

Impact of open burning of crop residues on air pollution and climate change in Indonesia

Ade Andini^{1,2}, Sébastien Bonnet^{1,2,*}, Patrick Rousset^{1,2,3} and Udin Hasanudin⁴

¹The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi, Bangkok, Thailand

²Center for Energy Technology and Environment, Ministry of Education, Bangkok, Thailand

³CIRAD – Agricultural Research for Development Biomass, Wood, Energy, Bioproducts team Internal Research Unit – BioWooEB, Montpellier, France

⁴Research and Development Center for Tropical Biomass, Institute for Research and Community Services, University of Lampung, Lampung, Indonesia

Crop residues are subjected to open burning in Indonesia. These farming practices were studied to determine the proportion of open burned and their contribution to air pollution based on crop and air pollutant specific emission factors. On an annual basis, it was estimated that 45 million tonnes of crop residues are open burned. This leads to emission of greenhouse gases and toxic pollutants. On an average, CO₂ and CO dominate the overall emissions with 90% and 8% respectively. The remaining 2% are contributed by CH₄, SO₂, NO_x, NH₃, N₂O, NMVOC and particulate matter. Climate charging emissions were assessed to contribute 12–14% towards global warming potential by the global crop residues open burning.

Keywords: Crop residues, emission factors, global warming, Indonesia, open burning.

BIOMASS burning is defined as the combustion of world's living and dead vegetation, including grasslands, forests and agricultural lands following the harvest for land clearing and land use change. It is not limited to one area but is a global phenomenon and has been recognized as a key driver for global change¹. Biomass burning is one of the major sources of gaseous and particulate emissions to the atmosphere² and studies on climate change have shown that it is more frequent during dry season³. It contributes to global environmental change by affecting local, regional and global air quality as well as by disrupting rainfall patterns. Most of the world's biomass burning occurs in the tropics and includes among others, tropical forests, savannas and agricultural land after the harvest⁴. A study on air quality in Asia indicated that biomass burning constitutes a major source of air pollution, particularly in China, India, Indonesia and countries of the Mekong River Basin Sub-Region⁵.

Air pollutants emitted from biomass open burning whether forest fires or crop residues, include common greenhouse gases (GHGs) such as carbon dioxide (CO₂),

carbon monoxide (CO), methane (CH₄) and nitrous oxide (N₂O) as well as volatile organic compounds (VOCs), ammonia (NH₃), sulphur dioxide (SO₂), nitrogen oxides (NO_x) and particulate matter (PM). Agricultural residues burning also releases a huge amount of pollutants to the atmosphere, which apart from the above includes aerosols and hydrocarbons^{6–9}. Haze formation is one of the major impacts of open burning. It is a recurrent issue of concern in Southeast Asia where biomass-burning haze has become an important source of tropospheric ozone and the aerosols resulting from such events have contributed largely to the formation of atmospheric brown clouds^{10,11}. Vegetation fires in Sumatra and Kalimantan Islands in Indonesia have caused trans-boundary haze pollution events affecting the entire Southeast Asian region; the most well-known event occurred in 1997–98 (refs 12, 13). In October 2015, vegetation fires in Kalimantan resulted in the pollution standard index (PSI) reaching a level of 2400, the maximum hazardous level being 1000. The daily GHG emissions from Indonesia's fires in October 2015 were estimated at 15.95 million tonnes CO_{2eq} which comparatively exceeded the emissions from the entire US. If Indonesia could curtail open burning of biomasses, it would be able to meet its stated target of reducing GHG emissions by 29% by the year 2030 (refs 14, 15).

