Chapter 3
Emission of Toxic Air Pollutants and Greenhouse Gases from Crop Residue Open Burning in Southeast Asia

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Abstract Agricultural crop production plays an important role in the economic development of Southeast Asia (SEA) countries. Annually, large amounts of crop residues are generated and field open burning for land clearing is commonly practiced which emits considerable amounts of toxic air pollutants and climate forcing agents. This study estimated the emissions of toxic gases, aerosol, and greenhouse gases from the crop residue open burning (CROB) in SEA countries. Emission inventory (EI) was done using the activity data gathered from primary surveys and published records for the SEA countries. The best estimates of emission species were calculated using the emission factors and the activity data that were most relevant for the considered SEA countries. In 2010, the SEA CROB emissions, in Gg were: 16,160 for CO; 320 for NO_x; 28 for SO_2; 980 for NMVOC; 550 for NH_3; 2060 for PM_{10}; 1880 for $PM_{2.5}$; 80 for BC; 885 for OC; 178,370 for CO_2; 580 for CH_4; and 14 for N_2O. Indonesia was the top contributor of all emission species (25–39%) followed by Vietnam (17–30%), Myanmar (8–19%), and Thailand (7–16%). Among 8 crop types considered, rice straw field burning contributed dominantly (85–98%) to the total SEA CROB emissions, followed by sugarcane, maize, and soybean. Low and high emission estimates were calculated using the ranges of activity data and available emission factors, respectively, to assess the uncertainty of the emission estimate for each species. The obtained gridded SEA CROB emissions with a resolution of 0.1° × 0.1° revealed higher emission intensity over the agricultural land areas, especially of rice, sugarcane, and maize. Temporal emissions showed higher peaks in the months following major crop harvesting periods in the dry season. The EI data for CROB produced in this study provided a key input for assessment of relative contributions of the emission sources in the SEA for further development of emission reduction strategies.

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3.1 Introduction

Biomass open burning is an important emissions source of air pollutants and greenhouse gases (GHGs) globally. The term generally refers to forest fires, open burning of agricultural crop residue and also open burning of municipal solid waste (Marshall et al., 1996). The Southeast Asia (SEA) countries are mainly agrarian countries with the economic development largely depending on the agricultural sector. Intensification of agricultural production has been accompanied by the generation of huge amounts of crop residues. To quickly clear the land from the above ground biomass for faster crop rotation, farmers prefer to burn the residues directly in the field after harvesting in several regions of south and southeast Asia (Gadde et al., 2009; Kim Oanh et al., 2011; Vadrevu et al. 2011, 2015; Vadrevu and Lasko, 2015). This field burning activity releases a huge amount of toxic air pollutants which may significantly deteriorate the ambient air quality in the neighboring areas and contribute to the regional transport of air pollution. As farmers become wealthier, the amount of crop residues used off-site such as for cooking or animal feeding is projected to decrease (Kim Oanh, 2012) hence the field burning activity is projected to rise up in near future if no measures are taken.

The crop residue open burning (CROB), normally happens with incomplete combustion, releases significant amounts of toxic particles and gases which cause adverse effects on human health and local environment. A large amount of GHGs and short-lived climate forcing pollutants (SLCPs), such as black carbon (BC) and ozone precursors, are also released (Andreae and Merlet, 2001; Badarinath et al., 2007, 2008, 2009; Kim Oanh et al., 2011, 2015; Vadrevu et al., 2013a, b; Le et al., 2014) that can affect the regional/global climate. Locally, the CROB emissions were reported to deteriorate the air quality in the Bangkok Metropolitan Region (Tipayarom and Kim Oanh, 2007). People who live close to CROB areas are exposed to higher levels of toxic pollutants than those living in areas with less CROB (Klinmalee, 2008). Realizing the negative impacts of CROB emissions, some SEA countries took steps forward to implement mitigation measures. For example, the Pollution Control Department (PCD) of Thailand has imposed a ban on CROB in certain areas and introduced alternative non-burning measures through a cross-agency initiative called the "Eight-Point Plan" (Lualon et al., 2013).

In order to address the negative impacts of the CROB practices and to widely promote environment-friendly crop residue management in the SEA countries, the emissions from CROB should be quantified. The results of the emission inventory (EI) can be further used, e.g., in air quality dispersion modeling to assess the impacts of CROB emissions and emission reduction measures on air quality, human health, and ecosystem.

Several existing global EI databases also present the CROB emission data for SEA. For example, the databases compiled by the Emission Database for Global Atmospheric Research (EDGAR) and the Global Fire Emission Database (GFED) also provide seasonal and gridded emissions of CROB. However, these databases were developed using mainly the top-down approach, for example, GFED-derived activity data mainly from satellite observations. At the regional scale, Woo et al. (2003) conducted the CROB EI in Asia for the Transport and Chemical Evolution over the Pacific (TRACE-P) project using a combination of international statistical data and active fire satellite product. Shi and Yamaguchi (2014) estimated emissions of CROB for four crop types (rice, maize, sugarcane, and wheat) in SEA for the period of 2001–2010 using the activity data taken from the Food Agriculture Organization (FAO) reports. Several national scale EI studies are also available with more detail country-specific activity data, such as the EI for rice straw open field burning in India, Thailand, and the Philippines by Gadde et al. (2009). Kanabkaew and Kim Oanh (2011) conducted an EI for CROB in Thailand using locally measured emission factors (EFs) and statistical data collected from the provincial agencies and by primary surveys. A similar approach was also used in the CROB EI for Indonesia, i.e., by incorporating locally measured EFs and relevant statistical data collected from the national/provincial agencies (Permadi and Kim Oanh, 2013). In the last two cited studies, geographical variations of the activity data, for example, the fraction of crop residues subjected to field burning was extracted from the relevant reports of available primary surveys. Overall, the existing global and regional studies normally have coarse spatial resolutions and do not necessarily contain all important emission species. Those studies normally focus on only a few crop types while the SEA may have many other crops which also contribute large amounts of residues subjected to field burning. In addition, most existing databases present only annual emissions, i.e., there is a common lack of detailed temporal variations which might vary due to the local agricultural practices in the SEA countries.

This study, therefore, aimed to provide a comprehensive emission database of CROB in the SEA (SEA CROB) for the year of 2010 for eight major types of crops. Country-specific information available from primary surveys was scrutinized to estimate the amounts of crops residues that were open burned in the countries. Existing EFs for different crop residue types were screened to select the relevant values for different countries in the SEA. This SEA CROB emission database includes multiple toxic gases (NO_x, SO_2, CO, NMVOC, and NH_3), particles (PM_{10}, $PM_{2.5}$, BC, OC), and GHGs (CO_2, CH_4, and N_2O). The EI results are presented as the low, high, and best estimates to include the uncertainty range of the data. Further, monthly emissions and the gridded emissions with a resolution of 0.1° × 0.1° were prepared that can be used for three-dimensional regional air quality modeling purposes.

3.2 Methodology

3.2.1 Emission Calculation

This study used the general framework of the emission calculation, i.e., using the activity data and emission factors, presented in the Atmospheric Brown Cloud Emission Inventory Manual (ABC EIM), as detailed in Shrestha et al. (2013).

