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Assessment of biomass open burning emissions in Indonesia and potential climate forcing impact

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HIGHLIGHTS

- ► Emission inventory for biomass open burning in Indonesia was conducted for 2007.
- ► Best estimates and ranges of pollutants and GHG emission were produced.
- ► Methodology for solid waste open burning emission inventory was developed.
- ► Monthly and gridded (0.25°) emissions were obtained for 3D modeling.
- ► Climate forcing associated with Indonesian biomass open burning was assessed.

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ABSTRACT

This paper presents an emission inventory (EI) for biomass open burning (OB) sources including forest, agro-residue and municipal solid waste (MSW) in Indonesia for year 2007. The EI covered toxic air pollutants and greenhouse gases (GHGs) and was presented as annual and monthly average for every district, and further on a grid of 0.25° × 0.25°. A rigorous analysis of activity data and emission factor ranges was done to produce the low, best and high emission estimates for each species. Development of EI methodology for MSW OB which, to our best knowledge, has not been presented in detail in the literature was a focus of this paper. The best estimates of biomass OB emission of toxic air pollutants for the country, in Gg, were: 9.6 SO_2; 98 NO_x; 7411 CO; 335 NMVOC; 162 NH_3; 439 PM_{10}; 357 $PM_{2.5}$; 24 BC; and 147 OC. The best emission estimates of GHGs, in Gg, were: 401 CH_4, 57,247 CO_2; and 3.6 N_2O. The low and high values of the emission estimates for different species were found to range from −86% to +260% of the corresponding best estimates. Crop residue OB contributed more than 80% of the total biomass OB emissions, followed by forest fire of 2–12% (not including peat soil fire emission) and MSW (1–8%). An inter-annual active fires count for Indonesia showed relatively low values in 2007 which may be attributed to the high rainfall intensity under the influence of La Niña climate pattern in the year. Total estimated net climate forcing from OB in Indonesia was 110 (20 year horizon) and 73 (100 year horizon) Tg CO_2 equivalents which is around 0.9–1.1% of that reported for the global biomass OB for both time horizons. The spatial distribution showed higher emissions in large urban areas in Java and Sumatra Island, while the monthly emissions indicated higher values during the dry months of August–October.

1. Introduction

The term of 'biomass open burning' generally refers to open burning (OB) of various biomass materials including forest vegetation, grass, crop residue and also municipal solid waste. OB smoke is reported to be a cause of the reoccurring transboundary haze problem in Southeast Asia (SEA) region (Koe et al., 2001). Specific weather anomalies such as those occurred during the El Niño year 1997 was responsible for most of the large forest fire events in Indonesia. The haze from forest fires in Indonesia was reported to affect regional air quality in terms of particulate matter (PM), ground level ozone and visibility locally and also in the neighboring SEA countries annually (Pentamwa and Kim Oanh, 2008).

Crop production in Indonesia generates a huge amount of residues which are commonly field burned after harvesting. OB problem is also commonly seen in most of the urban areas where municipal solid waste (MSW) is poorly managed. In the Asian developing countries and in Indonesia in particular, agriculture residue and

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MSW OB often take places in crowded areas hence can severely deteriorate air quality and cause adverse human health effects.

A proper quantification of the OB emission in the country is required in order to provide an overall assessment of the potential effects and the relevant information for formulation of appropriate mitigation measures. However, a comprehensive national emission inventory (EI) for this OB sources has not yet been reported. Although several global or regional EI databases also provided emission estimates for Indonesia they are not necessarily up-to-date nor have been developed using the detailed local activity data and relevant emission factors (EFs) suitable for the country. Several available global databases, for example, were compiled using the amount of biomass burned obtained from extrapolation of local data and partly from satellite data. The updated Global Fire Emission Database (GFED) provided long-term seasonal and gridded emissions of OB (i.e. deforestation, savanna, forest fire, and agricultural waste burning) using different satellite products (Van der Werf et al., 2010). Streets et al. (2003) conducted an EI for regional studies of forest fire and agriculture residue burning using statistics data for the 1950s–1990s and the total emissions were spatially distributed using Advanced Very High Resolution Radiometer (AVHRR) fire counts to produce the gridded dataset (1° resolution). Likewise, long-term seasonal and gridded emissions of non-agricultural open fires for Asia was developed by Song et al. (2010) using MODIS (Moderate Resolution Imaging Spectroradiometer) burned area product (MCD45A1) at a resolution of 500 m, considering geographical variation and country specific fuel load data. None of the reported studies have reported the emission estimate for MSW OB.