Indonesia is an agrarian country consisting of more than 17,000 islands. It is composed of five major islands namely Sumatra, Kalimantan, Java, Sulawesi and Papua. FAO¹⁶ revealed that 30% of Indonesia's land is dedicated to agricultural production. The major food crops produced in the country based on harvested area are rice, corn, cassava, soybean and peanut. Oanh *et al.*¹⁷ indicated that post harvest, a proportion of crop residues is used by farmers as composting material and animal feed, for roof thatching, and as fuel for domestic use. However, for a number of reasons including limited access to labour and enhanced access to modern energy, large amount of residues remain unused in the field and subjected to open burning. Such a practice has become an issue of growing concern as responsible for various adverse impacts such as air pollution, climate change and health and economic

*For correspondence. (e-mail: sebastien_b@jgsee.kmutt.ac.th)

impacts. These also affect bilateral relationships with neighbouring countries¹⁸⁻²⁰. Although area-wise forest fires dominate with about 70% of its surface subjected to open burning, the largest emissions (~80%) are observed from agricultural burning followed by forest fire and Municipal Solid Waste (MSW)²⁰. Several studies have attempted to assess potential emissions from crop residues burning using satellite data (fire hotspots), default activity data and emission factors^{5,18,20,21-23}. However, the results were characterized by lots of uncertainties. Hence results should be refined using country- and crop-specific information in particular with regard to the proportion of residues subjected to open burning and the emissions factors used.

The objectives of this study were: (1) to determine the proportion of crop residues subjected to open burning in Indonesia based on farming practices, and (2) to estimate the corresponding emissions of air pollutants and potential contribution to climate change in the form of global warming potential (GWP).

Methodology

Assessment of farming practices

In order to study farming practices that represent the situation in Indonesia, an island with the highest crop production potential was selected. For the year 2015, based on the data from the Indonesian Ministry of Agriculture (IMA)²⁴, Sumatra was identified as the suitable island. Similarly, using the same data²⁴, the Lampung province in Sumatra, with a significant crop variety and production potential was considered for the field survey. The field survey was conducted using a questionnaire to study farming practices, including open burning of crop residues. The sampling size (n) for the survey was determined based on the Yamane equation²⁵ as

$$n = \frac{N}{1 + N(e)^2}, \quad (1)$$

where N is the population of farmers and e is the desired level of precision, also called sampling error, and was set at 95%. It represents the range in which the true value of the population is estimated to lie. Based on eq. (1), a sample of 400 farmers was selected for interview spread over 13 areas in the province.

The questionnaire for the field survey was designed as detailed by Andini *et al.*²⁶. It consisted several sections, including locations of agricultural production sites and types of crops cultivated and detailed information about the farming practices followed by farmers. From the survey, information about the proportion of crop residues burned in the field and proportion used for other purposes was identified. The data collected from the survey was divided into two groups, i.e. crop residues unburned and crop residues burned. Concerning the fraction of crop

residues unburned, the data was further subdivided into two groups, namely crop residues used and crop residues unused. Regarding the utilization of crop residues, there were five main areas, such as animal feed, fertilizer, fuel, food and other purposes. In case of open burning of crop residues, there were three main areas, such as soil enrichment (nutrients), pest control and elimination of residues.

Assessment of crop residues open burned and emissions

Based on data collected from the field survey, the amount of crop residues subjected to open burning was estimated for each of the crops studied, using eq. (2) as

$$Q = P \times R \times B, \quad (2)$$

where for a specific crop, Q is the quantity of crop residues subjected to open burning (mg/year) and P is the crop production (mg/year). The data was obtained from IMA²⁴; R the residue-to-product ratio and refers to the amount of crop residues produced per amount of product (on a dry mass basis). Crop-specific values for this parameter were estimated based on data from Permadi and Oanh²⁰; B is the proportion of crop residues subjected to open burning. Values for this parameter, which is country- and crop-specific, and mainly influenced by farming practices, were determined through the questionnaire survey performed with farmers.

