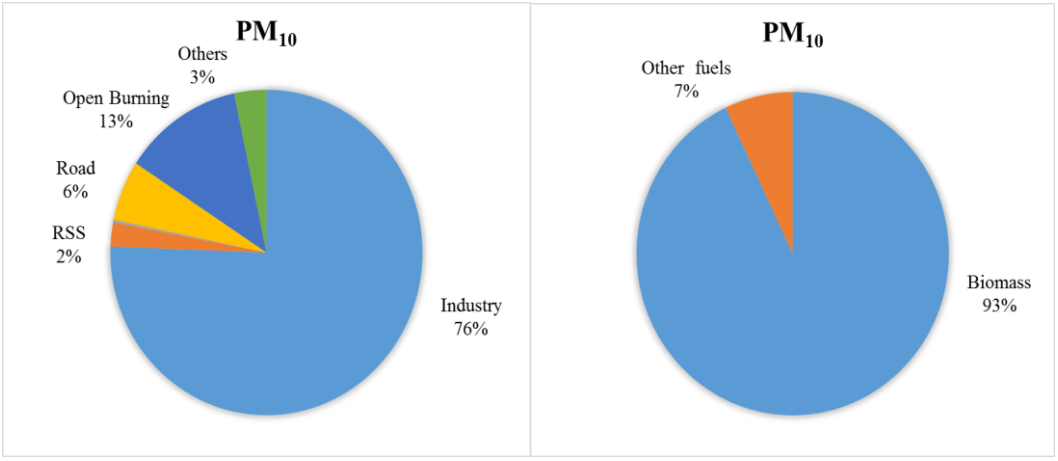


Fig. 3.3 Contribution of air pollutant emission from agro-industry in Songkhla, Thailand

Table 3.6 Total emission inventory in Songkhla by emission source

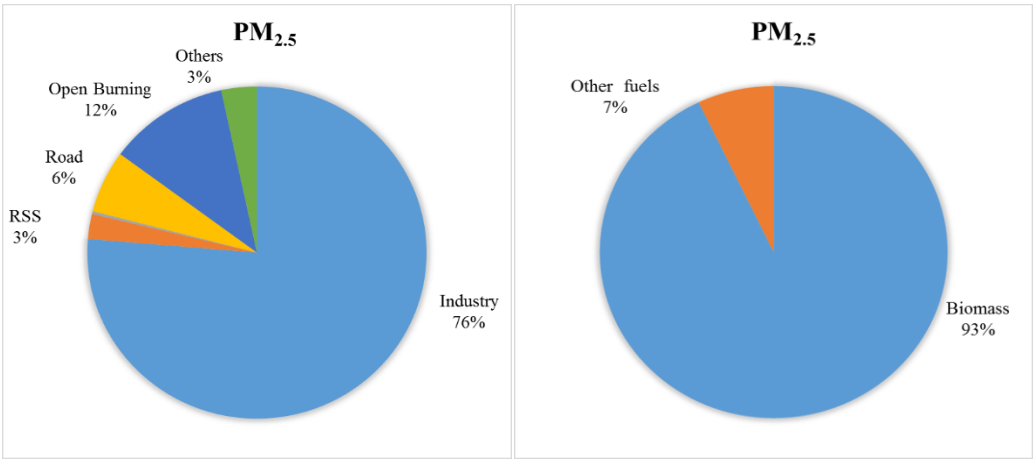
Type	Annual Emission (tons/year)			
	PM_{10}	$PM_{2.5}$	NO_X	SO_2
Industry	2,877	2,859	4,335	8,691
- Biomass fuel	2,674	2,656	2,625	731
- Other fuels	203	203	1,710	7,960
RSS	91	91	91	7
Resident	10	10	43	0
Road	228	228	1,174	62
Open Burning	473	431	292	41
Others	127	127	555	1,181
Total	3,806	3,746	6,490	9,981

Table 3.6 shows that a very large part of the PM_{10}, $PM_{2.5}$, and NO_x emissions came from biomass boilers in relation to other source types in the Songkhla province. On the other hand, SO_2 was mostly emitted from other fuel types in the industry. Other sources, such as road transportation, resident, and open burning, had a small share of total emissions in the Songkhla ambient air.



(a) (b)

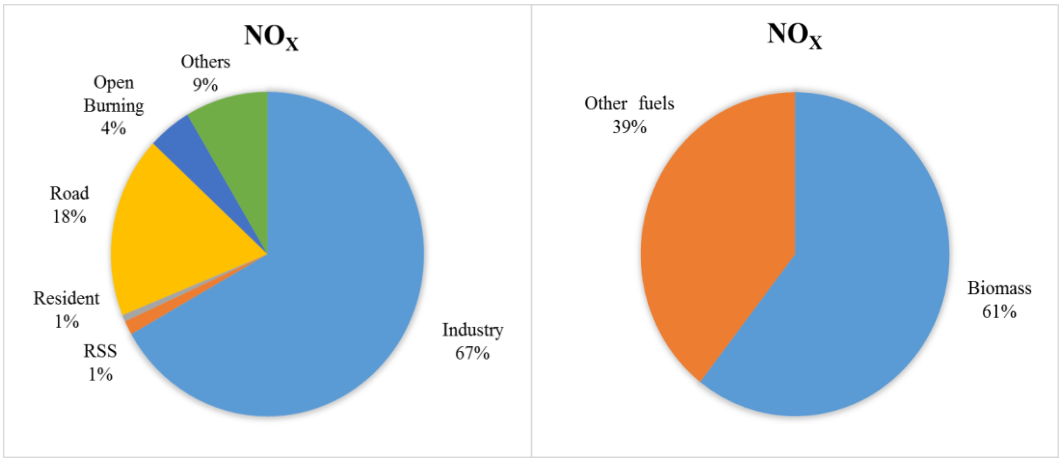
Fig. 3.4 (a) PM_{10} emissions by source in Songkhla;
(b) Contribution of biomass combustion for PM10 emissions



(a) (b)

Fig. 3.5 (a) $PM_{2.5}$ emissions by source in Songkhla;

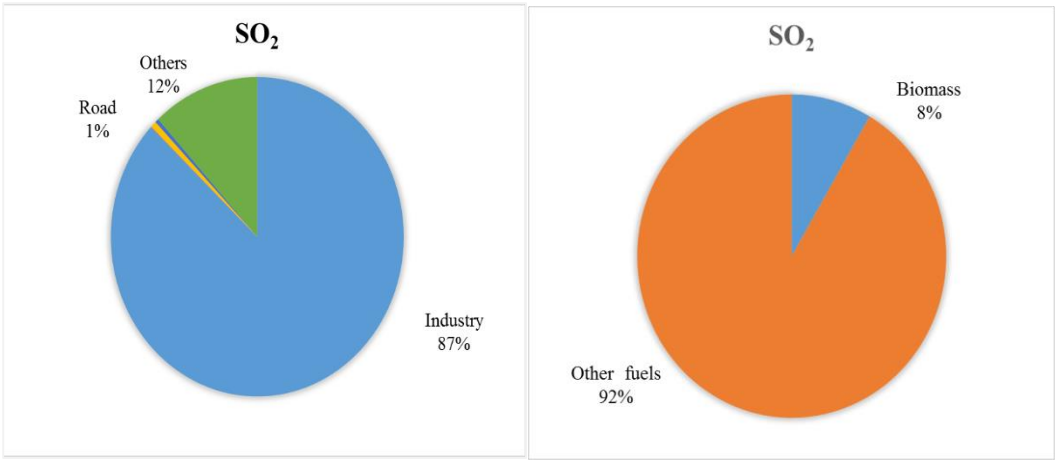
(b) Contribution of biomass combustion for $PM_{2.5}$ emissions



(a) (b)

Fig. 3.6 (a) NO_x emissions by source in Songkhla;

(b) Contribution of biomass combustion for NO_x emissions



(a) (b)

Fig. 3.7 (a) SO_2 emissions by source in Songkhla;
(b) Contribution of biomass combustion for SO_2 emissions

Fig. 3.4-3.7 show the percentage of each pollutant contribution in Songkhla province. PM_{10} and $PM_{2.5}$ were largely contributed from agro-industry boilers. Industry emissions contributed to up to 76% of the PM emissions in Songkhla. Moreover, biomass consumption in agro-industry accounted for approximately 93% of the emitted amount. NOx mainly originated from industry (67%), followed by road transportation (18%), and other sources representing a small emission share. In agro-industry, 61% of NOx emissions came from biomass consumption and 39% from other fuel, including crude oil and diesel. SO_2 emissions came mainly from industry (87%). However, the biggest source of SO_2 emissions in the agro-industry was by far other fuels (92%), with solid biomass consumption making up the remaining 8%.

Chapter 4

Carbon Components in Size-segregated Distribution of Particulate Matter in Thailand

This chapter studies carbon composition in the size distribution of particulate matter in Thailand during 2014-2015. Particulate matter was collected at two sampling sites in Thailand, namely Bangkok and Chiang Mai. Samples were collected by a Nano-sampler that consists of a four stage impactor and an inertial filter to separate particulate matter according to size. The carbon component was determined for confirming the particle sources and identify potential sources. The identification of carbonaceous compounds of particulate matter, including organic carbon (OC) and elemental carbon (EC), is very important. The major sources of EC are incomplete combustion of fossil and biomass fuel, whereas OC originates from primary sources or is produced by chemical reactions involving gaseous organic precursors. The aim of this study is to investigate the size distributions and identify possible sources of carbon components in ambient air in Thailand depend on emission inventory analysis. The methodological condition and backward trajectory used for described the contribution of biomass burning and transportation.

4.1 Sampling Locations

1) Bangkok

Bangkok is the capital and economic center of Thailand. The climate in Bangkok is tropical and influenced by monsoons. Moreover, the year can divided into a rainy and a dry season. The rainy season starts in mid-May, depending on the southwest monsoon, and ends in October each year. The wettest month with the highest precipitation is September. The cool dry season runs between November and February under the northeast monsoon. Finally, the summer dry season is in March and April.

The sampling site was located on the rooftop of the 10^{th} floor, Faculty of Applied Science, King Mongkut's University of Technology North Bangkok (KMUTNB) (Fig 4.1). This location is representative of the Bangkok Metropolitan Region (BMR) in Thailand.