The annual emission in a country was calculated using Eq. (3.1).

$$E_{m,k} = \sum_{m,k} M_k \times \eta_k \times EF_{m,k} \tag{3.1}$$

$E_{m,k}$ = Emission (mass amount per year) of species m and crop residue biomass type k
M_k = Amount of biomass of crop type k burned per year (mass amount per year)
η_k = Burning efficiency (fraction, 0–1)
$EF_{m,k}$ = Emission factor of species m from biomass type k burning (with consistent unit)

The total biomass amount of crop residue type k burned per year was estimated using Eq. (3.2).

$$M_k = P_k \times S_k \times D_k \times B_k \tag{3.2}$$

P_k = Crop production for crop type k (mass amount per year)
S_k = Crop-specific residue-to-production ratio
D_k = Dry matter-to-crop residue ratio (fraction, 0–1)
B_k = Fraction of dry matter residues that are burned in the field (0–1).

3.2.2 Activity Data

The activity data used for the CROB emission inventory is the amount of biomass (metric tons, t) burned per year (M_k). The eight crop types considered in this study are those commonly cultivated in the SEA countries that have residues subjected to open burning, namely, rice, maize, soybean, potato, sweet potato, groundnut, sugarcane, and cassava. Wheat was not included as its production is quite small in the region (FAO Statistics, 2015).

The parameters required to calculate M_k, following Eq. (3.2), were gathered from the previous survey results and from relevant published information. For three countries of Vietnam, Thailand, and Indonesia, that are recognized as the top producers of rice (major crop in the SEA), the crop production data (P_k) for the year of 2010 was obtained from the provincial statistical reports. Accordingly, the P_k data was obtained for all 33 provinces in Indonesia (MoA, 2011), 76 provinces of Thailand (OAE, 2011), and 63 provinces of Vietnam (GSO, 2011). For the other

SEA countries, due to the lack of the provincial information, this study relied on the national production data available from the FAO statistics (http://faostat3.fao.org/download/Q/*/E).

Table 3.1 presents the production data of the selected crops of 10 SEA countries, in Teragram per year (Tg/year) or Gigagram per year (Gg/year, for East Timor and Brunei). Note that, the types of cultivated crops varied with countries. For example, Brunei was reported to have only three types of crops (rice, cassava, and sweet potatoes) while most other SEA countries have all the eight crops cultivated. Singapore was not included in this EI as it has only a small agricultural production and also due to the fact that open burning is strictly prohibited in the country (Environmental Protection and Management Act, Cap. 94A).

The largest source of uncertainty in the M_k calculation may originate from the selection of a fraction of dry matter residues subjected to open burning (B_k) because this value depends on the local agricultural practices in a country. Note that in some countries such as Vietnam the open burning happens both in the field and off-site in villages hence should be included in the estimation of B_k. A wide range of values for this B_k parameter has been found in the global/regional EI reports. The Intergovernmental Panel on Climate Change (IPCC, 2006) suggested a value of 0.25 to be used for developing countries and < 0.10 for developed countries, while Streets et al. (2003) suggested a value of 0.25 for South Asian countries and 0.17 for the remaining countries in Asia. The information of B_k, especially for rice straw, was available for Thailand from the primary surveys which show significantly higher values than those suggested in the international databases.

For Thailand, this study applied the B_k values for rice straw used previously in Kanabkaew and Kim Oanh (2011), i.e., 0.9 for the central part of Thailand in the dry season (based on a survey by Tipayarom and Kim Oanh, 2007) and 0.48 for other parts of the country (DEDE, 2003). For other crops in the country, relevant values reported in the regional and global studies for the Asian countries (Streets et al., 2003; Yevich and Logan, 2003) were used. For Indonesia, the B_k values for rice straw used in Permadi and Kim Oanh (2013) were also applied because they were taken from local studies, specifically $B_k = 0.43$ in Java Island (Sasongko et al., 2004) and 0.75 in other islands (Makarim and Sumanto, 2007). For Vietnam, this study used results of a survey conducted by Dong (2013) for several provinces in the Northern Vietnam which reported the most probable B_k value of 0.77 for rice straw, 0.95 for sweet potato, 0.43 for cassava, 0.55 for sugarcane, 1.0 for groundnut, and 0.75 for soybean. For other countries in Continental Southeast Asia (CSEA), i.e., Myanmar, Cambodia, and Laos, the B_k values obtained by the survey for Vietnam were used. For countries of Malaysia, Brunei and East Timor, the B_k values of Indonesia were adopted. For the Philippines, the values for rice straw reported in Launio et al. (2013) were also used in this study.

The B_k values used for EI of CROB in different SEA countries used in this study is given along with other parameters in Table 3.2. The best emission estimates of the inventory species were produced using the B_k values given in brackets (if more than one value are presented). Note that the B_k selected for the best emission estimates of a certain crop type were different for different countries reflecting the local survey

Table 3.1 Crop of production of SEA countries, in Tg/year (if not otherwise specified) in 2010 and the population

SEA country[a]	Rice	Maize	Sugarcane	Potato	Soybean	Root tubers	Ground-nut	Sweet potatoes	Population (million)[b]
Cambodia	14	0.5	0.6	NA	0.17	4	0.01	0.03	14
East Timor, Gg/year	113	149	NA	1.2	9.3	NA	2	10	1.1
Indonesia	66	18	2.2	1.1	0.9	24	0.8	1	242
Laos	3	1	0.8	0.04	0.02	0.5	0.05	0.23	6.3
Malaysia	2	0.05	0.8	NA	NA	0.04	0.001	0.023	28
Myanmar	33	2	9	0.6	3	0.6	1	0.1	52
Philippines	16	6	34	0.1	0.05	2	0.03	0.5	93
Thailand	36	5	69	0.1	0.6	22	0.01	NA	67
Vietnam	40	5	16	0.4	0.5	9	0.5	1.3	87
Brunei, Gg/year	1	0.04	NA	0.1	NA	0.003	NA	0.0002	0.4
Total	210	38	133	2	6	62	3	3	590

Note: For East Timor and Brunei, the production is presented in Gg/year

NA not available

[a]Crop data for Indonesia, Vietnam, and Thailand were obtained from the national statistical reports; Crop production data for other countries was taken from the FAO statistic website

[b]Population data for 2010 from: http://data.worldbank.org/indicator/SP.POP.TOTL?page=1

Table 3.2 Summary of relevant activity data used in CROB SEA emission inventory

Biomass types	S_k[a]	D_k[a]	η_k[b]	B_k[b]
Rice straw	0.8–2.9 (1.75[c])	0.7–0.88 (0.85)	0.85–0.89 (0.89[d])	0.17–0.9 (0.43[e], 0.75[f], 0.48, 0.70 [g], 0.77[h])
Maize	0.19–4 (2[c])	0.3–0.5 (0.4)	0.35–0.92 (0.92[i])	0.17–0.61 (0.61[h])
Sugarcane	0.05–1.6 (0.3[c])	0.71	0.35–0.68 (0.68[i])	0.17–0.55 (0.55)
Potato	0.5[c]	0.3–0.6 (0.45[j])	0.9[k]	0.17–1.0 (0.73[h])
Soybean	0.21–2.1 (0.21)	0.71	0.68[d]	0.17–0.76 (0.75[h])
Root tubers	0.12–0.21 (0.21)	0.71	0.68[d]	0.17–0.43 (0.43[h])
Ground-nut	1.5–2.1 (2)[b]	0.8[j]	0.35–0.92 (0.68[d])	0.17–1.0 (0.73[k], 1[h])
Sweet potatoes	0.1–0.27 (0.15)	0.6	0.35–0.92 (0.92[i])	0.17–1.0 (0.73[k], 0.41, 0.95[h])