As reported in Gadde *et al.*¹⁸, the approach to quantify air pollutants emissions from biomass open burning is based on the methodology proposed by the Intergovernmental Panel on Climate Change (IPCC) guidelines 2006 (ref. 27), except for the step to quantify the amount of crop residues subjected to open burning. Air pollutant emissions from specific crop residues field burning were quantified using eq. (3)

$$E_a = Q \times \eta \times EF_a, \quad (3)$$

where for a particular crop residue, E_a the emission of a (mg/year) and η the fraction of biomass oxidized during combustion. Biomass specific values were collected from Turn *et al.*²⁸; EF the emission factor of a of dry crop residues (g/kg). Crop-specific values were obtained from literature review; Q the quantity of crop residues subjected to open burning (mg/year) (for a specific crop); a the pollutant species.

Results and discussion

Proportion of crop residues subject to open burning

Information from IMA²⁴ shows that rice, corn, cassava and sugarcane are the top four main crops produced in

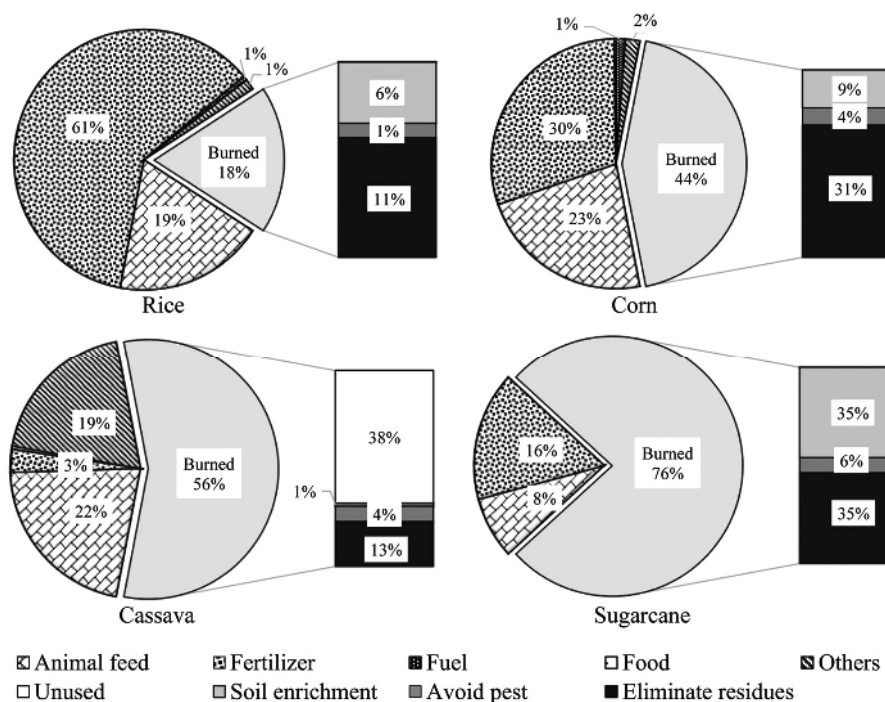


Figure 1. Proportion of crop residues burned and unburned.

Table 1. Crop production, residue generation and coefficients used for inventory

Crop	P (10^6 tonnes year ⁻¹) ^a	R ^b	B (%)	Q (10^6 tonnes year ⁻¹)
Rice	70.85	1.49	18	19.30
Cassava	23.44	1.42 ^c	56	18.50
Corn	19.01	0.80	44	6.70
Sugarcane	2.58	0.21	76	0.40
Total	115.88			44.90

^aMinistry of Agriculture of Indonesia²⁴; ^bPermadi and Oanh²⁰; ^cKoopman and Koppejan⁴⁴.

Indonesia whose residues are also subjected to open burning. Rice is the dominant crop with a largest area harvested, i.e. 12.5 m ha, followed by corn with 3.3 m ha, cassava with 0.9 m ha and sugarcane with 0.4 m ha.