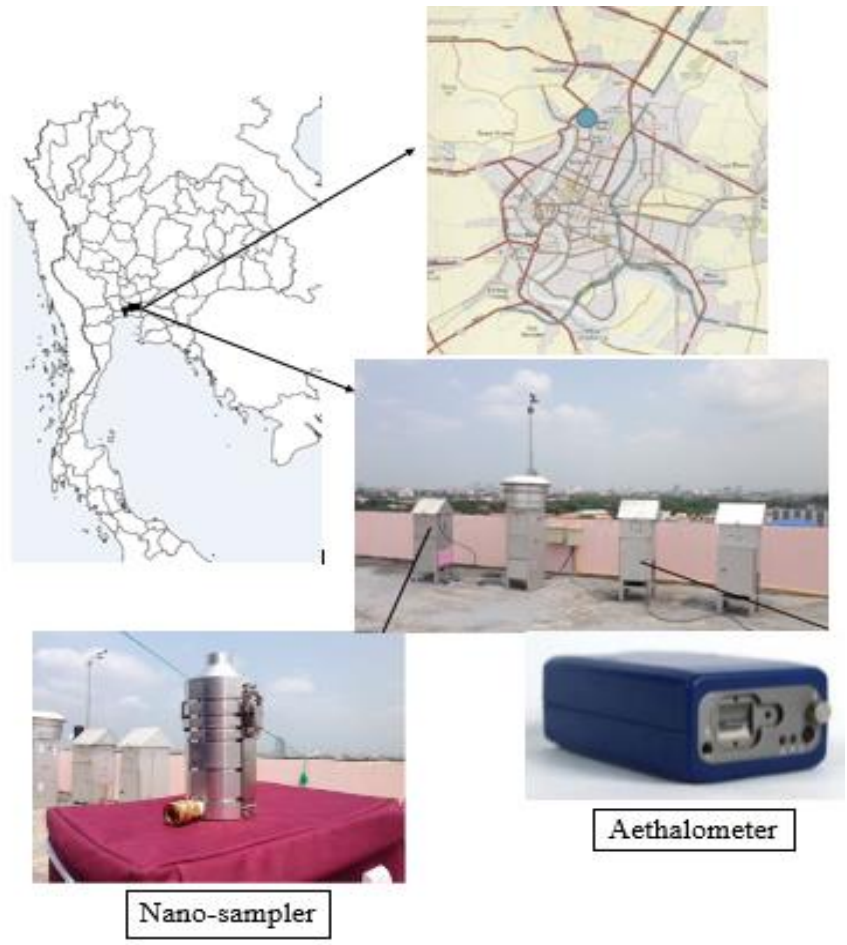


Fig. 4.1 Sampling site at King Mongkut's University of Technology North Bangkok, Bangkok

2) Chiang Mai

Chiang Mai is the second largest city in Thailand after Bangkok and the largest municipality in northern Thailand. The climate of Chiang Mai is tropical with a wet and a dry season, influenced by monsoons. The wet and the dry seasons correspond to those in Bangkok. However, Chiang Mai is tempered by the low latitude and moderate elevation, with warm to hot weather year-round. The sampling site was located on the fifth floor of the biology department, Faculty of Science, Chiang Mai University (CMU) (Fig 4.2).

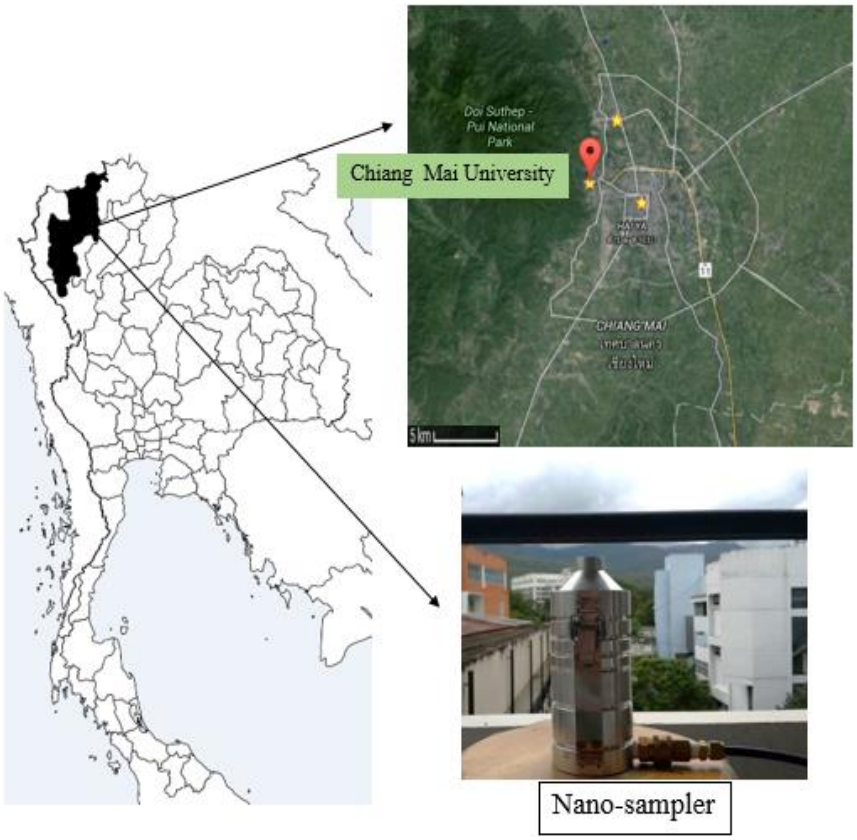


Fig. 4.2 Sampling site at Chiang Mai University, Chiang Mai

4.2 Experimental conditions

For field sampling, both the KMUTNB and CMU sites used a Nano-sampler with four impactor stages (>10, 2.5-10, 1-2.5, 0.5-1 µm), and an inertial filter stage (0.1-0.5 µm) as well as a backup filter (<0.1 µm). The operation air inlet of the Nano-sampler was 40 l/min. The KMUTNB sampler collected every six days (5 times/month) for 24 hours per sampling. In contrast, the CMU sampler collected every ten days (3 times/ month) for 24 hours per sampling.

Each of the five size-segregation stages used a 55 mm diameter quartz filter (Pallflex Tissuquartz filter 2500AT-UP). Pre-baking of the filters at high temperature is compulsory to reduce organic components. In this study, the author baked the quartz fiber filters in the furnace at 350 ºC for 1 hour. Before and after sampling, the filters were put into the chamber. The chamber controlled temperature and humidity to reduce negative effects to mass concentration and carbon components in each sampling. In the chamber, conditions were controlled with relative humidity

at 35±5% and air temperature at 21.5±2 ºC. Moreover, travel blanks were used to investigate the adsorption of gas-phase carbon components during sampling.

4.3 Carbon Analysis

1) Thermal-Optical Method

Carbonaceous components were analyzed by a Sunset Laboratory Carbon Aerosol Analyzer, according to the Improve_TOR method (Improve_Thermal/Optical Reflectance) (Chow *et al.*, 2004; Watson *et al*., 2005). The organic carbon (OC) and elemental carbon (EC) was detected by difference in temperature. OC was defined as the sum of OC fractions (OC1, OC2, OC3 and OC4 at 120, 250, 450 and 550 ºC, respectively) in the non-oxidizing helium atmosphere. The EC was examined (EC1, EC2, and EC3 at 550, 700, 800 ºC, respectively) in a 2% O_2 and 98% Helium atmosphere), as well as POC (a pyrolyzed carbon fraction). Therefore, EC fractions refer to EC1+EC2+EC3-POC. EC can be further divided into Char-EC and Soot-EC. Char-EC was defined as EC1-POC, while Soot-EC refers to EC2+EC3 (Han *et al*., 2007).

2) Optical Method

Black carbon (BC) is identical to Elemental carbon (EC). The term BC is used when the optical method is applied, while EC is preferred when the thermal method is used. BC concentrations at KMUTNB site were measured using an aethalometer (MicroAeth® Model AE51, Magee Scientific). Particulate matter was collected by a glass fiber filter and light absorption was analyzed to calculate BC concentration. The aethalometer operated according to the same schedule as the Nano-sampler, on a 24-hour basis for 6 days.

4.4 Air Mass Trajectories

Backward trajectories were calculated from air mass directions using Hybrid Single-Particle Langrangian Integrated Trajectory Model version 4 (HYSPLIT4). This model is available online at http://ready.arl.noaa.gov/HYSPLIT.php. The author calculated the 48-hour backward trajectory in Bangkok and Chiang Mai. Furthermore, the HYSPLIT4 model includes a vertical motion option to estimate the air mass arriving at 50 m from Average Ground Level (AGL) in each province.

4.5 Results and Discussion

4.5.1 Characteristics of Particulate Matter in Bangkok, Thailand

1) Mass Concentration

At the KMUTNB site, the sampling period was 5 times per month, running from August 2014 to July 2015, including both a Nano-sampler and an Aethalometer. The mass concentration of each size-segregated PM was divided into a wet and a dry season. The rainy season was defined as August-October 2014 and also included May- July 2015 (6 months). Consequently, the dry season comprised November-December 2014 and January-April 2015.

The seasonal variation of particulate matter according to diameter is displayed in Fig. 4.4. For both of the wet and dry season, the highest particle concentration peak was seen in the 2.5-10 µm range. In the dry season, the second highest in mass concentration was observed for the particle size range of 0.5-1.0 µm. In the rainy season, on the other hand, the particle size range >10 µm was the second highest. Overall, particulate matter concentrations were lower in the rainy season than in the dry season, most likely because regular rainfalls reduced particle concentrations.