This study aimed to provide detailed emission database of OB in Indonesia for the year of 2007. The biomass OB included forest fire, crop residue field burning and MSW OB. Step-wise activity data collection and analysis for the rigorous selection of relevant EFs are presented. EI for multiple gaseous species (NO_x, SO_2, CO, NMVOC, and NH_3), primary particles (PM_{10}, $PM_{2.5}$, BC, OC), and GHGs (CO_2, CH_4, and N_2O) was conducted. The uncertainty analysis was conducted and the EI results were presented as the low, high and best estimates. The climate forcing effect introduced by the OB was assessed using the global warming potential (GWP) metric. Further, monthly emissions and the gridded ($0.25° \times 0.25°$) emissions suitable for three-dimensional modeling purposes were prepared.

2. Methodology

For emission estimation, this study used the general framework and emission calculation equations adopted from the Atmospheric Brown Cloud Emission Inventory Manual (ABC EIM) (Shrestha et al., in press) which are summarized in Fig. S1, Supplementary Information (SI).

2.1. Emission factors

The variation range of emission factors (EFs) and the variation in activity data were used to analyze the EI uncertainty, i.e. to produce the low, high and best emission estimates for each species. The lower and higher values of the compiled EF ranges were used to determine the low and high estimates, respectively, while the determination of the "best estimates" for the EF was similar to that used in Thongchai and Kim Oanh (2010). Accordingly, for the agricultural residue OB, whenever available the EFs for specific type of crop/land cover were used; otherwise EF for general crop residues (combined crops) was used. The EF values measured for the sources in Indonesia were the first choice, followed by values generated for similar biomass types and open burning practices in the Asian region. If there were no data available for the Asian region, relevant data from other parts of the world were used. Range of EFs for major crop residues OB used in this study is compiled in Fig. S2, SI.

Due to the lack of the local EF measurement data for forest fire and savanna OB, compiled data in Andreae and Merlet (2001), Van der Werf et al. (2010) and Akagi et al. (2010) were used. Furthermore, it was reported that most of fires occurred in Indonesian peatland swamp forest were due to land-clearing for agriculture land (deforestation). However, EFs specific for peatland swamp forest (above ground biomass) fires are not readily available in the literature. Therefore, most of EFs were taken from Van der Werf et al. (2010) under the deforestation fire category except for four species (CO, NH_3, CO_2 and CH_4) which were taken from the peat soil emission EF measured locally in Kalimantan (Borneo), Indonesia (Christian et al., 2003). Accordingly, for these four species (CO, NH_3, CO, and CH_4) the estimation may be conservatively high as the EFs are more suitable for below surface peat soil burning. The EFs used in this study are summarized in Table S1, SI. Not many literature sources reported EFs from MSW OB, therefore the EFs given in AP-42 (US EPA, 1995) and by Akagi et al. (2010) were used which are also presented in Table S1, SI.

For the QA/QC purpose, the mass balance check was done to ensure that the selected EFs satisfied the conditions of $PM_{2.5} \leq PM_{10}$ and $BC + OC < PM_{2.5}$.

2.2. Activity data

2.2.1. Forest fire

Active fire count data are commonly used to estimate the forest burned area (fire) for both global and regional scales with varying success. To reduce the uncertainty related to fires with a size well below a pixel of a hotspot (1 km^2), the MODIS (Moderate Resolution Imaging Spectroradiometer) burn scars product (MCD45A1) was used in our study. This product was downloaded from http://modis-fire.umd.edu/ and was analyzed with the land cover map to derive the burned area. A step-wise data extraction and processing procedure is presented in Fig. S3, SI. The national land cover map for the year 2005 was obtained from the 'Glob Cover' archive with a resolution of 300 m (http://www.iscgm.org/cgi-bin/). The dataset with original Land Cover Classification System (LCCS) legend was then re-classified into 6 broad types of vegetation susceptible to burning in Indonesia (primary tropical forest, secondary tropical forest, savanna, shrubland, mangrove, and peatland swamp forest). MODIS MCD45A1 was overlaid with the land cover map and the number of burn scars was determined for each district (within the district administration boundary).