According to data obtained from the survey and the corresponding results reported in Figure 1, it is observed that more than 80% of rice residues and more than half of all corn residues are unburned and used mainly as fertilizers and animal feed. For sugarcane, the reverse is observed with over three quarters of its residues being open burned. The remaining fraction is used mainly as fertilizer and animal feed as is the case for rice and corn. The results obtained for cassava, which is a perennial woody shrub, are quite different. It is observed that 80% of its residues are unburned, almost half of which is unused and consists mainly of stalk and stubbles. The other half of the unburned residues consist of leaves, which are mainly used as animal feed and some other unidentified purposes. Concerning the fraction of crop residues open burned, some similarities are also observed for rice, corn and

sugarcane in terms of soil enrichment, next crop preparation and elimination of residues. For rice and corn, having two or three cycles of production and harvest in a year, open burning is mainly practised to eliminate residues for next crop preparation. For sugarcane, burning of crop residues is practised prior to harvesting to eliminate residues in the case of green harvesting. It is also practised following harvesting to enrich the soil in nutrients for the next ratoon (there can be 3–5 ratoons) as well as to eliminate residues to facilitate for the next production cycle. With regard to cassava, farmers eliminate residues via open burning and to avoid fungal contamination from residues decomposition.

Table 1 shows the details of open burning of rice, corn, cassava and sugarcane residues. Based on the proportion of crop residues subjected to open burning, sugarcane shows the highest amount with 76%, followed by cassava (56%), corn (44%) and rice (18%). These results are comparatively lower than that of a study by Seiler and Crutzen²⁹ which reported that 80% of crop residues are

Table 2. Crop specific oxidation factors and pollutant specific emission factors

Description		Rice straw	Corn	Cassava	Sugarcane
Oxidation factor	η^a	0.89	0.92	0.68	0.68
Emission Factors (g kg ⁻¹)	CO ₂	1,216 ^c	2327.14 ^h	1130 ^k	1130 ^k
	CO	179.9 ^c	80.3 ⁱ	86.30 ^k	34.66 ⁱ
	CH ₄	9.59 ^c	3.4 ⁱ	4.56 ^k	0.41 ⁱ
	NO _x	3.10 ^d	3.7 ⁱ	0.70 ^k	2.63 ⁱ
	N ₂ O	0.07 ^b	0.07 ^b	0.07 ^b	0.07 ^b
	NH ₃	4.10 ^c	1.6 ⁱ	1.30 ^b	0.95 ⁱ
	SO ₂	2.00 ^e	0.44 ^j	0.216 ^k	0.216 ^k
	NM VOC	4.00 ^f	4.40 ⁱ	4.35 ^k	2.18 ⁱ
	PM ₁₀	9.4 ^g	4.26 ⁱ	8.05 ^k	3.99 ⁱ
	PM _{2.5}	4.2 ^c	4.13 ⁱ	3.88 ^l	3.77 ⁱ
	EC	0.51 ^g	0.95 ^h	0.47 ^l	0.77 ^m
	OC	2.99 ^g	2.25 ^h	0.91 ^l	0.91 ^l

^aTurn *et al.*²⁸; ^bAndreae and Merlet³²: Default EFs for several types of biomass burning. ^cChristian *et al.*³³: Specific EFs for rice straw open burning in Indonesia. ^dKadam *et al.*³⁴: Specific EFs for rice straw open burning in California. ^eJenkins and Bhatnagar³⁵: Specific EFs for rice straw open burning. ^fUS EPA³⁶: EFs for rice straw from the AP-42 database developed by the USEPA. ^gOanh *et al.*¹⁷: Specific EFs for rice straw open burning in Thailand. ^hCao *et al.*³⁷: Specific EFs for corn residues based on combustion tower experiment in China. ⁱDennis *et al.*³⁸: Specific EFs for corn and sugarcane open burning in Texas. ^jLi *et al.*³⁹: Specific EFs for corn stover open burning in China. ^kZhang *et al.*⁴⁰: Default EFs for crop residues open burning in China. ^lReddy and Venkataraman⁴¹: Default EFs for crop residues open burning in India. ^mPenner *et al.*⁴²: Specific EFs for sugarcane at developing areas.

open burned in developing countries. Specifically for Asia, Chang *et al.*³⁰ reported much lower values (17–25%) for all types of crop residues subjected to open burning. However, Yevich and Logan³¹ reported that in Indonesia 73% of all types of crop residues are burnt in the field. Sasongko *et al.*²³ who studied more specifically rice straw open burning in Indonesia, reported that 43% of rice straw are open burnt on Java Island, while a default value of 75% was considered for other rice production centres in Indonesia.