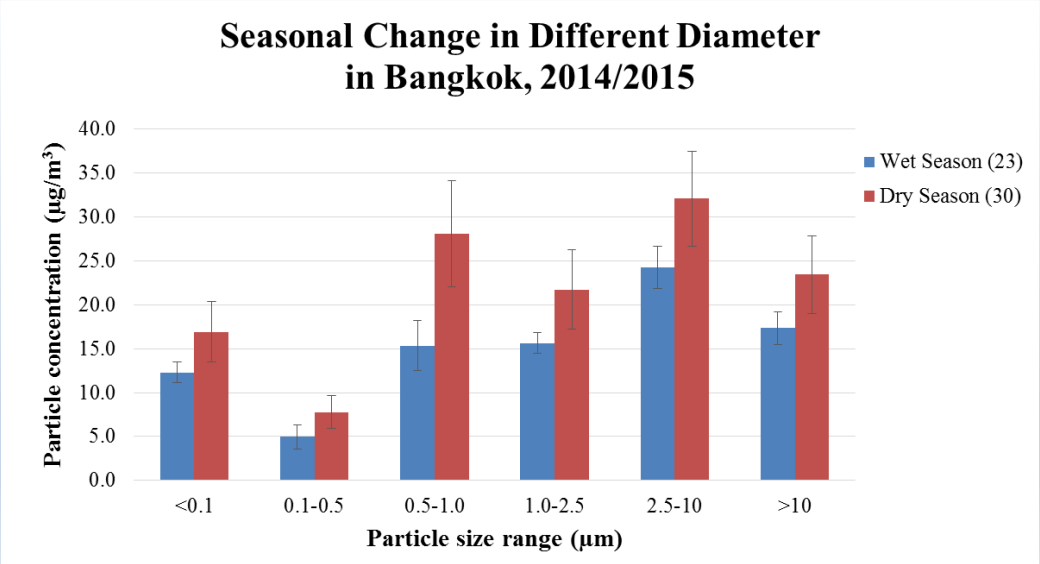


Fig. 4.3 Seasonal changes by diameter in Bangkok, 2014/2015

The concentration of $PM_{0.1}$, $PM_{0.5}$, PM_{1}, $PM_{2.5}$, PM_{10} and TSP were 14.80±3.23 µg/m^3, 21.13±4.96 µg/m^3, 42.99±12.60 µg/m^3, 61.74±16.90 µg/m^3, 89.57±22.63 µg/m^3 and 109.68±27.14 µg/m^3, respectively. According to Thailand Ambient Air standard, 24-hr of total particulate matter (TSP) should not exceed 330 µg/m^3, PM_{10} should be below 120 µg/m^3 and $PM_{2.5}$ should be less

than 50 µg/m^3. The results show that while the TSP did not exceed Thai standard, PM_{10} exceeded the standard in 9 dry season samples out of 53 total annual samplings. Regarding $PM_{2.5,}$ 37 out of 53 $PM_{2.5}$ samples exceeded the daily standard in Thailand. Fig 4.5 shows the mass concentration for each particle size, divided between the wet and dry season in Bangkok ambient air.

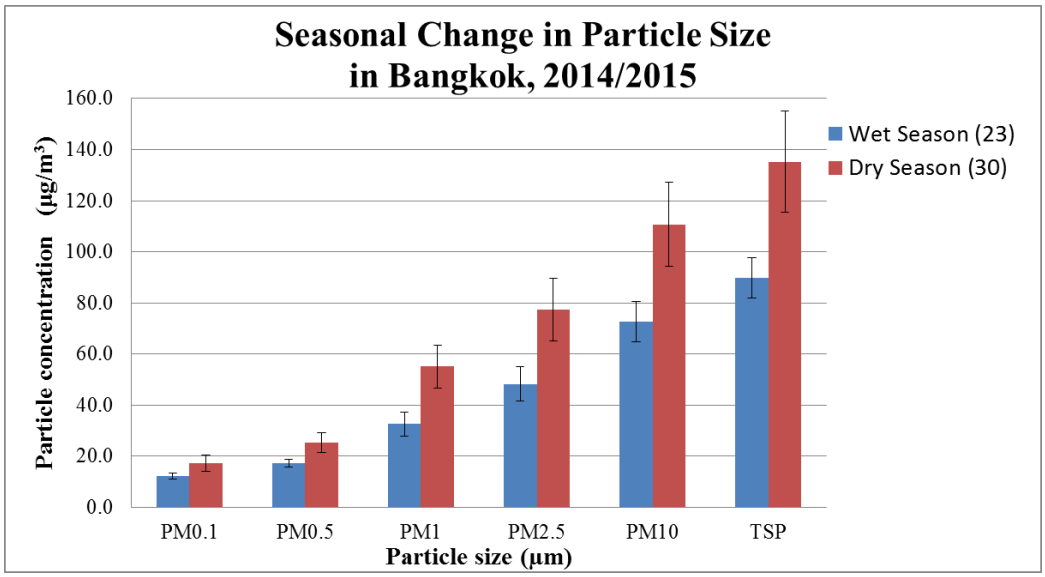


Fig. 4.4 Seasonal changes in particle size in Bangkok, 2014/2015

Monthly average mass concentrations of size-segregated particulate matter collected from August 2014 to July 2015 are displayed in Fig. 4.5 and Table 4.1. The particulate matter was low in August–October, and rapidly increased in November, which is the start of the early dry season in Thailand. Then, the particulate matter decreased slightly in December and increased again in January, after which it dropped continuously from February to July. The results show that the mass concentration peaked in the dry season, especially in the November and January. The burning of biomass residue is very small in Bangkok, but Bangkok Metropolitan Region (BMR) includes 6 provinces near Bangkok, where November and January are high season for rice residue burning after harvesting for major rice producers. Therefore, the particulate matter is much higher than during other periods when there is no crop residue burning in the neighboring provinces.

Table 4.1 Monthly average concentrations (µg/m^3) in Bangkok from 2014-2015

	2014					2015						
	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July
$PM_{0.1}$	12.9	13.5	12.3	23.3	16.4	17.7	15.6	14.8	16.0	13.4	12.3	11.6
$PM_{2.5}$	47.3	53.5	55.8	92.8	74.5	91.0	68.2	62.1	75.8	50.5	42.5	44.5
PM_{10}	69.6	78.9	80.2	132.4	107.1	127.6	99.2	89.3	108.9	73.7	63.6	69.8
TSP	86.4	98.0	96.3	162.2	127.9	155.2	122.0	110.7	132.8	90.3	78.8	86.6

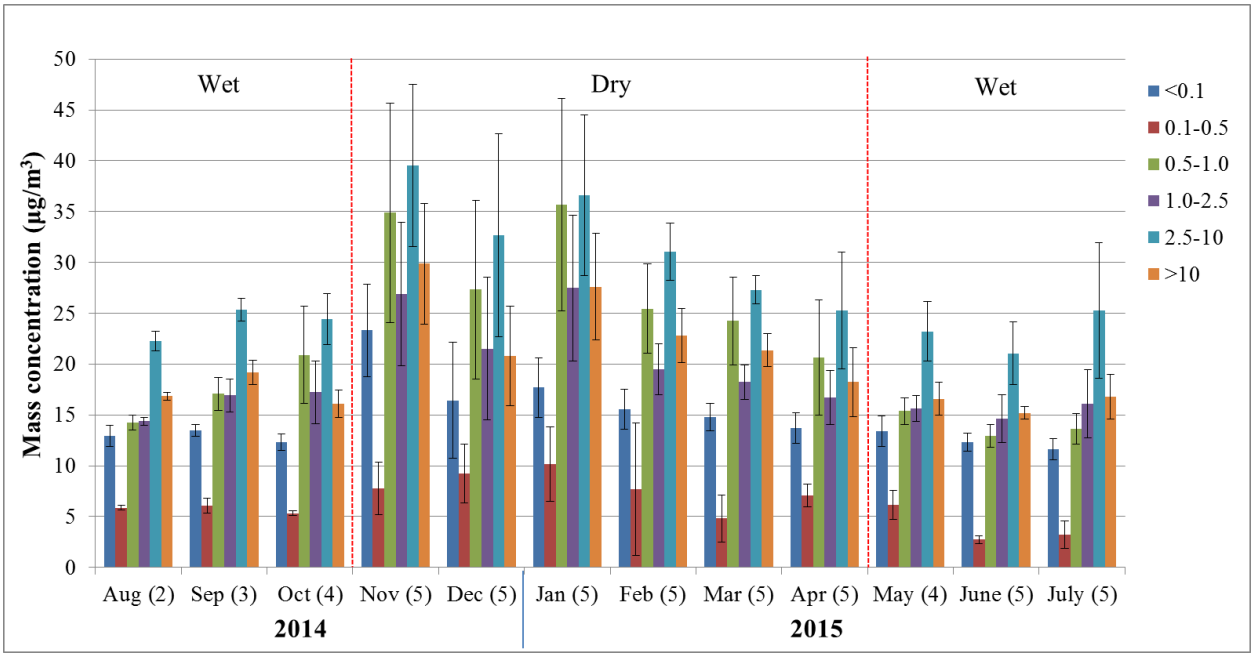


Fig. 4.5 Monthly average particle concentrations according to size in Bangkok from 2014-2015

2) Potential Sources of PMs

The mass concentration in Bangkok ambient air is mainly affected by source emission intensity. The author compared emission inventories of total biomass burning in some provinces near Bangkok, including 5 provinces in Bangkok Metropolitan Region (Nakhon Pathom, Nonthaburi, Pathum Thani, Samut Sakorn and Samut Prakan) as well as Ayutthaya, Suphanburi, Chachoengsao, Nakhon Sawan and Nakhon Ratchasima, with air quality data from the KMUTNB station.