The above ground dry matter density (fuel load in tonne per hectare, t ha^{-1}) is important activity data but it varies significantly with the type of vegetation and geographical location. We used the measurements data for Sumatra and Kalimantan forests reported by Murdiyarso et al. (2002) of 14.7–93.6 t ha^{-1} with the best estimate of 16.8 t ha^{-1} for the primary forest and 37.8–54.8 t ha^{-1} with the best estimate value of 38.2 t ha^{-1} for the secondary forest. The values were somehow lower as compared to the values reported for tropical forest in Thailand, 48–90 (primary) and 75–80 (secondary) t ha^{-1} (Piyaphongkul et al., 2011). Murdiyarso et al. (2002) also reported the typical value for Borneo mangrove and peatland swamp forests of 128 t ha^{-1}. This study also used the typical value of 0.6 t ha^{-1} for savanna and shrubland (14.3 t ha^{-1}) that was obtained from the measurements for Kalimantan (Christian et al., 2003). The best estimate values of burning efficiency used were 36% for primary tropical forests, 62% for secondary tropical forests, 85% for savanna, 48% for shrubland, and 57% for the rest, based on relevant references listed in Table S2, SI. Gridded emissions (0.25° or 28 km resolution) were then constructed based on the longitude–latitude coordinates given from the processed burn scars product.

Data on amount of peat soil (below surface soil) burned in the country were not available hence this emission was not included in this study. In general, peat soil fires should contribute significantly to the forest fire emissions, e.g. 80% of carbon released to the atmosphere during the massive 1997 Indonesian forest fire (Page et al., 2002), hence our forest fire emission may be somewhat underestimated.

A summary of available and selected activity data of forest fires in the country is presented in Table S2, SI.

2.2.2. *Municipal solid waste*

The total amount of the MSW subjects to OB is commonly dealt with a large uncertainty. In developing countries the burning is usually done in 3 locations: in the backyard (at generation site), at the transfer depot, and in landfills/dumping sites. In Asian developing countries including Indonesia, open dumping sites, i.e. without a proper daily soil covering, are still the most common disposal method. According to our observation, in urban areas burning occurred mainly at the transfer depot after the MSW was collected from the households. This mostly happens during the lag time period before the MSW was picked up from depots to transfer to dumping sites. The burning at source also occurs intensively in the peri-urban areas where no proper collection service was provided. In the rural areas the solid waste was not normally burned as it was used for composting or directly discharged into the environment. In this study we tried to separately estimate the MSW OB emission at source and transfer sites, and that at dumping sites for urban population in Indonesia. The urban population in the country composed around 40% of the total national population. The data on solid waste generation (MSW_{GR}) factor for Indonesia (1–2.5 kg cap^{-1} d^{-1} with the best estimate of around 2 kg cap^{-1} d^{-1}) from Enri et al. (2010) were used. The portion of the MSW OB at source and at transfer sites out of the total generated (P_{frac}) of 4–6%, typically for Bandung City, West Java (Enri et al., 2010), was used for the whole country. For the high estimate, P_{frac} value of around 20% found by Chanchampee (2010) for the Bangkok Metropolitan Region (BMR), Thailand, was used. Note that this study estimated MSW OB emission only for urban areas using the statistic data on urban population of almost all districts in the country. A substantial portion of MSW OB in other areas thus was not included. In fact, the λ values for peri-urban areas are actually higher than the urban areas due to the general lack of collection service. In Indonesia, the rapid urbanization was observed with a rapid growth of the peri-urban population hence the total MSW OB emission contribution may be even more substantial in the near future. The fraction of MSW burned at dumping sites is estimated based on our observation which shows that the open burning in the final dumping sites (FDS) frequently occurred especially during the dry season. First, the amount of the MSW being transferred to the FDS was estimated based on the data given by Enri et al. (2010) for the Bandung area with the amount of MSW transferred to dumping sites (ε) of 40–60% of the total generated MSW (best estimate of 50%). Data on the amount of waste burned in FDS were not available hence the estimation was done using the combustible fraction of MSW (δ_m) at the FDS of 1–9% of the total waste at FDS. Best estimate of 9% was used which has been reported (Enri et al., 2010) to be typical for open dumping sites with lower recovery rates of recyclable materials. The λ value was assumed to be 10%. The burning efficiency, $\eta_m = 58\%$ (IPCC, 2006) was used for both OB at sources and at FDS. The emissions were then aggregated into the same grid network of 0.25° × 0.25° for the country using district population data. A summary of the MSW OB activity data used is presented in Table S2 (SI) together with the data for forest fires.