Remarks: The range represents selected low and high values while values in the bracket are best estimates (if more than 1 value is given)

[a]Koopmans and Koppejan (1998). Range of values was compiled from several studies conducted in Asia

[b]Kanabkaew and Kim Oanh (2011). Applicable for Thailand, compiled from various sources. For Bk, 0.9 for central part of Thailand while 0.48 was applicable for other regions of the country

[c]Rumbayan (2004). Value was based on a study in North Sulawesi, Indonesia

[d]Streets et al. (2003)

[e]Sasongko et al. (2004). Value is applicable for rice straw provided by a survey in Java, Indonesia. The same value was used for East Timor

[f]Makarim and Sumanto (2007). Survey taken in Sumatera, Kalimantan, and Sulawesi, Indonesia. The same value was used for Malaysia and Brunei

[g]Gadde et al. (2009). Value of Bk for Philippines was taken from survey conducted by Christian et al. (2009)

[h]Dong (2013). Values were obtained from questionnaire surveys in Northern Vietnam for rice straw, maize, potato, soybean, root tubers, groundnut, and sweet potato

[i]Penner et al. (1996). Data selected for developing countries compiled from various literature sources

[j]IPCC (2006). Default value from IPCC EI manual (lowest and highest values reported for Asian countries)

[k]Yevich and Logan (2003). Average value for agro-residue dominated by rice straw

results. For the low and high emission estimates, the variation ranges of B_k values, reported in the literature, presented in Table 3.2 were used. For example, the B_k range for rice straw is 0.17–0.9; hence, the lower value (0.17) was used to calculate the low emission estimate and the upper value (0.9) was used for the high emission estimate. Further details on the low, best, and high emission estimates are presented in the uncertainty assessment section.

Other parameters required for the amount of biomass burned (M_k) calculation using Eq. (3.2) were compiled from the available country-specific information to the extent possible. For Indonesia, following the approach used in Permadi and Kim Oanh (2013), the values of the residue-to-production ratio (S_k) and the dry matter to crop residue ratio (D_k) were obtained from a local study (Rumbayan, 2004). The same values of these two parameters were also used for Malaysia, Brunei, and East Timor. For Thailand, following the approach used in Kanabkaew and Kim Oanh (2011), the values for S_k and D_k for different crop types were extracted from various published reports that are considered relevant for Asian countries (Koopmans and Koppejan, 1998; Towprayoon et al., 2007; Yevich and Logan, 2003). These values were also applied for the emission calculation for other countries located in CSEA. For the Philippines, the corresponding values were taken from Gadde et al. (2009) who used the values suggested by IPCC (2006).

The information on the combustion efficiency of crop residues (η_k), i.e., the fraction oxidized per total amount of crop residue biomass subjected to open burning, was not available at the country level. Therefore, relevant values reported in the international data sources were used, following the previous studies (Permadi and Kim Oanh, 2013; Kanabkaew and Kim Oanh, 2011). A summary of the values of all parameters required for estimation of the amount of biomass burned in this study is presented in Table 3.2.

Table 3.3 presents the compilation of CROB emission factors for different pollutant species and for various crop types that were used in this study. The available EFs were scrutinized to select the most relevant value for each crop type in a specific country for the calculation of the best estimates. Accordingly, EFs that have

Table 3.3 Summary of the emission factors used in this study

Species	Rice straw	Maize	Sugarcane	Others[d]
$PM_{2.5}$	3.2–8.3 (8.3, 18.1)[a]	4.1–11.7 (4.1)	3.8	3.9
PM_{10}	3.5–9.1 (9.4, 20.1)[a]	4.3–6.2 (4.3)	4	4
SO_2	0.18–0.62 (0.51)[a]	0.04–0.44 (0.44)	0.2–0.4 (0.2)	0.2–0.4 (0.2)
CO_2	791–1674 (1177)[a]	1160–2327 (1350)	1130–1515 (1130)	1130–1515 (1130)
CO	31.4–179 (93[a], 179[b])	36.4–114.7 (114.7)	34.7	86–92 (86)
NO_x	0.49–2.8 (0.49)	1.3–4.3 (3.6)	2.6	0.7
NH_3	4.1	0.68–7 (0.68)	1	1.3
CH_4	9.6	1.5–4.4 (4.4)	0.4	2.7–4.6 (4.6)
NMVOC	7	4.4–10 (10)	2.2	7
BC	0.51–0.86 (0.53, 0.56)[a,c]	0.35–0.96 (0.95)	0.78	0.47–0.69 (0.47)
OC	1.9–2.9 (3.1, 9.4)[a,c]	2.2–3.9 (2.2)	3.3	0.7

Note: In brackets are the EFs used for the best estimates

[a]EFs mostly by measurement for rice straw in Thailand; Lower EFs for $PM_{2.5}$ and PM_{10} are for spread burning of rice straw while higher values are for pile burning (Kim Oanh et al., 2011)

[b]EF for CO taken from Christian et al. (2009) and is used for rice straw burning in Indonesia

[c]EFs of BC and OC: lower values for spread burning and higher values are for pile burning (Kim Oanh et al. 2011)

[d]EFs for "combined crops" were used for other crops; values mainly taken from Andreae and Merlet (2001)

Other EFs, not marked, were taken the compilation made by Kanabkaew and Kim Oanh (2011) been produced by measurement in a particular country were used for the best estimates. If not available, corresponding values reported for other Asian countries were applied. The ranges of the EFs given in Table 3.3 were used to calculate the low and high emission estimates. For some crop types, the EFs of certain pollutants were not available hence this study used the corresponding EFs reported for combined crops compiled by Andreae and Merlet (2001) which are specified under the "Others" column in Table 3.3.

Kim Oanh et al. (2011) reported that depending on the harvesting methods, the rice straw field burning can be practiced as "spread burning" and "pile burning" and the different burning methods produced significantly different EFs. The information on local harvesting methods was therefore gathered, i.e., using traditional (manual) or mechanized (harvesting machine), so as the most appropriate EFs can be applied. For Thailand, EFs for rice straw field burning of selected trace gases (N_2O, SO_2, and CO), PM (PM_{10} and $PM_{2.5}$), and GHGs (CO_2) were mainly taken from measurements conducted by the Asian Institute of Technology (AIT) in Thailand (Kim Oanh et al., 2011, 2015). The EFs for other crops in Thailand were obtained from the compiled values by the ABC EIM (Shrestha et al., 2013). In Vietnam and Indonesia, rice straw burning was done by both pile and spread burning hence the appropriate values of EFs were therefore selected.