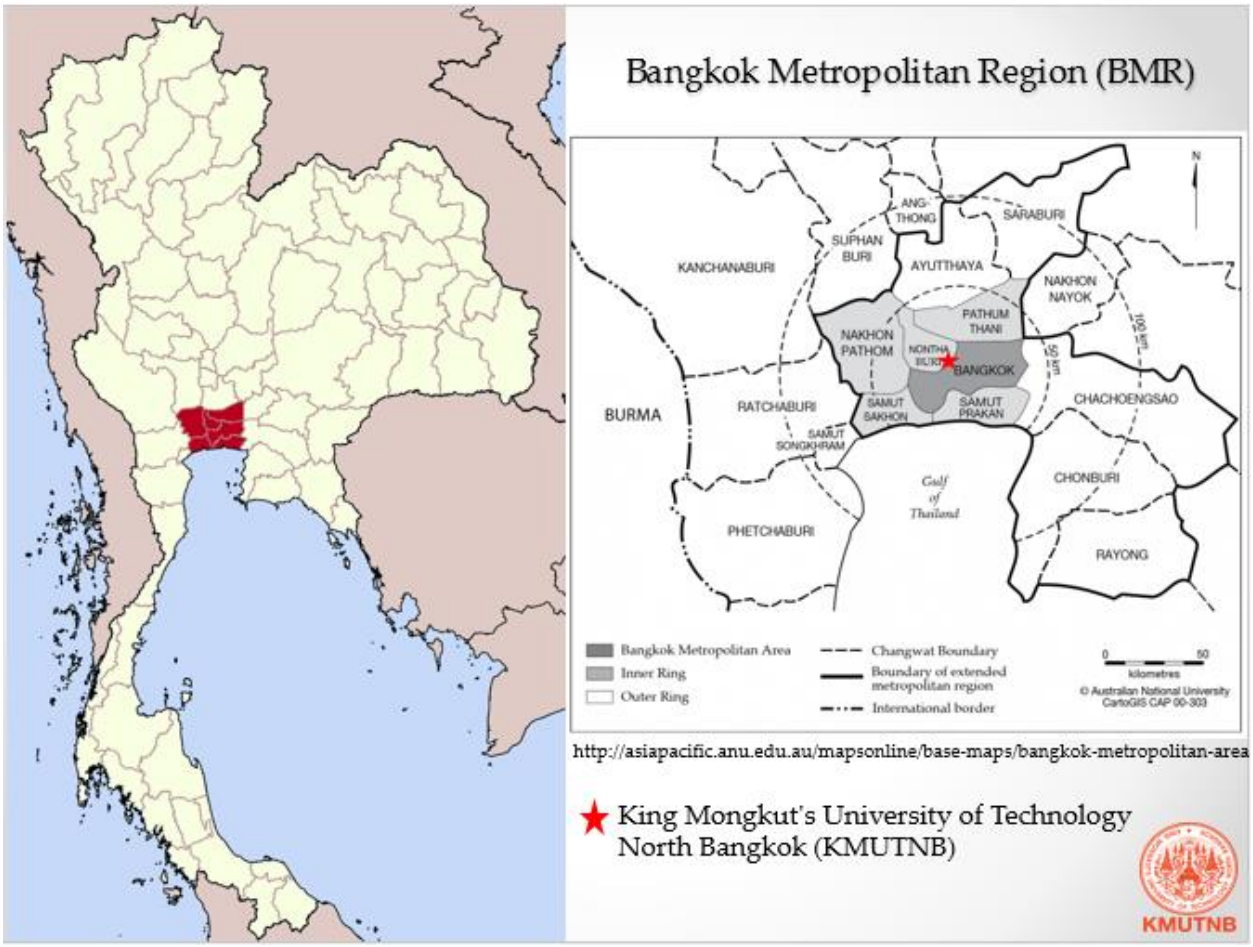
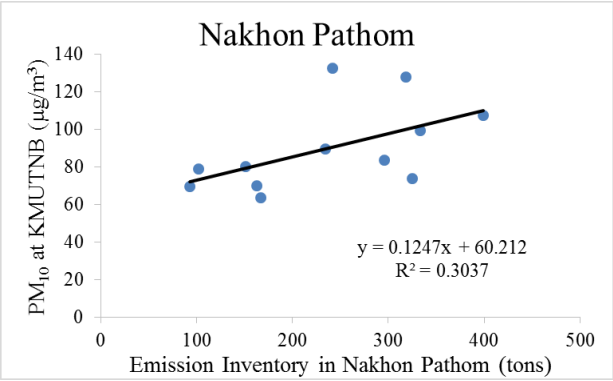
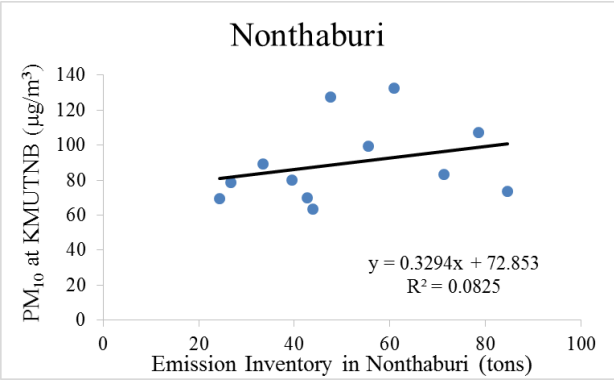


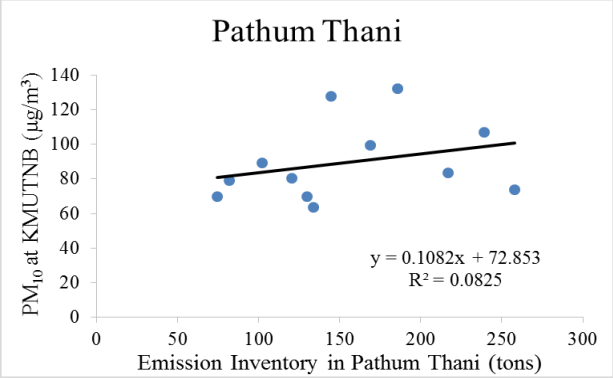
Fig 4.6 Potential sources of particulate matters at the Bangkok site



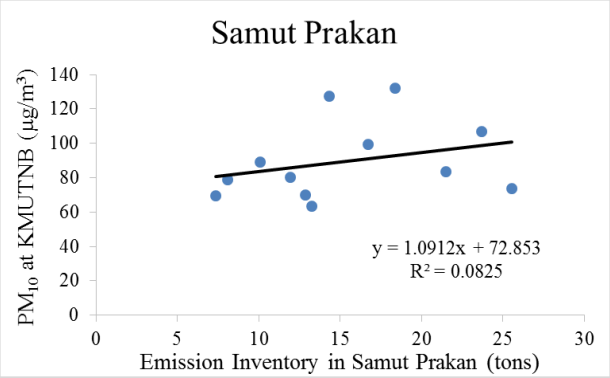
(a) Nakhon Pathom



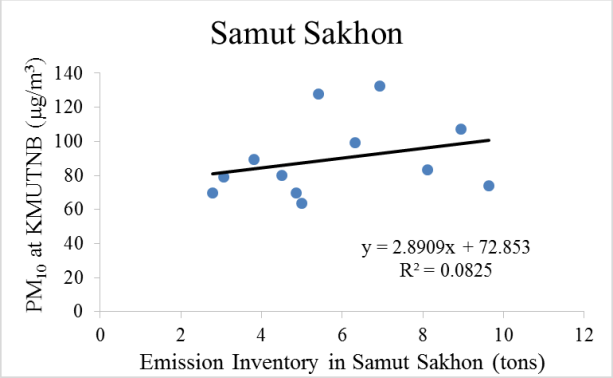
(b) Nonthaburi



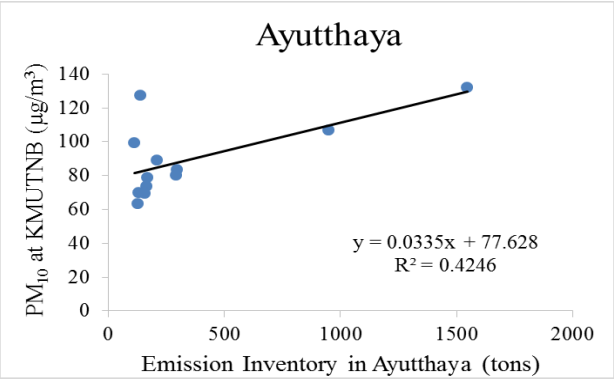
(c) Pathum Thani



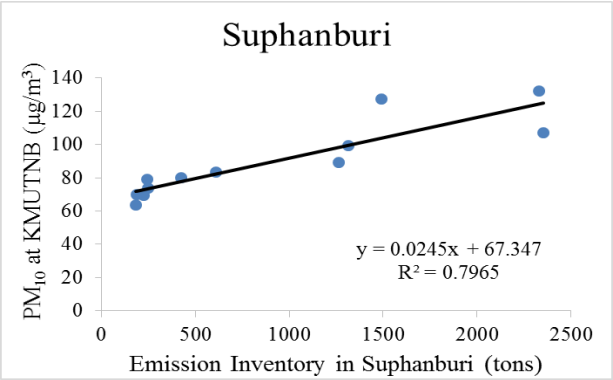
(d) Samut Prakan



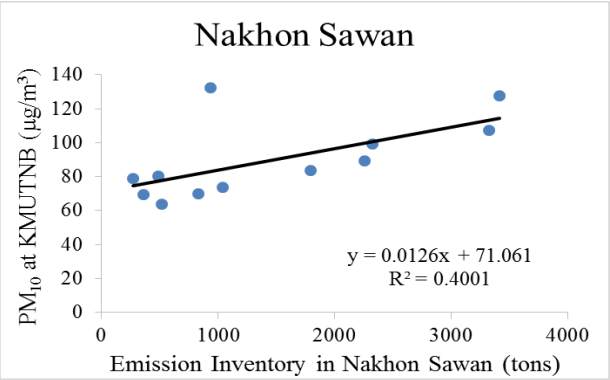
(e) Samut Sakhon



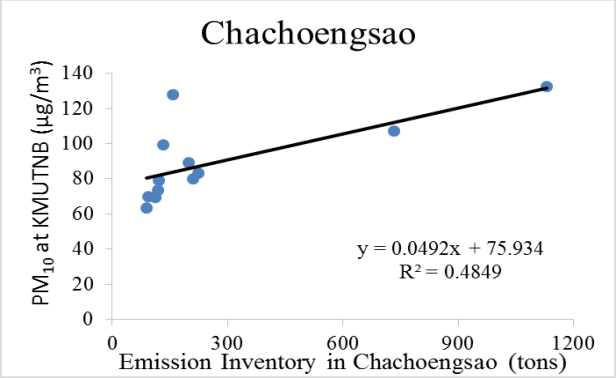
(f) Ayutthaya



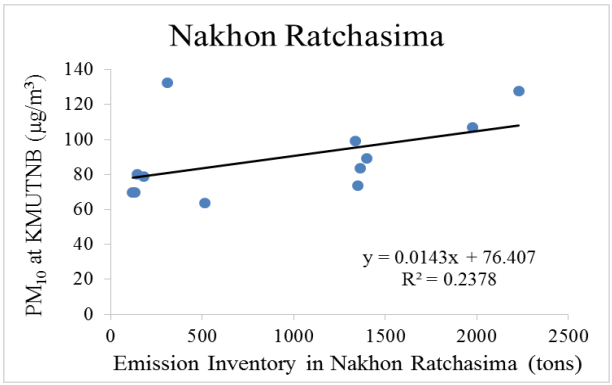
(g) Suphanburi



(h) Nakhon Sawan



(i) Chachoengsao



(j) Nakhon Ratchasima

Fig. 4.7 Correlation between emission inventories in each province and PM_{10} concentration at KMUTNB (a) Nakhon Pathom (b) Nonthaburi (c) Pathum Thani (d) Samut Prakan (e) Samut Sakhon (f) Ayutthaya (g) Suphanburi (h) Nakhon Sawan (i) Chachoengsao (j) Nakhon Ratchasima

Fig 4.7 (a-j) shows the correlation between emission inventories and average PM_{10} concentration in 10 provinces near Bangkok during a 1-year period (August 2014-July 2015). The best correlation was observed for the emission inventory in Suphunburi province, situated north of Bangkok, with a coefficient of determination (R^2) of 0.7965. This was followed by Chachoengsao, Ayutthaya, Nakhon Sawan, Nakhon Pathom and Nakhon Ratchasima, with R^2 of 0.4849, 0.4246, 0.4001, 0.3037 and 0.2378, respectively. On the other hand, the Bangkok Metropolitan Region showed a low correlation for EI and PM_{10} (R^2 = 0.0825), because of small agricultural activities in this area compared to other regions in Thailand. The most important potential source of PMs was Suphunburi province, a major province for crop cultivation, including rice and sugarcane, in the central part of Thailand.