2.2.3. *Crop residue field burning*

The MODIS satellite passes the Southeast Asia region twice a day hence the MODIS MCD45A1 burn scars product, with a medium resolution of 500 m, may not efficiently capture the field crop residue fires which are mostly short-lived, of a small size and sporadic in nature (Song et al., 2010; Kim Oanh et al., 2010). Thus, the approach using hotspot (active fire counts) to estimate the burning area poses a high uncertainty and can only provide preliminary information on field burning activities/intensities. In this study the crop production data (Streets et al., 2003) were used together with the data on land use/crop types instead of plantation area as the latter does not consider number of crop cycles in a year. In total, 8 major crop types were considered, including rice, soya, maize, potato, oil crops, groundnut, sugarcane, and root/tubers for which the residue is commonly field burned in Indonesia. The crop production data were obtained from provincial statistic report (BPS, 2008). The large production of crops with manual methods of harvesting and post harvesting processing in the country generates a huge amount of residues annually.

The important parameters for estimation of the amount of dry biomass burned included: (1) crop production data (P), (2) residue-to-crop ratio (S), (3) dry matter-to-crop residue ratio (D), (4) fraction of biomass burned in the field (B) and (5) burning efficiency (η_m). P value for rice and other crops is available in the national agriculture statistics (MOA, 2008). For rice, P values of the rough (un-milled) were available for 3 crops: (i) major rice, which are harvested during March–April, (ii) second rice, harvested during July–August and (iii) third rice, harvested during November–December. As S and D values vary with variety of crops, local agronomical and harvesting practices, the local specific values are required for an accurate estimation. We used the S value for rice and maize for Indonesian crops (Rumbayan, 2004). The S value for rice, and both S and D values for other crops reported for Thailand (Koopmans and Koppejan, 1998; Yevich and Logan, 2003) were used. The ranges of these values provided by IPCC (2006) were used in the uncertainty analysis. For B values, Seiler and Crutzen (1980) proposed that 80% of available crop residues were burned in developing countries and 50% in developed countries, while the values ranged from 10 to 90% were reported by other studies (IPCC, 2006; Streets et al., 2003; Thongchai and Kim Oanh, 2010). This value mainly depends on the country specific practices and is reported to be 73% for biomass open burning (all type of crops) in Indonesia (Yevich and Logan, 2003). For rice straw field burning, the B values of 0.3 and 0.9 (Thongchai and Kim Oanh, 2010) were used to produce low and high estimates, respectively. For the best estimates, the value of 0.43 reported by a survey conducted in Java (Sasongko et al., 2004) was used. For other regions, the value of 0.75 was taken based on the findings of Makarim et al. (2007) who conducted a survey on rice straw management in several rice production centers in Indonesia. Lower value in Java is expected due to increasing trend of organic farming where around 40% of generated rice straw was used for mulching and composting, and around 17% for cattle feedstock (Sasongko et al., 2004). The value used in Yevich and Logan (2003) of 0.73 was used for potato, groundnut and oil crops, while for other, crop specific values reported for Thailand (Thongchai and Kim Oanh, 2010) were used. The crop production data of 300 districts in the country were used to produce the gridded emission of 0.25° resolution. The available and selected activity data for crop residue OB are presented in Table S3, SI.

2.3. Temporal distribution

Various activity data were used to construct OB monthly emissions for Indonesia. The summary of the data and assumptions taken are presented in Table S4, SI.

2.4. Global warming potential assessment

Global warming potential (GWP) metric is used to determine the relative radiative effect of a given emission mass of a species compared to CO_2, integrated over a chosen time horizon. GWP of common GHGs and other short-lived climate forcers emitted from biomass OB in Indonesia is assessed using CO_2-equivalent emissions reported in various studies as presented in Table S5, SI. For the short-lived species (NO_x, CO, BC, OC, and SO_2) GWP values in principle depend on the geographical location of the emissions (Fuglestvedt et al., 2010) hence whenever available the regional GWP (Asia/Southeast Asia) values were used.