3.2.3 Uncertainty Assessment

In this study, uncertainty in the emission inventory data was assessed by incorporating the uncertainty of both activity data and emission factors. Determination of the "best", "low," and "high" values for the EFs and activity data was followed as in Kanabkaew and Kim Oanh (2011) and Permadi and Kim Oanh (2013). The range of the EFs and the values of EFs used for the best estimates are presented in Table 3.3 above. As for the activity data uncertainty, the ranges of the parameters used for M_k calculation and the range of burning efficiency η_k, are given in Table 3.2, were used for the low and high estimates as discussed above. For the crop production (P_k), this study assumed that the data taken from the various National Agencies or Ministerial Departments had an uncertainty level of 5% while for those collected from the international agencies, e.g., the FAO statistics or other international agencies had a higher uncertainty, i.e., 10%, as suggested by IPCC (2006).

Accordingly, the most relevant values considered for a country of EFs and of the parameters used in the M_k calculation were used along with selected η_k to calculate the best emission estimate. The low and high emission estimates were calculated using the lower and upper values of the activity data and EFs ranges, respectively.

3.2.4 Spatial and Temporal Distribution

Mapping of the spatial distribution of the SEA CROB annual emissions of different species was done with the geographical information system (GIS) technique. The crop cultivation land in SEA was based on the land cover product provided by the Moderate Resolution Imaging Spectroradiometer (MODIS), available at https://lpdaac.usgs.gov/dataset_discovery/modis. The spatial distribution emissions were prepared at the grid resolution of $0.1° \times 0.1°$ ($\sim 10 \times 10$ km^2).

The monthly emissions for Indonesia and Thailand was constructed using the monthly production data for the year of 2010 following the approach presented in the previous works (Kanabkaew and Kim Oanh, 2011; Permadi and Kim Oanh, 2013). For Vietnam, monthly emission of CROB was constructed based on the information of crop cycles (mainly for rice seasons) as reported in Dong (2013). There were three rice crops (cycles) in Vietnam (Autumn–Summer, Spring–Winter, and Seasonal rice crops) and the monthly rice productions were used to allocate the monthly emissions. For other countries where the monthly crop production was not available, the information on open burning activity was taken from the daily MODIS MCD45A1 (https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mcd45a1) after being overlaid with the land cover map to differentiate the agricultural fires from other fires, e.g., forest fires.

3.3 Results and Discussion

3.3.1 Annual CROB Emissions in Southeast Asian Countries

The annual emissions of SEA CROB in 2010 presented as the best emission estimates for different species in Gg/year were: 16,160 for CO; 320 for NO_x; 28 for SO_2; 980 for NMVOC; 550 for NH_3; 2060 for PM_{10}; 1880 for $PM_{2.5}$, 80 for BC, 885 for OC; 178,370 for CO_2; 580 for CH_4; and 14 for N_2O. The emissions by country are presented in Fig. 3.1 along with the SEA total.

Country-wise, Indonesia contributed dominantly to the total SEA CROB emissions of all species, i.e., 25–39%, followed by Vietnam (17–30%), Myanmar (8–19%), Thailand (7–16%), the Philippines (8–14%), and Cambodia (3–7%). The remaining four countries considered in this study had relatively low emission shares, collectively for 1.1–3.2%, ranking from Laos (0.7–1.7%), Malaysia (0.4–1.4%), East Timor and Brunei (0.02–0.12%).

The emission rates are explained by the country crop production rates which are linked to the population (domestic use) and export of the agricultural product of the countries. For example, Indonesia had the highest production of the total 8 crops of 114 Tg with rice having the largest portion of 66 Tg, cassava/root tubers of 24 Tg, and maize of 18 Tg. These products were mainly used for the domestic consumption. Vietnam followed with a total production of 72 Tg of crops and Thailand with

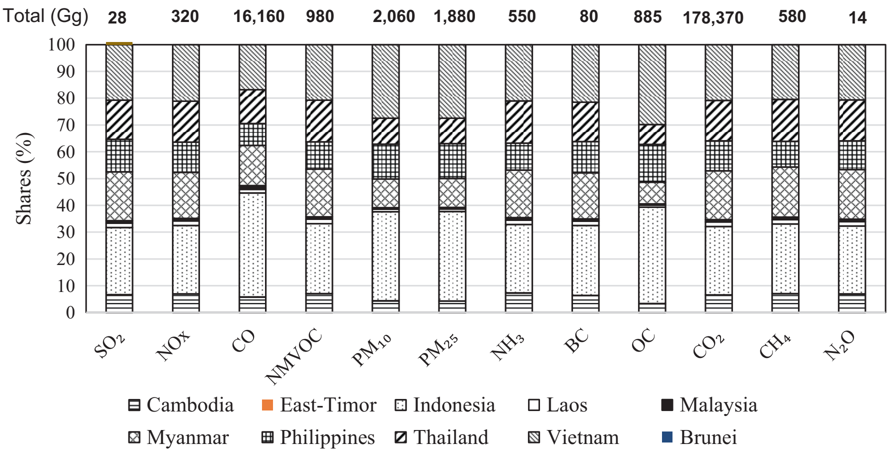

Fig. 3.1 Total emissions and shares by country for different species

64 Tg. Rice was also dominating the total crop production in this two countries, i.e., 40 Tg in Vietnam and 36 Tg in Thailand, which was for both domestic use and export. The high CROB emissions in these three countries were mainly due to large crop production coupled with the high fractions of crop residues subjected to open burning. It is noted that this study did not cover other types of crops (rather than the eight specified), for example, the palm oil plantation. Open burning emissions related to the palm oil crop should be important in some SEA countries, for example, Indonesia and Malaysia being the world top two palm oil producers and to some extent Thailand (World Growth, 2011). The CROB emissions from Malaysia was only a small fraction of the SEA CROB emissions inventory results because the country had only small production of the eight considered crops. Future studies should focus on the open burning emissions from various types of oil crops to provide a fuller picture of the CROB emissions in all SEA countries.

Contributions of different types of crops to the total CROB emissions are presented in Fig. 3.2. Rice straw open burning contributed dominantly to the total CROB emissions, sharing 85–98% (vary by pollutants) followed by sugarcane (0.3–6.0%), maize, and soybean (0.6–5.0%), and the rest crops (0.5–4.0%). Sugarcane residue open burning was high in Thailand as it is the world's second largest sugar exporter (Sornpoon et al., 2014).