2) Carbonaceous Compositions

Source identification by carbon ratio

The ratio of carbonaceous species can differentiate the emission source from all combustion processes (Cao *et al*., 2005). Varying amounts of organic carbon (OC) and elemental carbon (EC) is generated from different source types. The OC/EC ratio in size-segregated particulate has been widely used to classify emission sources. However, the OC/EC ratio often depend on other factors for correctly identifying the emission source. The three factors that can

interrupt OC/EC ratio are primary emission source, removal rate by deposition, and secondary organic aerosol (SOA) (Cachier *et al.*, 1996).

Table 4.2 shows the annual average concentration of OC, EC, Char-EC, Soot-EC and TC from August 2014-July 2015 in Bangkok ambient air. On average, the annual average of OC and EC was highest in $PM_{0.5-1.0}$, with values of 1.93 ± 1.53 and 0.53 ± 0.24 μg/m^3 respectively. Also, OC and EC were dominant in $PM_{0.1}$ and $PM_{2.5-10}$; OC values were 1.49 ± 0.90 and 1.24 ± 0.64 μg/m^3, while EC was 0.44 ± 0.17 and 0.48 ± 0.16 μg/m^3. TC was highest in $PM_{0.5-1.0.}$

Table 4.2 Annual average of Mass, OC, EC, Char-EC, Soot-EC and TC in Bangkok

	OC (μg/m^3)	EC (μg/m^3)	Char-EC (μg/m^3)	Soot-EC (μg/m^3)	TC (μg/m^3)	PM (μg/m^3)
$PM_{0.1}$	1.49 ± 0.90	0.44 ± 0.17	0.18 ± 0.10	0.25 ± 0.08	1.92 ± 1.04	14.80 ± 1.99
$PM_{0.5-1.0}$	1.93 ± 1.53	0.53 ± 0.24	0.41 ± 0.20	0.12 ± 0.06	2.46 ± 1.71	21.85 ± 4.62
$PM_{1.0-2.5}$	1.11 ± 0.75	0.39 ± 0.19	0.30 ± 0.16	0.08 ± 0.04	1.50 ± 0.88	18.76 ± 3.34
$PM_{2.5-10}$	1.24 ± 0.64	0.48 ± 0.16	0.31 ± 0.11	0.17 ± 0.08	1.72 ± 0.77	27.83 ± 4.43
$PM_{>10}$	0.60 ± 0.36	0.19 ± 0.10	0.09 ± 0.11	0.11 ± 0.06	0.79 ± 0.45	20.11 ± 2.59

The ratio of Char-EC to Soot-EC is more efficient for source identification of carbonaceous aerosol than the OC/EC ratio. The Char-EC/Soot-EC at the KMUTNB site was separated into the wet and the dry season for each size-segregated distribution of PM. The same pattern was found for $PM_{0.5-1.0,}$ $PM_{1.0-2.5}$ and $PM_{2.5-10,}$ with average Char-EC/Soot-EC ratios of 4.73 ± 2.36, 3.94 ± 1.83, 2.60 ± 1.05 for the respective sizes in the wet season, compared to 3.25 ± 3.20, 4.52 ± 3.79, 2.40 ± 1.63 in the dry season. These ratios suggest that the PM samples are more highly affected by the biomass burning activities. On the other hand, Char-EC/Soot-EC values for particulate sizes $PM_{0.1}$ and $PM_{>10}$ were less than 1.0 both in the rainy and in the dry season. These samples are influenced to a higher degree by vehicle exhausts (Table 4.3). A higher Char-EC/Soot-EC ratio indicates the dominance of biomass burning associated Char-EC contributions to total EC contents; while ratios < 1.0 suggests that Soot-EC from fossil fuel combustion is a large contributor to total EC.

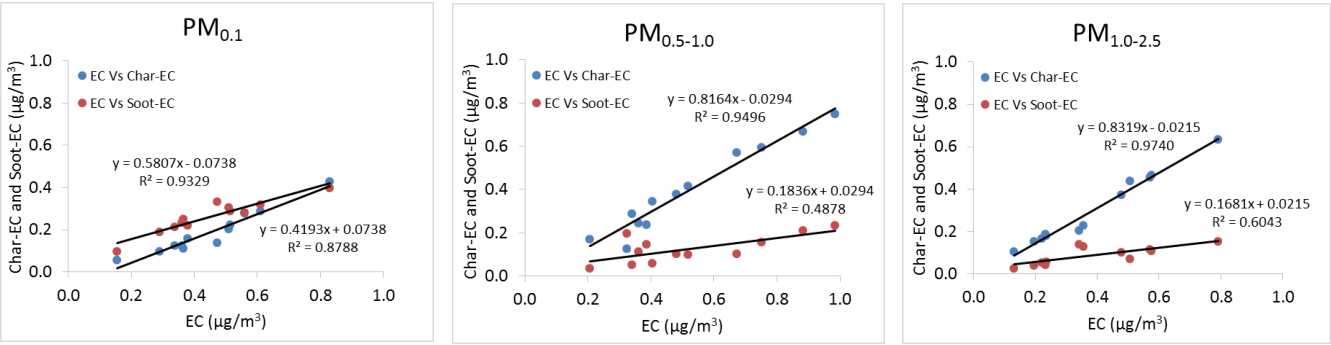
Chuersuwan et al. (2008) studied PM_{10} and $PM_{2.5}$ mass concentrations in BMR 2002–2003, and suggested that major sources of PM_{10} were automobiles and biomass burning. Biomass

burning sources range from 28-36% in PM_{10} and 6-41% in $PM_{2.5}$ depending on sampling sites. However, in this paper it is suggested that biomass burning originated from a residential site in the northeast of Bangkok, referring to Char-EC/Soot-EC ratios from biomass combustion (2.0-5.0), (Chen *et al*., 2007) being quite similar to ratios produced by residential cooking (2.0-6.0) (Chow *et al*., 2004). However, the OC/EC values range from 7.0 to 8.0 from crop residue burning (Zhang *et al.*, 2007), to 32.9-81.9 from the residential site (He *et al*., 2004). In this study, average OC/EC ratios were 3.65-6.45, indicating that the potential source was open biomass burning rather than residential sites from the northeast direction.

Table 4.3 Average carbon concentration in wet and dry season in Bangkok.

		TC (ug/m^3)	OC (ug/m^3)	EC (ug/m^3)	char-EC (ug/m^3)	Soot-EC (ug/m^3)	char-EC/ Soot-EC(-)	Soot-EC /TC	OC/EC ratio
Wet	<0.1	1.09 ± 0.47	0.78 ± 0.41	0.31 ± 0.11	0.11 ± 0.05	0.20 ± 0.07	0.57 ± 0.20	0.20 ± 0.05	2.55 ± 1.28
	0.5-1.0	1.14 ± 0.80	0.76 ± 0.73	0.38 ± 0.18	0.30 ± 0.17	0.08 ± 0.04	4.73 ± 2.36	0.08 ± 0.02	2.64 ± 1.49
	1.0-2.5	0.84 ± 0.58	0.56 ± 0.46	0.29 ± 0.17	0.22 ± 0.14	0.06 ± 0.05	3.94 ± 1.83	0.09 ± 0.03	1.98 ± 1.94
	2.5-10	1.09 ± 0.54	0.70 ± 0.45	0.39 ± 0.13	0.27 ± 0.09	0.12 ± 0.06	2.60 ± 1.05	0.11 ± 0.02	1.71 ± 0.87
	>10	0.54 ± 0.47	0.38 ± 0.28	0.16 ± 0.10	0.08 ± 0.04	0.09 ± 0.06	0.97 ± 0.26	0.20 ± 0.06	1.98 ± 1.37
Dry	<0.1	2.89 ± 0.99	2.31 ± 0.83	0.58 ± 0.25	0.26 ± 0.15	0.32 ± 0.11	0.77 ± 0.20	0.12 ± 0.05	4.47 ± 2.17
	0.5-1.0	3.92 ± 1.99	3.26 ± 1.69	0.66 ± 0.48	0.49 ± 0.47	0.17 ± 0.07	3.25 ± 3.20	0.05 ± 0.03	6.45 ± 4.71
	1.0-2.5	2.13 ± 1.00	1.68 ± 0.81	0.44 ± 0.33	0.34 ± 0.29	0.10 ± 0.07	4.52 ± 3.79	0.05 ± 0.02	5.11 ± 3.23
	2.5-10	2.18 ± 0.86	1.62 ± 0.65	0.55 ± 0.33	0.36 ± 0.25	0.19 ± 0.13	2.40 ± 1.63	0.08 ± 0.03	3.65 ± 2.07
	>10	0.94 ± 0.41	0.73 ± 0.32	0.21 ± 0.12	0.09 ± 0.06	0.12 ± 0.08	0.95 ± 0.62	0.12 ± 0.04	3.99 ± 2.06

Correlation between carbon species in size-segregated aerosol sample



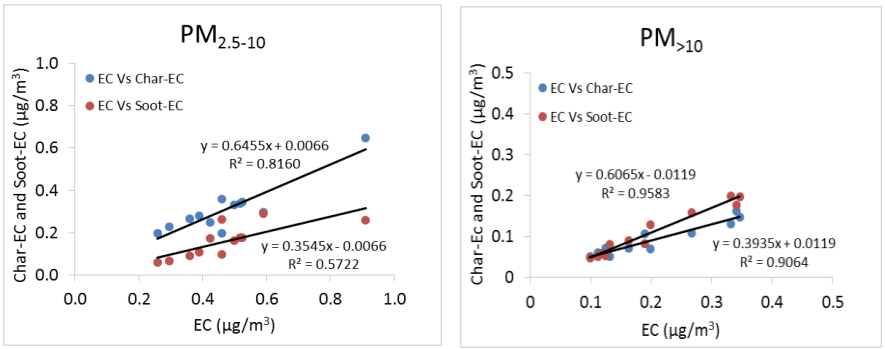


Fig 4.8 Correlations of EC with Char-EC and Soot-EC in Bangkok

In general, Char-EC is emitted largely from biomass combustion in lower temperatures, while Soot-EC is produced from high-temperature gas phases in motor vehicles and forest fires (Han *et al.*, 2010). The observed correlations of Char-EC and Soot-EC with EC in size-segregated PMs are plotted together to show and give a better overview of the correlation. As shown in Fig 4.8, Char-EC displayed the strongest correlation with EC in all size distributions, indicating that Char-EC dominated the total EC, whereas Soot-EC showed a good correlation with EC in $PM_{0.1}$ and $PM_{>10}$. On the other hand, it was found that $PM_{0.5\text{-}1.0}$, $PM_{1.0\text{-}2.5}$ and $PM_{2.5\text{-}10}$ had a good correlation in Char-EC and EC. This suggests that dominant contributions of Char-EC to total EC content in Bangkok ambient air originated from biomass combustion in the suburban area. In contrast, both Char-EC and Soot-EC had strong correlations with EC in $PM_{0.1.}$ This result could explain the high Soot-EC content relative to Char-EC in $PM_{0.1}$.