These studies reveal that on a dry mass basis, rice straw contributes highest amount of residues open burnt with 19.3 million tonnes. This is closely followed by cassava residues with 18.5 million tonnes, then corn residues with 6.7 million tonnes and sugarcane with 0.4 million tonnes. In total, an annual amount of 44.9 million tonnes of crop residues were subjected to open burning. Streets *et al.*⁵ reported that in the year 2000, with 17% of the crops subjected to open burning, an equivalent amount of 5.8 Tg crop residues were eliminated by fire in Indonesia. Yevich and Logan³¹ reported that 73% of Indonesia's crop residues were open burned equating to 64.2 Tg. This large gap in the estimation of open burned crop residues is due to a number of factors like crops considered, residue-to-product ratio, and the fraction open burned. However, the latter appears to be the most important factor for estimating the amount of crops residues burned.

Pollutant-specific emission factors of selected crops

Emission factors specific to air pollutants and the corresponding types of crop residues subjected to open field

burning are presented in Table 2. The emission factors are expressed in grams of released pollutant per kilogram of burned dry matter of crop residues. As mentioned before, the emission factors were obtained from literature review. For each crop, emission factors were selected that are country (Indonesia) or region (Asia) specific. When crop specific emission factors were not available, default values for crops in general were used³².

With regard to rice straw, emission factors for CO₂, CO, CH₄, NH₃ and PM_{2.5} were retrieved from Christian *et al.*³³ based on the rice straw open burning in Indonesia. For NO_x, SO₂ and non-methane volatile organic compounds (NMVOC), emission factors were sourced respectively from Kadam *et al.*³⁴, Jenkins and Bhatnagar³⁵ and the AP-42 database developed by the US Environmental Protection Agency³⁶. Emission factors for PM₁₀, elemental carbon (EC) and black carbon (BC) were sourced from Oanh *et al.*¹⁷ based on the rice straw open burning in Thailand.

With regard to corn, emission factors for CO₂, EC and OC were collected from a study done in China by Cao *et al.*³⁷. Specific emission factors for CO, CH₄, NO_x, NH₃, NMVOC, PM₁₀ and PM_{2.5} were retrieved from Dennis *et al.*³⁸ and for SO₂, from Li *et al.*³⁹.

In case of cassava, due to the scarcity of information on specific emission factors for this crop, default values were retrieved from different sources, like Zhang *et al.*⁴⁰ for CO₂, CO, CH₄, NO_x, SO₂, NMVOC and PM₁₀, Andreae and Merlet³² for N₂O and NH₃ and Reddy and Venkataraman⁴¹ for PM_{2.5}, EC and OC.

For sugarcane, specific emission factors for CO, CH₄, NO_x, NH₃, NMVOC, PM₁₀ and PM_{2.5} were sourced from