3.3.2 *Comparison with Other Emission Inventory Databases*

The best estimates of the total SEA CROB emissions calcualted in this study are compared with those presented in other global and regional databases (Table 3.4), i.e., EDGAR, Shi and Yamaguchi (2014), and GFED (2010). The base years of the

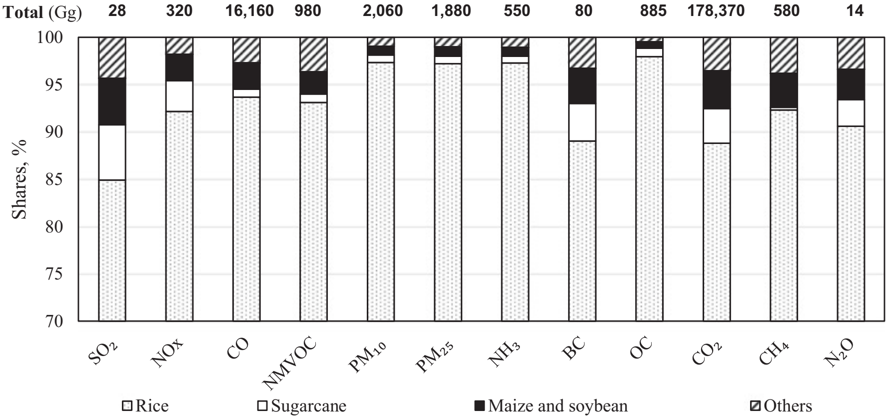

Fig. 3.2 Total annual emissions of different species and shares by crop types

Table 3.4 Total SEA CROB emissions by different studies (in Gg/year)

Species	SEA CROB (This study, 2010)	SEA CROB (EDGAR[a], 2008)	SEA CROB (Shi and Yamaguchi[b] (2001–2010 average)	(GFED[c], 2010) SEA CROB	(GFED[c], 2010) SEA forest fires
SO_2	28	166	22	6.0	263
NO_x	320	823	180	34	934
CO	16,160	26,773	4431	1434	37,600
NMVOC	980	1516	498	168	2560
PM_{10}	2060	2816	NE	187	4680
PM_{25}	1880	NE	NE	125	3440
NH_3	550	282	155	172	642
BC	80	NE	45	10	220
OC	885	NE	144	55	1770
CO_2	178,370	328,220	106,315	21,850	655,000
CH_4	580	585	536	135	2300
N_2O	14	15	4	1.5	82

Note: *NE* not estimated
[a]EDGAR (2012). Data was retrieved from: http://edgar.jrc.ec.europa.eu/overview.php?v=42
[b]Shi and Yamaguchi (2014). Including emission from Southern regions of China
[c]Van der Werf et al. (2010). GFEDv.3.1, SEA forest fires include deforestation, savanna, and peatland

EI presented in Table 3.4 were not the same, EDGAR data was for 2008 while Shi and Yamaguchi (2014) was the average over 10 years (2001–2010).

Emission estimates by EDGAR were the highest of all three datasets presented, i.e., about 1.2–3 times higher than the estimates by this study, except for NH_3 which had a lower estimate (two times). As for CH_4 and N_2O emissions, the results of this study are comparable with those by EDGAR. It is worth emphasizing here that

EDGAR included also palm oil and other oil crops (together with rice, maize, sugarcane, peanut, and root tubers) while this study did not consider those oil crops which may be a reason for the discrepancies. The differences in the emission results between this study and EDGAR may be largely linked to the differences in the parameters used to calculate the amount of biomass burned and differences in the selected emission factors.

The emission estimates provided by Shi and Yamaguchi (2014) produced lower values than this study, consistently for all species. Shi and Yamaguchi (2014) developed the EI for a larger domain, i.e., including also Southern territory of China, but focusing only on four crop types of rice, maize, sugarcane, and wheat. Given the fact that the three crops of rice, maize and sugarcane (wheat production was negligible in the SEA) already contributed the major shares in the total SEA CROB emission (Fig. 3.2), the main reasons for the differences in the EI may be linked to the differences in the activity data used. In particular, this study based on the survey results and local-specific values of the parameters used for calculation of M_k with the aim to provide relevant emission rates for the SEA region. For example, the B_k values of 0.39–0.90 (Table 3.2) used for rice straw open burning in this study were taken from the local surveys in Thailand, Vietnam, and Indonesia which are well above that (0.10) used by Shi and Yamaguchi (2014).

The CROB emission database of GFED for 2010 showed the lowest emission rates of all the EI datasets presented in Table 3.4. GFED used satellite data which may not be able to fully capture small size, sporadic, and short fire periods (30 min to 1 h) of the crop residue open burning hence the amount of dry biomass burned may be likely underestimated. A survey conducted in Thailand showed that the CROB activity was mainly conducted in the late afternoon, i.e., outside the daily passing time of the MODIS satellite over the region of around 10:00 and 13:30 LST. For Thailand, the GFED CROB emission estimates for most species were 2–3 times lower than that reported by Kanabkaew and Kim Oanh (2011) who used mostly bottom-up survey data for the EI in 2007.

To roughly compare the magnitude of the SEA CROB emissions (produced in this study) with the forest fire emissions, the data of forest fires in SEA in 2010 was extracted from the Global Fire Emission Database (GFED) version 3.1 (Van der Werf et al., 2010) and is also presented in Table 3.4. Regionally, the GFED forest fire emissions, including both above and below ground biomass (peat) burning, were about 2–3 times higher than the SEA CROB emissions produced by this study (covering eight crop types) for most of species. For some species, forest fires had even higher emissions compared to CROB, i.e., by four times for CO_2, CH_4, and N_2O and nine times for SO_2.

It is important to emphasize that the CROB emissions mainly occur in the populated areas and happen mostly in dry months of a year when the air pollution levels in SEA countries are high. Therefore, the emissions may cause significant effects on human health and the local environment. Forest fires, however, often attract more attention internationally because these massive fires normally cause severe haze episodes which are of transboundary nature and are more visible on large scale.

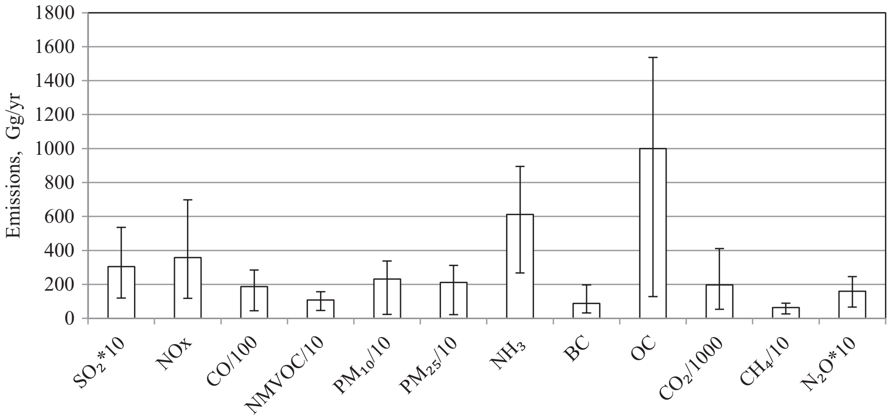

Fig. 3.3 Total SEA CROB emission in 2010 showing with low, best, and high emission estimates of species

3.3.3 Uncertainty in the Emission Estimates

Figure 3.3 presents the result of the uncertainty analysis. The best emission estimate of a species is shown as a bar while the whiskers indicating the high and low estimates, respectively. Note that the whiskers shown in Fig. 3.3 show the variation range of the emission of each species and not the standard deviation of the best estimate.

To show the magnitude of the variations, the uncertainty is normally presented as the relative difference between the low and the best estimate [(Low-Best)/Best], (% negative) and that between the best and the high emission estimate (%, positive). On average, the uncertainty range of the emission estimates of all species was −70 to 66%, ranging from the lowest for CH_4 (−58 to 40%) to the highest for BC (−64 to 124%). A large variation range of EFs found in the literature for BC contributed to this large uncertainty range of the BC emission estimates.