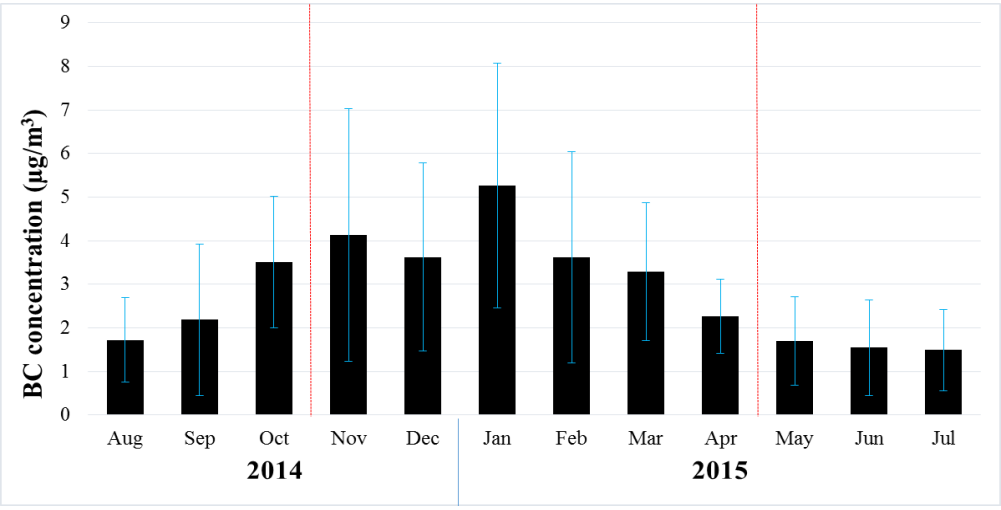
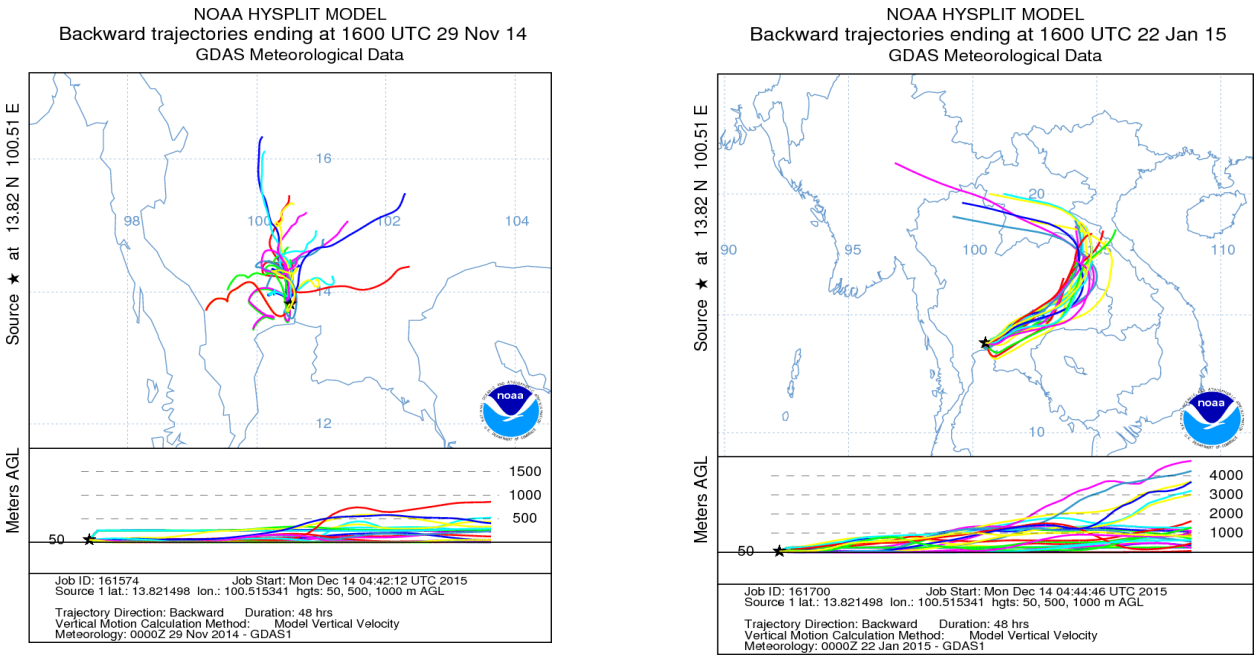


Fig. 4.9 Monthly average BC concentration in Bangkok, 2014-2015

Furthermore, the results of black carbon (BC) aethalometer samplings indicated a higher BC level in the dry season compared to the rainy season (Fig. 4.9). The highest peak of BC was in January, coinciding with high biomass activities in the neighboring provinces, in particular Suphanburi and Ayutthaya north of Bangkok.

3) Backward trajectory for source identification



(a) November, 2014 (b) January, 2015

Fig 4.10 Backward trajectories during the sampling periods at KMUTNB during high episode

(a) November 2014 (b) January 2015

Backward trajectories were also calculated during the sampling period to identify the potential sources using HYSPLIT model arriving at 50 m above ground level at the KMUTNB site. As shown in Fig 4.10, air mass movement came from the north of Bangkok in November (the beginning of the dry season) and the northeast of Bangkok in January. Fig 4.10 (a) shows that the air mass came from a large area of agricultural activities that predominantly cultivate rice in the Chaopraya river basin in Thailand. In the dry season, rice residue burning after harvesting is extensive during November-April (Tippayarom, 2004; Kanokkanjana, 2010). Consequently, there was a large amount of smoke emitted and transported to Bangkok during that period. Moreover, Fig 4.10 (b) reveals that air mass movement came from the northeast depending on the northeast

monsoon during the dry season in Thailand. The air mass trajectories moved northeast through the northeastern part of Thailand with extensive burning of sugarcane and rice.

4.5.2 Characteristics of Particulate Matter in Chiang Mai, Thailand

1) Mass Concentration

At the CMU site, the sampling period was 3 times per month between September 2014 and June 2015, using a Nano-sampler. The concentration of each size-segregated PM was divided into a wet and a dry season. Just like for Bangkok, the Chiang Mai rainy season was defined as August-October 2014 and also included May-July 2015 (6 months). Consequently, the dry season ran from November 2014 to April 2015. Seasonal mass concentrations are shown in Fig 4.11-4.12 below.

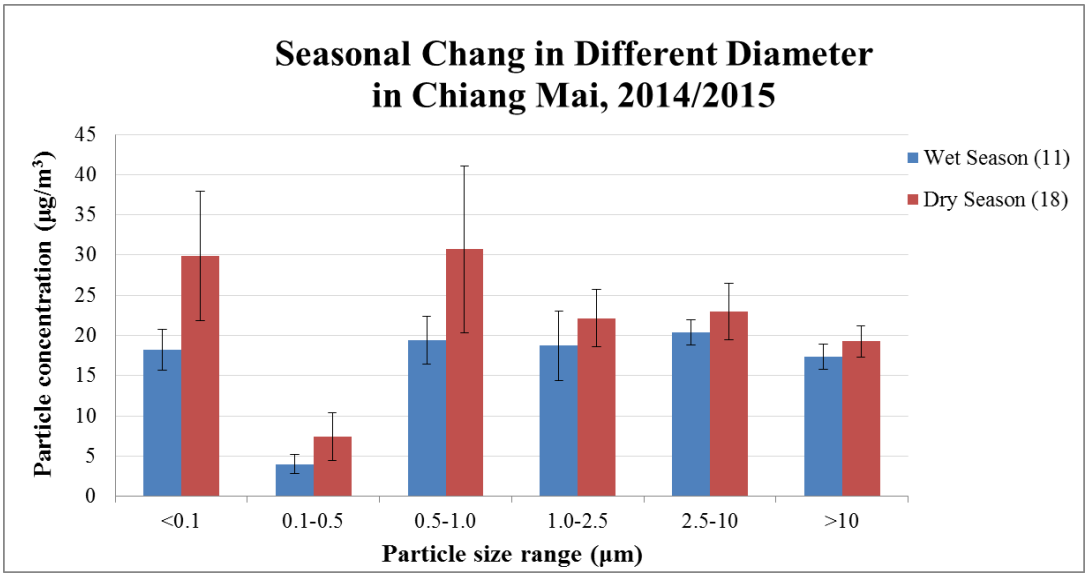


Fig. 4.11 Seasonal changes by diameter in Chiang Mai, 2014/2015

Seasonal variations in particulate matter for different diameters is displayed in Fig 4.11. In the wet season, the highest particle concentration peak was for 2.5-10 µm. However, all particle size ranges (except 0.1-0.5 µm) had a comparable level of mass concentration at around 17-19 µg/m^3. In the dry season, the particle size range of 0.5-1.0 µm showed the highest mass concentration, followed by nanoparticles (particulate smaller than 0.1 µm). The average concentration of nanoparticles in the dry season was about 30 µg/m^3.

The concentration of $PM_{0.1,}$ $PM_{0.5}$, $PM_{1,}$ $PM_{2.5,}$ PM_{10} and TSP were 25.21±8.38 µg/m^3, 31.74±12.01 µg/m^3, 57.74±19.70 µg/m^3, 77.52±23.80 µg/m^3, 100.453±28.38 µg/m^3 and

117±31.85 µg/m^3, respectively. According to Thailand Ambient Air standard, 24-hr of total particulate matter (TSP) should not exceed 330 µg/m^3, PM_{10} should be below 120 µg/m^3 and $PM_{2.5}$ should be less than 50 µg/m^3. The results show that TSP did not exceed Thai standard, however, PM_{10} exceeded the standard in 7 samples out of 29 total samples. For $PM_{2.5}$, 25 out of 29 $PM_{2.5}$ samples exceeded the daily standard in Thailand. All of the $PM_{2.5}$ samples in the dry season exceed 24-h ambient air standard in Thailand. Fig 4.12 shows the mass concentration for each particle size, divided between the wet and dry season in Chiang Mai ambient air.