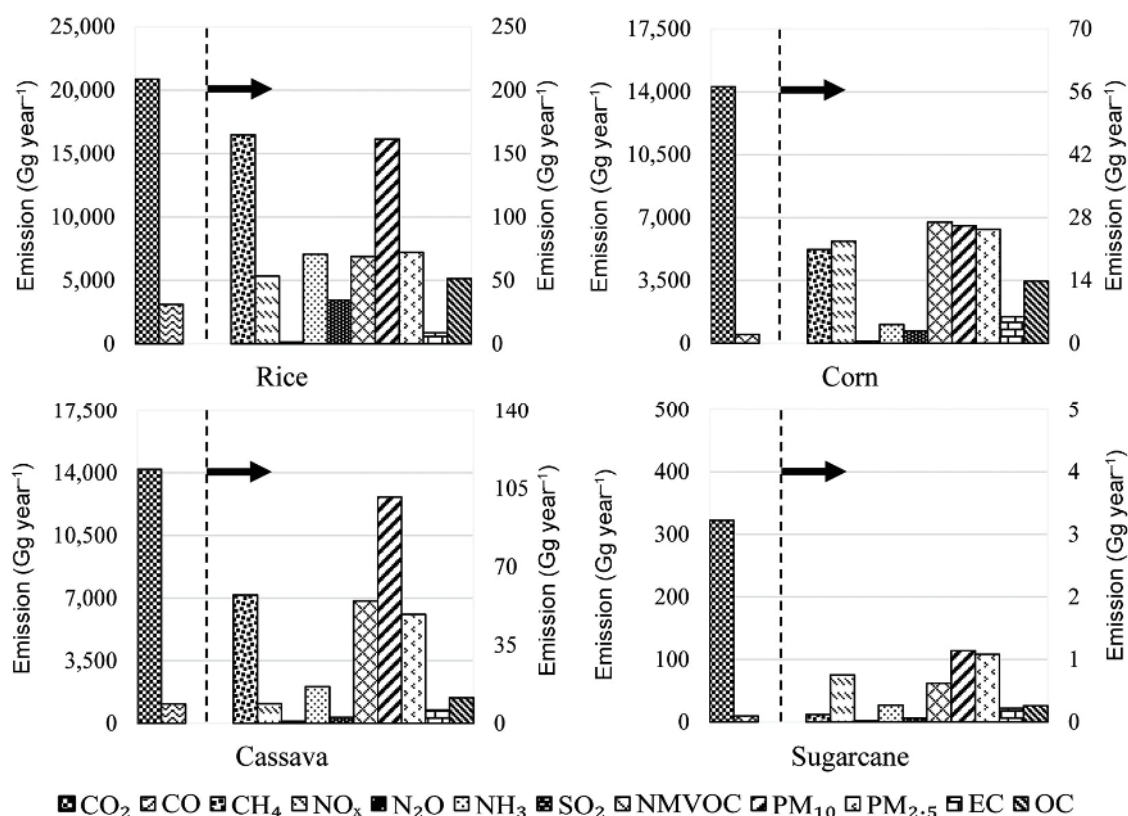


Figure 2. Annual emission of air pollutants from crop residues open burning in Indonesia.

Dennis *et al.*³⁸. Other emission factors were mainly retrieved from Zhang *et al.*⁴⁰ and Penner *et al.*⁴².

Emissions from crop residues open burning

Figure 2 shows that the open burning of all the selected crop residues contributes largely towards CO₂ emissions in the range of 85–96%, followed by CO in the range of 3–13%. The remaining fraction is contributed by the rest of the pollutants such as CH₄, NO_x, N₂O, NH₃, SO₂, NMVOC, PM₁₀, PM_{2.5}, EC and organic carbon (OC). Depending on the crop, the contribution towards air pollutant emissions varies. Open burning of rice straw is observed to contribute the largest emission of all the pollutants as shown in Figure 2. After rice, cassava is the next crop to contribute most to the annual emissions of CO, CH₄, N₂O, NH₃, SO₂, NMVOC, PM₁₀, PM_{2.5} and EC. Although sugarcane emissions appear to be the lowest and much less significant compared to rice, corn and cassava, it is the crop with the highest proportion of crop residues subjected to open burning (76%). As the government of Indonesia is considering promoting biofuels such as ethanol for transport in the near future, an expansion of sugarcane plantations is expected to meet future policy targets. However, this might magnify emission of air pollutants if open burning practices are not controlled.