3.3.4 Spatial and Temporal Distributions of SEA CROB Emissions

Spatial distributions of the annual emissions were mapped using the GIS technique based on the MODIS land cover product. The land use map of the SEA region is shown in Fig. 3.4. The SEA regional emissions for all considered species are presented in a grid net of 0.1° × 0.1° or about 10 × 10 km^2. The spatial distributions of the EI species have a similar pattern. For example, the gridded emission maps for $PM_{2.5}$ and BC are presented in Fig. 3.5, in t/year/grid. As expected, higher emissions were shown over the agricultural areas, especially over the paddy fields located in each country.

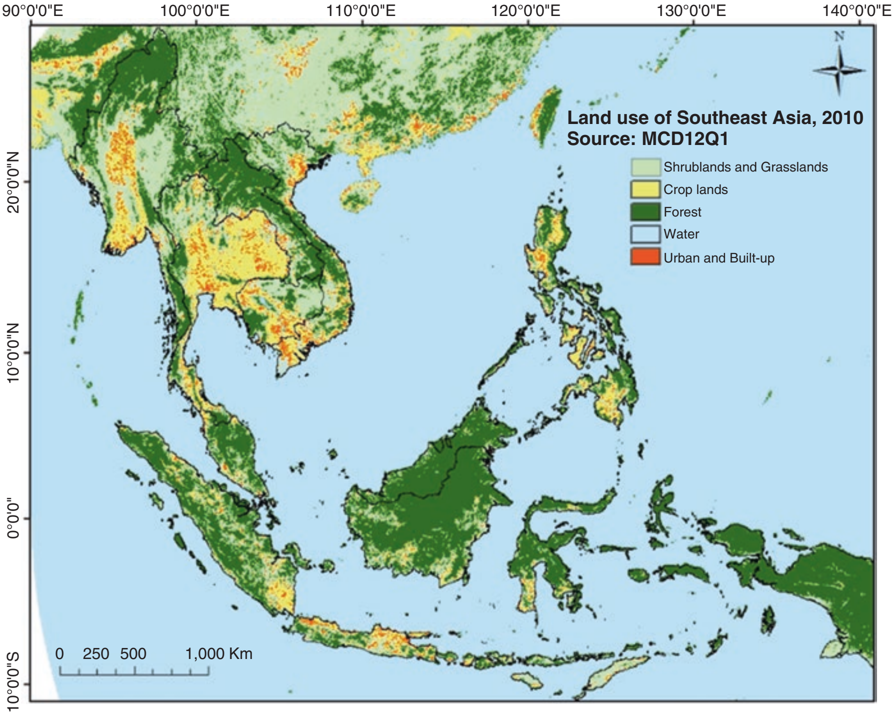

Fig. 3.4 Land use of SEA derived from MODIS (courtesy to National Aeronautics and Space Administration (NASA) and US Geological Survey (USGS) https://lpdaac.usgs.gov/dataset_discovery/modis)

In Indonesia, a higher emission intensity was seen over the West and Eastern Java which are known as the rice production hubs in the country. High emission intensity was also seen over the Sumatera Island areas where the maize and paddy plantation were concentrated. In Thailand, emissions were higher in the central and Northeastern parts of the country which are known as centers for the agricultural crop production. For example, sugarcane was mainly cultivated in these two regions and accounted for more than 50% of the total national production (Chetthamrongchai et al., 2001). In Vietnam, higher emissions were seen in the Mekong River delta, Red River delta, and Central coastal region, the areas of the agricultural crop productions, especially rice cultivation.

Monthly emission profiles are presented in Fig. 3.6 for three countries of Indonesia, Vietnam, and Thailand, which are the major contributors to the total SEA CROB emissions. The monthly variations in the emissions depend on the seasons (dry or wet) and the harvesting periods of different crops in a year. In Indonesia, emissions were higher during the period of August–October which was the dry season and coincidentally also the period following the major rice harvesting (August–September). For Thailand, Fig. 3.6 showed that major crop residue burning

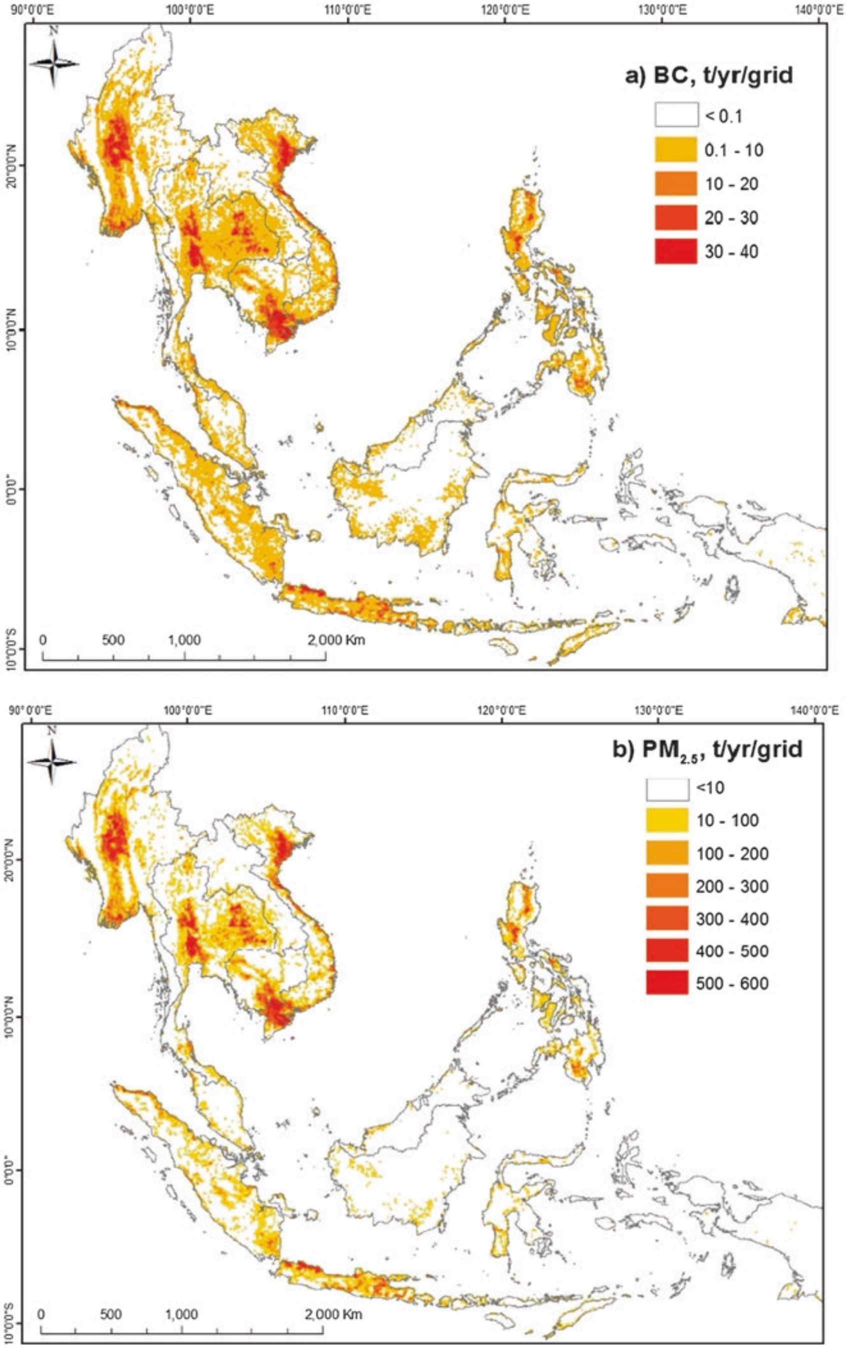

Fig. 3.5 Gridded SEA CROB emissions in t/year/grid with grid resolution of $0.1° \times 0.1°$