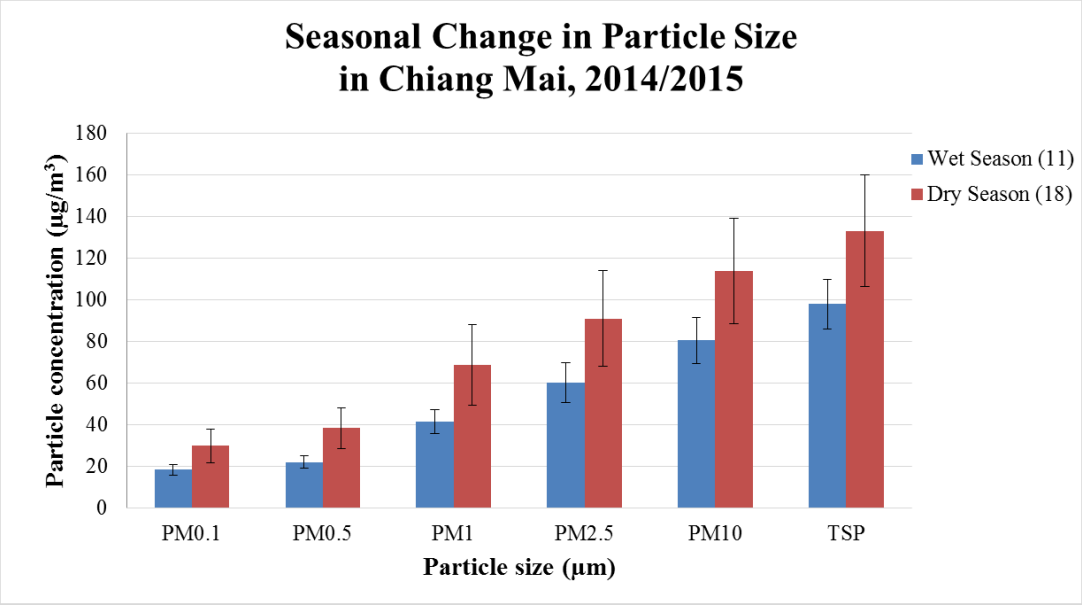


Fig. 4.12 Season changes in particle size in Chiang Mai, 2014/2015

Monthly average mass concentrations of size-segregated particulate matter collected from September 2014 to June 2015 are displayed in Fig 4.13 and Table 4.4. Mass concentrations in Chiang Mai ambient air were high compared to Bangkok. Particular matter concentrations increased in the dry season, starting in November. In the present study, mass concentration of TSP was highest in March, and it is interesting to note that the amount of ultrafine particles was extremely high during this month. Chiang Mai usually sees extremely high PM in March, related to open biomass burning season in the area (Pengchai *et al*., 2009; Chantara *et al*., 2012).

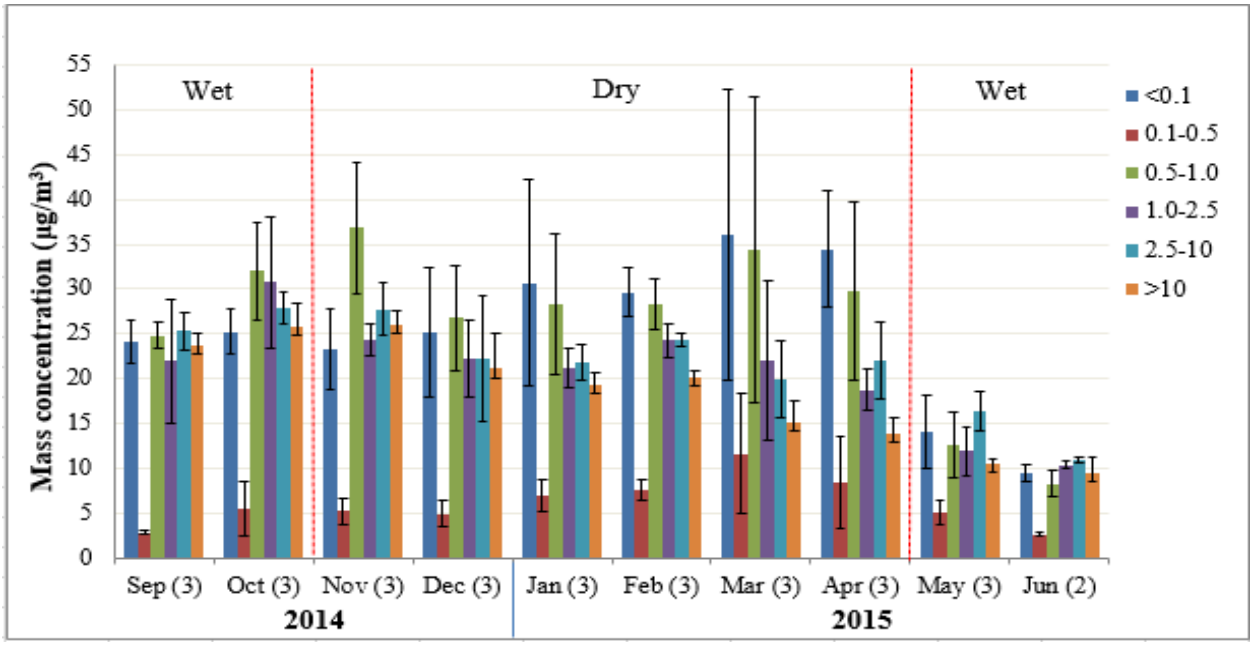


Fig. 4.13 Monthly average mass concentrations according to size in Chiang Mai from 2014-2015

Table 4.4 Monthly average concentrations (µg/m^3) in Chiang Mai from 2014-2015

	2014				2015					
	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
$PM_{0.1}$	24.2	25.2	23.3	25.2	30.7	29.6	36.1	34.5	14.1	9.4
$PM_{2.5}$	73.8	83.5	89.6	79.1	87.1	89.7	110.1	89.3	43.5	29.5
PM_{10}	99.0	122.3	117.3	101.3	108.9	114.1	129.9	111.3	59.9	40.5
TSP	122.8	138.1	143.3	122.4	128.2	134.2	145.1	125.1	70.4	49.9

2) Carbonaceous Compositions

Table 4.5 shows the annual average concentration of OC, EC, Char-EC, Soot-EC and TC from September 2014-June 2015 in Chiang Mai. On average, the annual concentration of OC was very high in $PM_{0.1}$ with 3.76 ± 2.53 µg/m^3, while EC was highest in $PM_{0.5\text{-}1.0}$ with a value of 1.37 ± 1.14 µg/m^3. Total carbon (TC) was higher in smaller particle sizes than in larger sizes. $PM_{0.1}$ had the highest TC mass concentration.

Table 4.5 Annual average of Mass, OC, EC, Char-EC, Soot-EC and TC in Chiang Mai

	OC (ug/m^3)	EC (ug/m^3)	Char-EC (ug/m^3)	Soot-EC (ug/m^3)	TC (ug/m^3)	PM (ug/m^3)
$PM_{0.1}$	3.76 ± 2.53	1.11 ± 1.06	0.66 ± 0.39	0.44 ± 0.26	4.87 ± 3.65	25.21 ± 4.73
$PM_{0.5\text{-}1.0}$	2.33 ± 1.64	1.37 ± 1.14	1.19 ± 1.34	0.18 ± 0.10	3.70 ± 2.94	26.20 ± 4.73
$PM_{1.0\text{-}2.5}$	1.24 ± 0.70	0.53 ± 0.36	0.40 ± 0.33	0.13 ± 0.09	1.77 ± 0.95	20.77 ± 2.84
$PM_{2.5\text{-}10}$	1.12 ± 0.42	0.35 ± 0.16	0.26 ± 0.14	0.09 ± 0.04	1.48 ± 0.53	21.83 ± 1.99
$PM_{>10}$	0.52 ± 0.40	0.11 ± 0.05	0.07 ± 0.03	0.04 ± 0.03	0.63 ± 0.44	18.51 ± 0.96

The ratio of Char-EC to Soot-EC at the Chiang Mai site was separated into the wet and the dry season for each size-segregated distribution of PM. The same pattern was seen in the dry season, with Char-EC/Soot-EC ratios in the range of 1.61 ± 0.66 to 8.33 ± 2.94 for each size. This ratio reveals that the dry season in Chiang Mai coincides with the biomass burning season. High Char-EC/Soot-EC ratios indicate that all particle size samples were highly affected by biomass activities in the area. However, in the rainy season only $PM_{0.1}$ was mainly influenced by vehicle exhausts. All other particulate size ranges were more significantly affected by open biomass burning (Table 4.6).

Table 4.6 Average carbon concentration in wet and dry season in Chiang Mai

		TC (ug/m^3)	OC (ug/m^3)	EC (ug/m^3)	Char-EC (ug/m^3)	Soot-EC (ug/m^3)	Char-EC/ Soot-EC(-)	Soot-EC /TC	OC/EC ratio
Wet	<0.1	4.86 ± 2.24	2.34 ± 0.82	0.51 ± 0.14	0.22 ± 0.11	0.30 ± 0.07	0.80 ± 0.51	0.10 ± 0.01	5.62 ± 1.22
	0.5-1.0	1.73 ± 0.92	1.34 ±0.91	0.40 ± 0.09	0.25 ± 0.15	0.15 ± 0.09	2.60 ± 1.65	0.09 ± 0.03	3.90 ± 2.82
	1.0-2.5	1.19 ± 0.75	0.93 ± 0.63	0.26 ± 0.10	0.14 ± 0.07	0.12 ± 0.10	2.23 ± 1.16	0.10 ± 0.05	3.57 ± 1.24
	2.5-10	1.48 ± 0.49	1.17 ± 0.51	0.32 ± 0.19	0.24 ± 0.16	0.07 ± 0.02	3.03 ± 1.37	0.06 ± 0.02	4.99 ± 2.22
	>10	0.62 ± 0.53	0.53 ± 0.47	0.10 ± 0.06	0.06 ± 0.04	0.04 ± 0.03	1.97 ± 0.53	0.07 ± 0.01	4.92 ± 1.37
Dry	<0.1	6.08 ± 2.08	4.57 ± 1.46	1.51 ± 0.66	0.96 ± 0.58	0.54 ± 0.13	1.61 ± 0.66	0.09 ± 0.01	3.51 ± 0.67
	0.5-1.0	4.84 ± 1.59	2.88 ± 1.01	1.97 ± 0.79	1.77 ± 0.76	0.20 ± 0.05	8.33 ± 2.94	0.05 ± 0.01	1.91 ± 1.01
	1.0-2.5	2.08 ± 0.41	1.39 ± 0.15	0.69 ± 0.29	0.56 ± 0.26	0.13 ± 0.04	4.23 ± 1.03	0.06 ± 0.01	2.32 ± 0.62
	2.5-10	1.42 ± 0.39	1.06 ± 0.32	0.37 ± 0.09	0.26 ± 0.07	0.10 ± 0.03	2.88 ± 0.72	0.07 ± 0.01	3.18 ± 0.79
	>10	0.61± 0.25	0.49 ± 0.22	0.12 ± 0.03	0.08 ± 0.02	0.04 ± 0.01	2.07 ± 0.44	0.07 ± 0.01	4.17 ± 0.90