As mentioned earlier, Streets *et al.*⁵ had assessed emissions from biomass burning in Asia, including Indonesia. The studies included open burning of crop residues in general using default values from the literature. In particular, the proportion of crop residues subject to open burning was assumed to be 17% and default emission factors from Andreae and Merlet³² were used. The results obtained for Indonesia are by using the default values from Streets *et al.*⁵ and the specific values identified in this study are compared for rice, corn, cassava and sugarcane (Figure 3). It is observed that the emissions are underestimated when default values from Streets *et al.*⁵ are used. This is particularly so for a number of climate pollutants. For instance, CO₂, N₂O, NMVOC, PM_{2.5} and EC emissions estimated using country and crop specific values from this study are 60% higher than based on default values from Streets *et al.*⁵. In the same way, CO, CH₄, NO_x, NH₃ and OC emissions are about 30% higher while PM₁₀ and SO₂ are about 50% and 10% higher respectively. These findings indicate that the potential contribution of open burning of crop residues in Indonesia towards air pollution is underestimated. This also implies that the contribution of Indonesian open burning of crop residues to climate change is underestimated and the mitigation of such practices could lead to larger GHG emission reduction benefits than expected.

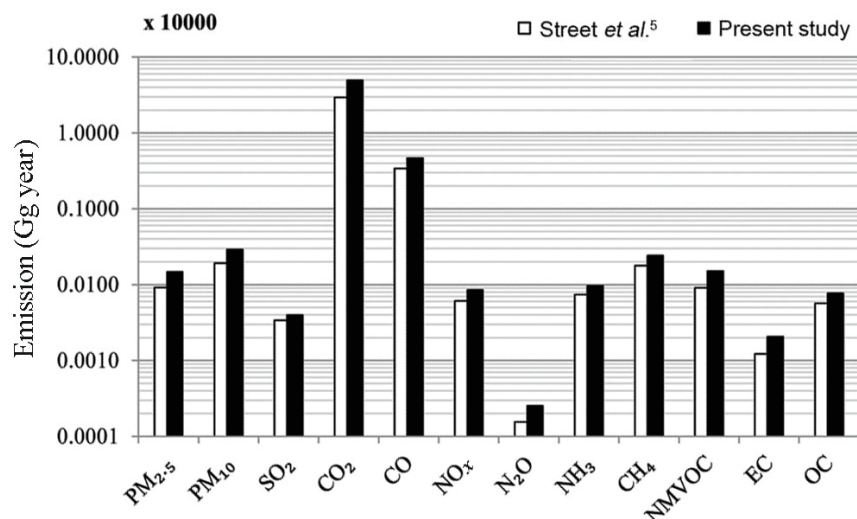


Figure 3. Comparative annual emissions of air pollutants from crop residues burning in Indonesia based on default factors from Streets *et al.*⁵ and specific factors as identified in this study.