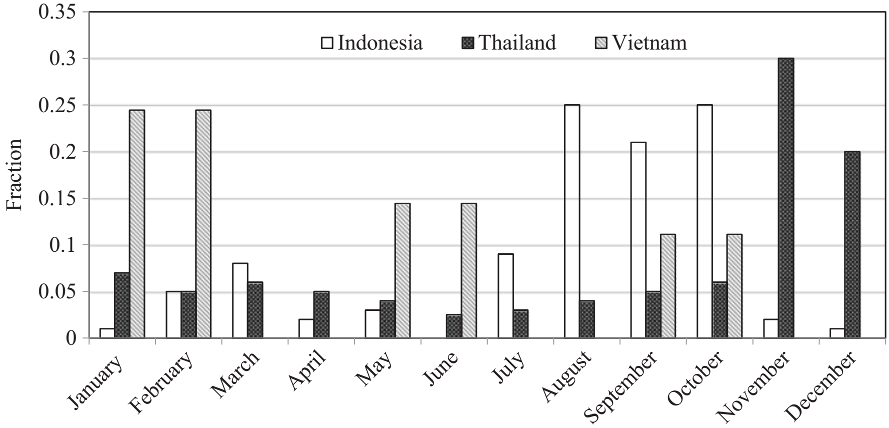

Fig. 3.6 Monthly fractions showing the emission variations in selected countries

emissions occurred during the dry season (October–April) with peaks in November and December coinciding with the harvesting of the major rice crop. In Vietnam, emissions from CROB were seen in three periods following the harvesting of three rice crops, in the highest peaks in January–February after the harvesting of spring–winter rice crop, second highest was in May–June following the harvesting of autumn–summer rice crop, and the third peak was in September–October after the harvesting of the seasonal rice crop.

The gridded SEA CROB emissions with the monthly distributions can be further used in the modeling studies to simulate the base case and various emission scenarios, e.g., implementation of non-burning alternatives and/or ban on CROB. The impact of various management strategies for the crop residue open burning on air quality and regional climate of SEA thereby can be assessed.

3.4 Summary and Conclusions

Emissions of toxic gases, aerosol species, and GHGs from the CROB in the SEA region were estimated for base year of 2010. The EI was developed using, to the extent possible, the country-specific activity data and EFs to produce the relevant emission data for the region. The results showed that the best emission estimates in Gg, in 2010 were: 16,160 for CO; 320 for NO_x; 28 for SO_2; 980 for NMVOC; 550 for NH_3; 2060 for PM_{10}; 1880 for $PM_{2.5}$; 80 for BC; 885 for OC; 178,370 for CO_2; 580 for CH_4; and 14 for N_2O. The EI data for CROB in SEA available in literature showed significant discrepancies for some species which may explain the approach (top-down or bottom-up) and the inclusion of the local-specific details.

As compared to the available forest fire emissions data of GFED, the SEA CROB emissions for eight crop species estimated in this study were about 2–3 times lower.

However, the adverse effects of the emission on human health and environment should not be overlooked as the CROB emission occurs in populated areas and mainly in the dry season when the air pollution in the SEA is significantly higher than other periods of the year. The uncertainty range of the emission estimates of all inventory species were averaged at −70 to 66%.

Indonesia was the top contributor to the total SEA CROB emissions (25–39%) followed by Vietnam (17–30%), Myanmar (8–19%), and Thailand (7–16%) because of the intensive agricultural activities, mainly rice, maize, and sugarcane production in these countries. The rice straw open burning contributed dominantly, 85–98%, to the total SEA CROB emissions while the remaining emissions were mainly from sugarcane, soybean, and maize. The spatial distributions of the SEA CROB emissions were developed with a grid resolution of $0.1° \times 0.1°$ using the MODIS land cover data. The results showed that the CROB emissions were high over the agricultural areas where the rice and sugarcane were located. Monthly emissions varied by country and were affected by the local agricultural practices (harvesting periods) and seasons (dry or wet). Emissions of CROB peaked in Indonesia during August–October, in Thailand during November–December, and in Vietnam during January–February because of the coincidence of the major harvesting periods with the dry season in the country enhancing open burning.

The EI developed in this study provides detailed information on relative contributions by country and by crop type to the total SEA CROB emissions. The emission data produced by this study, with spatial and temporal distributions, could be used for three-dimensional air quality modeling studies. Future emission inventory studies should also include other types of crops, such as palm oil, that is commonly cultivated in the region. Health effects of the CROB emission should be quantified to provide a driving force for reduction and elimination of this open burning activity and to promote non-open burning alternatives for the sustainable agricultural waste management.

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References

Andreae MO, Merlet P (2001) Emissions of trace gases and aerosols from biomass burning. Glob Biogeochem Cycles 15:955–966

Badarinath KVS, Kharol SK, Latha KM, Chand TR, Prasad VK, Jyothsna AN, Samatha K (2007) Multiyear ground-based and satellite observations of aerosol properties over a tropical urban area in India. Atmos Sci Lett 8(1):7–13

Badarinath KVS, Kharol SK, Krishna Prasad V, Kaskaoutis DG, Kambezidis HD (2008) Variation in aerosol properties over Hyderabad, India during intense cyclonic conditions. Int J Remote Sens 29(15):4575–4597

Badarinath KVS, Sharma AR, Kharol SK, Prasad VK (2009) Variations in CO, O3 and black carbon aerosol mass concentrations associated with planetary boundary layer (PBL) over tropical urban environment in India. J Atmos Chem 62(1):73–86

Chetthamrongchai P, Auansakul A, Supawan D (2001) Assessing the transportation problems of the sugarcane industry in Thailand, Transport and Communications Bulletin for Asia and the Pacific. No. 70

Christian TJ, Kleiss B, Yokelson RJ, Holzinger R, Crutzen PJ, Hao WM, Saharjo BH, Ward DE (2009) Comprehensive laboratory measurements of biomass-burning emissions: 1. Emissions from Indonesian, African, and other fuels. Geophysical Researc 108(D23):4719–4732

DEDE (2003) Rice in Thailand. Bangkok: Department of Alternative Energy Development and Efficiency (DEDE)

Dong NP (2013) Development of Spatial and Temporal Emission Inventory for Biomass Open Burning in Vietnam. AIT Master Thesis. Pathumthani, Thailand

EDGAR (2012) Global Emission Dataset. Emission Database for Global Atmospheric Research (EDGAR). http://edgar.jrc.ec.europa.eu/overview.php?v=42

FAO Statistics (2015) Food Agriculture Organization statistic division. http://faostat3.fao.org/download/Q/*/E