Correlation between carbon species in size-segregated aerosol sample

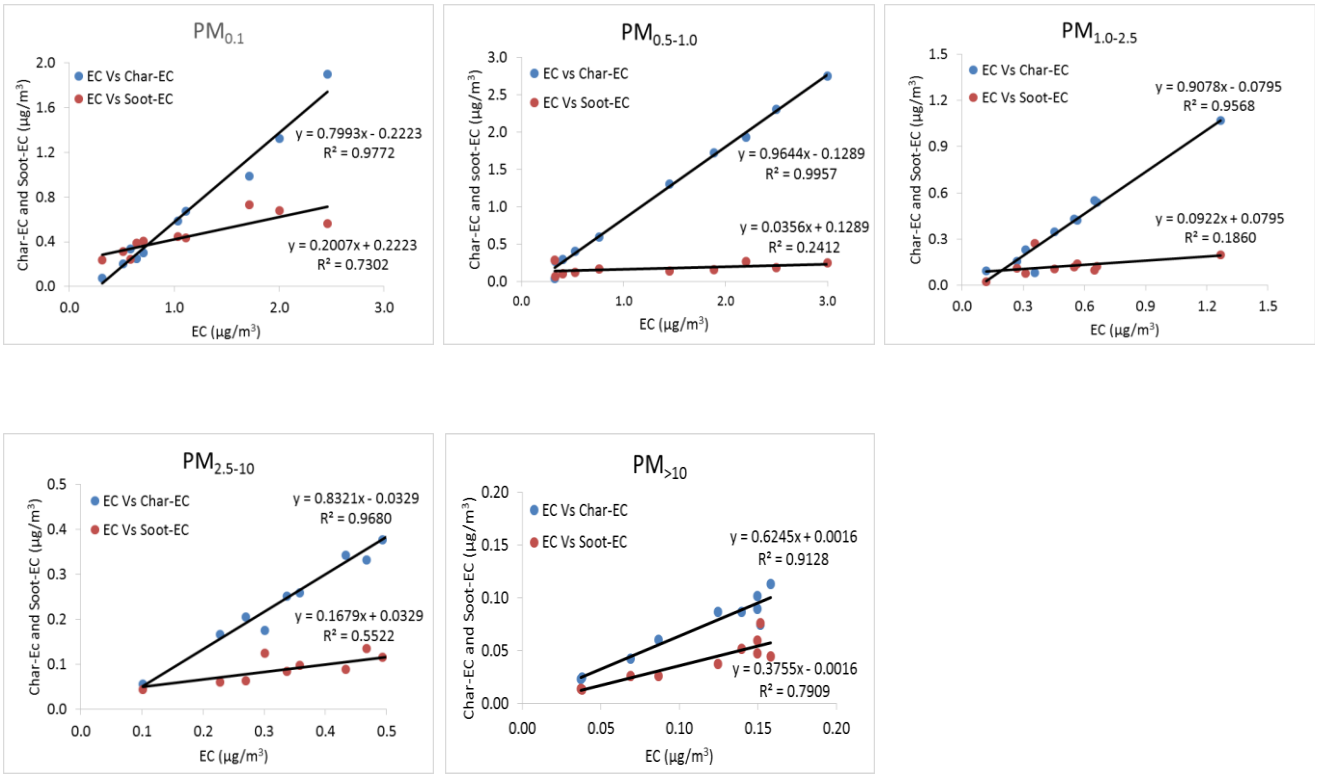
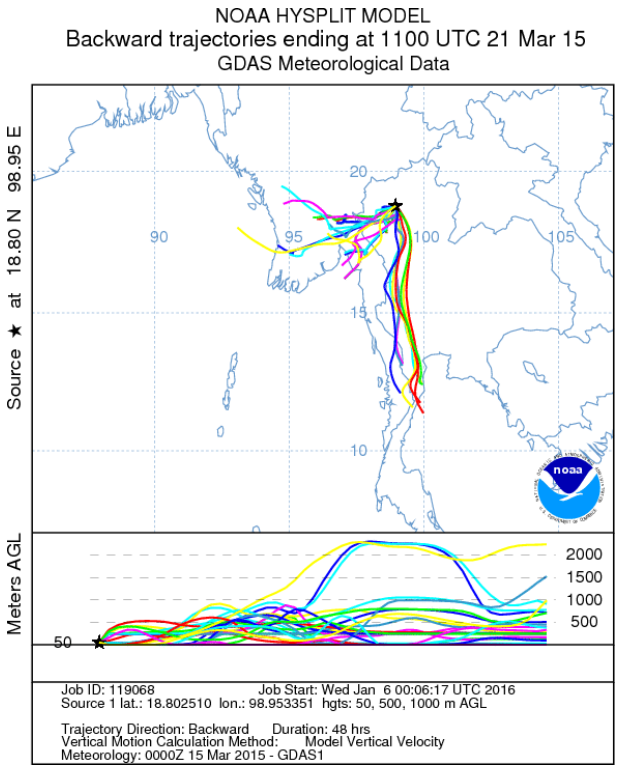


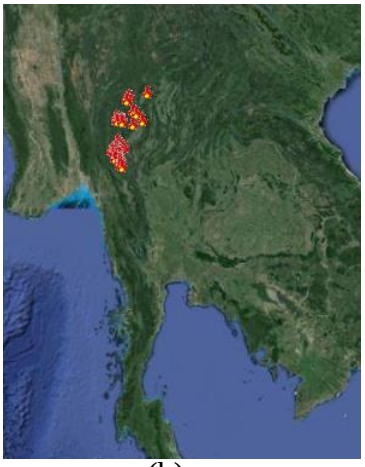
Fig 4.14 Correlations of EC with Char-EC and Soot-EC in Chiang Mai

The observed correlations of Char-EC and Soot-EC with EC in size-segregated of PMs in Chiang Mai are plotted together to provide an overview and demonstrate the relationships. As shown in Fig 4.14, Char-EC displayed the strongest correlation with EC in all size distribution, indicating that Char-EC dominated the total EC, whereas Soot-EC showed a good correlation with EC in $PM_{0.1}$ and $PM_{>10}$. Unlike the Bangkok site, the Chiang Mai University site was near biomass burning sources. The Char-EC/Soot-EC ratio in $PM_{0.1}$ was lower than 1.0 in the wet season, suggesting that motor vehicles and transportation were the primary sources. The dry season, however, was influenced by forest fires in the area.

$PM_{0.5\text{-}1.0}$, $PM_{1.0\text{-}2.5}$, and $PM_{2.5\text{-}10}$ showed a good correlation with Char-EC and EC. The result suggests that the most important contributions of Char-EC to total EC contents in Chiang Mai ambient air originated from biomass combustion in the suburban area. In contrast, both Char-EC and Soot-EC had high correlations with EC in $PM_{0.1}$. This result could explain the high Soot-EC content relative to Char-EC in $PM_{0.1}$.



(a)



(b)

Fig 4.15 (a) Backward trajectories during the sampling period at CMU during high episode, 21 March 2015

(b) Hot spots around Chiang Mai during sampling period on 21 March 2015 (available at http://www.forest.go.th/wildfire/hotspot/)

Backward trajectories were also calculated during the sampling time to identify the potential sources using HYSPLIT model arriving at 50 m above ground level at the CMU site. As displayed in Fig 4.15 (a), significant air mass movements were seen from the southwest and south. The air trajectories passed through the dense forest area in Chiang Mai province where forest fires are seen every year. Fig 4.15 (b) shows hot spots in the Chiang Mai area; there were 99 hotspots mainly southwest and northwest of Chiang Mai city on 21 March 2015 (sampling time). The high potential impact of biomass burning is a crucial contributor to particulate pollution at the CMU site. Every year during the dry season, especially February-April, forest fires are common in the upper northern part of Thailand. Consequently, a large amount of smoke was emitted and transported to Chiang Mai city during this period.

Chapter 5
Conclusion

Annual and monthly-based emission inventories were estimated to discuss the contribution of agricultural activity including crop residue burning, forest fires and related agro- industries to the air quality monitored in corresponding provinces in Thailand. An Emission Inventory (EI) of total biomass burning in Thailand was estimated for one year, from January to December 2014. Air quality in Thailand was found affected by biomass burning, including open burning as well as agro-industry with biomass consumption. The estimated monthly emission inventory was compared with air monitoring data obtained at monitoring stations operated by the Pollution Control Department, Thailand (PCD) to validate the estimated emission inventory and the contribution of other emission sources. The emission inventory identified sugar production as the agro-industry with the largest influence, and the contribution of sugarcane being used both as raw material and boiler fuel is discussed. However, emission sources were different in each region. Chiang Mai in upper northern Thailand was distinguished by PM_{10} mainly coming from forest fires, whereas emissions in the lower northern part (Nakhon Sawan) and the northeast (Khon Kaen and Nakhon Ratchasima) were predominantly related to open crop burning and sugarcane agro-industry. In the south of Thailand, Songkhla ambient air was affected by agricultural waste burning in biomass boilers. Moreover, characteristics of the size distribution of particulate matter and carbon components in Bangkok and Chiang Mai suggest that biomass activities influenced both study sites. In Bangkok, the carbon compositions pointed to agricultural activities in neighboring provinces. On the other hand, Chiang Mai ambient air was mainly affected by forest fires and crop residue burning in the area.

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Acknowledgments

First of all, I would like to express the deepest appreciation to my supervisor Prof. Dr. Masami Furuuchi, for giving me new experiences and opportunities in Japan. Thank you for kind suggestions, motivations and valuable discussions. Moreover, as my supervisor you provided valuable advice on how to be a scientist.

I would like to express the deepest gratitude to Assoc. Dr. Mitsuhiko Hata. Thank you for your great suggestions and valuable supports during my Ph.D. study.

I would like to thank Monbukagakusho scholarship from the Japanese Government for financial support throughout my Ph.D. period. Moreover, the Japan Society for the Promotion of Science (JSPS) for financial assistance during my research.

I also would like to thank all of the members of Laboratory of Atmospheric Environment and Pollution Control Engineering, Kanazawa University. In addition to my Thai friends in Kanazawa for their kind help and encouragement.

Last but not least, I would like to thank my family for their continuous support during my studies.

January 2016

Worradorn Phairuang