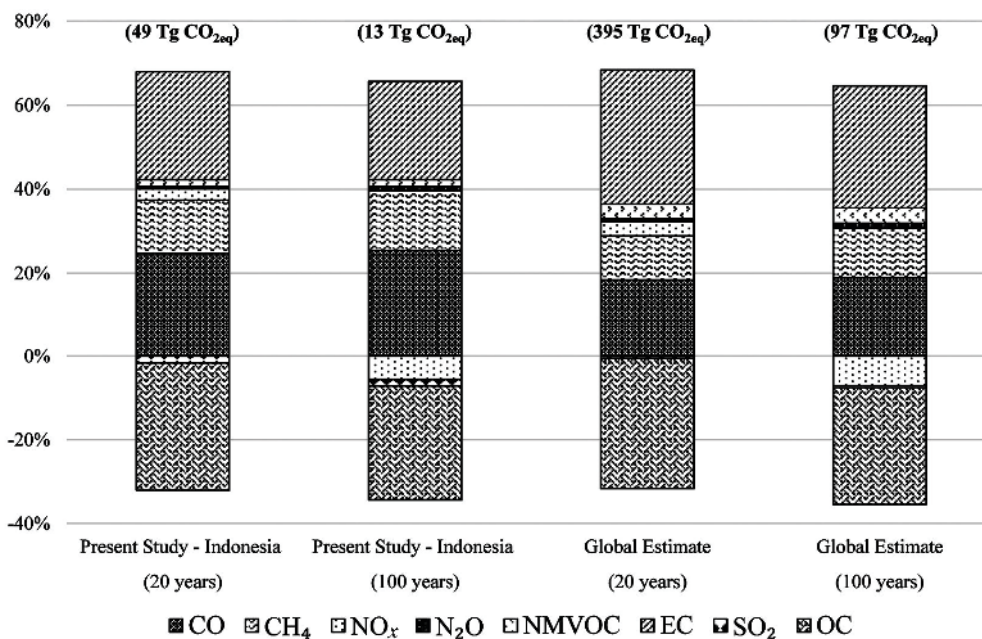


Figure 4. Contribution of Indonesia’s crop residues open burning to the global agricultural open burning GWP. The values in parentheses correspond to the net GWP (CO_{2eq}).

Contribution towards global open burning of crop residues GWP

Figure 4 shows the percentage contribution of GHGs towards GWP and the short-lived climate changers emitted from open burning of crop residues in Indonesia in 2014. Figure 4 shows the percentage contribution to GWP of both warming (CO, CH₄, NO_x, N₂O, NMVOC and EC with positive forcing) and cooling agents (SO₂ and OC with negative forcing). CO₂ is not accounted for as it is considered as carbon neutral for annual crops as per the IPCC 2006 guidelines²⁷. GWP is expressed in the

form of CO_{2eq}. The total GWP for 2014 is estimated at 93 Tg CO_{2eq} (20 year horizon) and 25 Tg CO_{2eq} (100 year horizon), while the net GWP is estimated at 49 Tg CO_{2eq} and 13 Tg CO_{2eq} respectively. For both time horizons, in terms of positive forcing, the largest contributors to the total GWP are EC (38–39%), CO (36–42%) and CH₄ (19–24%). These results highlight the importance of such pollutants to the GWP of crop residues subjected to open burning. The GWP of global crop residues subjected to open burning as estimated using data from Global Fire Emissions Database (GFED) 4 (ref. 43) for 2014 (Figure 4) amounts to about 395 Tg CO_{2eq} (20 year) and 97 Tg

CO_{2eq} (100 year). Therefore, Indonesian open burning of crop residues contributes about 12–14% of the GWP of global crop residues open burning for both time horizons.

Conclusion

Major crops produced in Indonesia include rice, corn, cassava and sugarcane. It was found that about 45 million tonnes of these crop residues were open burned on an annual basis. This represents about 29% of the total amount of crop residues produced nationwide with rice contributing 43%, cassava 41%, corn 15% and sugarcane 1%. In terms of emissions, it was found that they were dominated by CO₂ (85–96%), followed by CO (3–13%). The remaining 1–3% of the emissions were found to be contributed by CH₄, NO_x, N₂O, NH₃, SO₂, NMVOC, PM₁₀, PM_{2.5}, EC and OC. However, among those pollutants, agents forcing positive climate change such as EC, CO and CH₄ were identified to be the major contributors to the GWP of open burning of crop residues. Based on the country, crop and pollutant specific factors identified in this study, it was estimated that the Indonesian open burning of crop residues contributed a substantial 12–14% of the GWP of global crop residues open burning over a 20 year and 100 year horizon respectively. Such a contribution to climate change highlights the necessity of achieving the zeroburning policy that has been committed by Indonesia through the ASEAN agreement on transboundary haze pollution in 2014. Further studies are currently in progress to identify processes enabling to utilize those residues as energy feedstock for industrial applications.

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ACKNOWLEDGEMENTS. We thank the team from Research and Development Center for Tropical Biomass, Institute for Research and Community Services, University of Lampung, Indonesia for the support and guidance. We also thank the Joint Graduate School of Energy and Environment, Center of excellence for Energy Technology and Environment, King Mongkut's University of Technology Thonburi, Thailand and the French Agricultural Research and International Cooperation Organization (CIRAD), France, for providing the financial support.

Received 5 February 2018; revised accepted 17 July 2018

doi: 10.18520/cs/v115/i12/2259-2266