Gadde B (2007) Current uses of rice straw in Philippines—questionnaire survey. cum personal communication

Gadde B, Bonnet S, Menke C, Garivait S (2009) Air pollutant emissions from rice straw open field burning in India, Thailand and the Philippines. Environ Pollut 157(5):1554–1558

GSO (2011) General Statistic Office of Vietnam. http://www.gso.gov.vn

IPCC (2006) Intergovernmental Panel for Climate Change Guidelines for National Greenhouse Gas Inventories. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html

Kanabkaew T, Kim Oanh NT (2011) Development of spatial and temporal emission inventory for crop residue field burning. Environ Model Assess 16(5):453–464

Kim Oanh NT (2012) Chapter 13: Integrated approach to rice straw management for reduction of field-burning activity. In: Kim Oanh NT (ed) Integrated air quality management Asian Case Studies. CRC Press, Boca Raton, FL

Kim Oanh NT, Bich TL, Tipayarom D, Manandhar BR, Prapat P, Simpson C (2011) Characterization of particulate emission from open burning of rice straw. Atmos Environ 45(2):493–502

Kim Oanh NT, Tipayarom A, Ly Bich T, Tipayarom D, Simpson CD, Hardie D, Liu LJS (2015) Characterization of gaseous and semi-volatile organic compounds emitted from field burning of rice straw. Atmos Environ 119:182–191

Klinmalee A (2008) The development of assessment procedure for exposure to open rice straw burning emission: a case study of school children in Thailand. AIT dissertation, Pathumthani, Thailand

Koopmans A, Koppejan J (1998) Agricultural and forest residues—generation, utilization and availability. In FAO 1998. Regional consultation on modern application on biomass energy. January 6–10, 1997. Kuala Lumpur, Malaysia.

Launio CC, Constancio A, Asis Jr, Manalili RG, Javier EF (2013) Economic Analysis of Rice Straw Management Alternatives and Understanding Farmers' Choices. Published by WorldFish (ICLARM) - Economy and Environment Program for Southeast Asia (EEPSEA), Los Banos, Philippines

Le TH, Nguyen TNT, Lasko K, Ilavajhala S, Vadrevu KP, Justice C (2014) Vegetation fires and air pollution in Vietnam. Environ Pollut 195:267–275

Lualon U, Lerdphornsuttirat N, Zusman E, Sano D (2013) Environmental governance and short-lived climate pollutants (SLCPs): the case of open burning in Thailand. IGES Working Paper No. 2013-03. http://pub.iges.or.jp/modules/envirolib/upload/4770/attach/IGES_Working_Paper_2013-03.pdf

Makarim AK, Sumanto S (2007) Rice straw: management and utilization. Research and Development Center of Agriculture. Ministry of Agriculture. Bogor, Indonesia

Marshall S, Taylor JA, Oglesby RJ, Larson JW, Erickson DJ (1996) Climatic effects of biomass burning. Environ Softw 11(3):53–58

MOA (2011) Database of agricultural statistics. Ministry of Agriculture of Indonesia. http://aplikasi.deptan.go.id/bdsp/index.asp

OAE (2011) Thailand agricultural statistic yearbook in 2011. Bangkok: Office of Agriculture Economics (OAE)

Penner JE, Chuang CC, Liousse C (1996) The contribution of carbonaceous aerosols to climate change 14th International Conference on Nucleation and Atmospheric Aerosols, 26–30 August 1996, Helisinki, Finland

Permadi DA, Kim Oanh NT (2013) Assessment of biomass open burning emissions in Indonesia and potential climate forcing impact. Atmos Environ 78:250–258

Rumbayan M (2004) Biomass energy resources assessment in North Sulawesi. Biomass Energy Resour 10(3):223–226

Sasongko WR, Wishnu IMW, Yohannes GB (2004). Livestock farming systems technology application for goat in a dry land village, Sambelia. Research and Development Center of Ministry of Agriculture. http://ntb.litbang.deptan.go.id/ind/2004/NP/penerapanteknologi.doc

Shi Y, Yamaguchi Y (2014) A high-resolution and multi-year emissions inventory for biomass burning in Southeast Asia during 2001–2010. Atmos Environ 98:8–16

Shrestha RM, Kim Oanh NT, Shrestha R, Rupakheti M, Permadi DA, Kanabkaew T, Salony R (2013) Atmospheric Brown Cloud (ABC) Emission Inventory Manual (EIM). United Nation Environmental Programme (UNEP). Nairobi, Kenya

Sornpoon W, Bonnet S, Kasemsap P, Prasertsak P, Garivait S (2014) Estimation of emissions from sugarcane field burning in Thailand using bottom-up country-specific activity data. Atmos 5:669–685

Streets DG, Bond TC, Carmichael GR, Fernandes SD, Fu Q, He D, Klimont Z, Nelson SM, Tsai NY, Wang MQ, Woo JH, Yarber KF (2003) An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. J Geophys Res 108(D21):8809

Tipayarom D, Kim Oanh NT (2007) Effects from open rice straw burning emission on air quality in Bangkok Metropolitan Region. Sci Asia 33(3):339–345

Towprayoon S, Bonnet S, Garivait S, Chidthaisong A (2007) Greenhouse gas and aerosol emission from rice field and forest in the Mekong River Basin Sub-region. GMSARN International conference on Sustainable Development: Challenges and Opportunities for GMS

Vadrevu K, Lasko K (2015) Fire regimes and potential bioenergy loss from agricultural lands in the Indo-Gangetic Plains. J Environ Manag 148:10–20

Vadrevu KP, Ellicott E, Badarinath KVS, Vermote E (2011) MODIS derived fire characteristics and aerosol optical depth variations during the agricultural residue burning season, north India. Environ Pollut 159(6):1560–1569

Vadrevu KP, Csiszar I, Ellicott E, Giglio L, Badarinath KVS, Vermote E, Justice C (2013a) Hotspot analysis of vegetation fires and intensity in the Indian region. IEEE J Sel Top Appl Earth Observ Remote Sens 6(1):224–238

Vadrevu KP, Giglio L, Justice C (2013b) Satellite based analysis of fire–carbon monoxide relationships from forest and agricultural residue burning (2003–2011). Atmos Environ 64:179–191

Vadrevu KP, Lasko K, Giglio L, Justice C (2015) Vegetation fires, absorbing aerosols and smoke plume characteristics in diverse biomass burning regions of Asia. Environ Res Lett 10(10):105003

Van der Werf DG, Randerson JT, Giglio L, Collatz GJ et al (2010) Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). Atmos Chem Phys 10:11707–11735

Woo JH, Streets DG, Carmichael GR, Tang Y, Yoo B, Lee WC, Thongboonchoo N et al (2003) Contribution of biomass and biofuel emissions to trace gas distributions in Asia during the TRACE-P experiment. J Geophys Res 108(D21):8812

World Growth (2011) The economic benefit of palm oil to Indonesia: A Report by World Growth. http://worldgrowth.org/site/wp-content/uploads/2012/06/WG_Indonesian_Palm_Oil_Benefits_Report-2_11.pdf

Yevich R, Logan JA (2003) An assessment of biofuel use and burning of agricultural waste in the developing world. Journal of. Glob Biogeochem Cycles 17:1095