3. Results and discussion

3.1. Annual emission

The ranges of annual OB emissions (low, high and best estimates) are presented in Table 1 together with data extracted from other published EI works for comparison. For forest fire, the national best emission estimates in 2007 (Gg) were: 1.1 SO_2; 5.5 NO_x; 14.7 NMVOC; 16.9 $PM_{2.5}$; 19.9 PM_{10}; 2.4 NH_3; 1.2 BC; 9.7 OC; 194 CO; 3083 CO_2; 12.3 CH_4; and 0.4 N_2O. In the inventory year (2007), fires of secondary tropical forest and peatland swamp forest occurred mostly in Sumatra, Borneo (Kalimantan) and Java Island, which appeared to dominate the total forest fire emissions. Note that fires in these two forest types contributed of around 70% of the total burned area of 1600 km^2, followed by shrub land (19%), primary forest (6.5%), and savanna and mangrove forest (4.5%). For the crop residue OB, the national total best estimates in 2007 (Gg) were: 8 SO_2; 89 NO_x; 304 NMVOC; 330 $PM_{2.5}$; 387 PM_{10}; 159 NH_3; 22 BC; 132 OC; 7172 CO; 52,614 CO_2; 382 CH_4; and 3 N_2O. The rice straw OB contributed the largest shares of the total crop residue OB emission, i.e. 92% for CO, $PM_{2.5}$ and NOx, respectively, 81% for SO_2, and 84% for BC, thus only the rest 10–20% were contributed by other crop types. The national total best estimates for MSW OB in Gg were: 0.5 SO_2; 3.2 NO_x; 16 NMVOC; 10.5 $PM_{2.5}$; 32.0 PM_{10}; 1.0 NH_3; 0.7 BC; 5.6 OC; 45 CO; 1550 CO_2; 6.9 CH_4; and 0.16 N_2O. The emission from MSW OB at source contributed around 88% of the total emission of this kind, i.e. higher than that at the FDS, which was due to the low level of MSW collection service.

For the forest fire and crop residue OB, the difference between $PM_{2.5}$ and PM_{10} was small suggesting that majority of PM emitted from this burning activity belonged to the fine particle size range while for MSW OB the coarse particle size range was more dominant. More organic carbon than black carbon in the PM emission was found for all sources which are typically anticipated for the low combustion temperatures of OB. The smoke aerosol measurements made by aircraft (Gras et al., 1999) also showed that Indonesian fires had considerably greater light-scattering properties due to more smoldering fire which in principle produced more OC than EC.

Due to the inherent inter-annual variability in forest fires the comparison between the 2007 EI with EI for other base years, e.g. CGRER for 2000 and EDGAR for 2005, may be less meaningful. Our best emission estimates for forest fires were relatively higher than those of Song et al. (2010) but significantly lower than those of the Global Fire Emission Database (GFED) version 3, both for the same year of 2007. Note that both the cited EI included also a rough

Table 1
Total national emission and comparison with other EI works.

Pollutants	Emissions (Gg y^{-1})									
	This study			EDGAR[a]		CGRER[b]		Song et al., 2010[c]	GFED 3[d]	
	Forest fire (2007)	Crop residue OB (2007)	MSW OB (2007)	Forest fire (2005 & 2007)	Crop residue OB (2005 & 2007)	Forest fire (2000)	Crop residue OB (2000)	Forest fire (2007)	Forest fire (2007)	Crop residue OB (2007)
SO_2	0.4–2.5 (1.1)	4.8–48 (8.0)	0.08–1.8 (0.5)	31	29.1	38.8	2.3	0.5	24	0.3
NO_x	1.8–14.5 (5.5)	44–206 (89)	0.4–11 (3.2)	1040	277	166.7	22.3	1.3	81	1.8
CO	75–463 (194)	1756–13,630 (7172)	6.6–154 (45)	5550	6700	7078	536	95	4700	65.8
NMVOC	5.8–35 (14.7)	184–579 (304)	2.4–55 (16)	441	510	1315	91.5	9.8	240	8.8
PM_{10}	7.6–46.1 (19.9)	107–736 (387)	4.7–110 (32)	ne	ne	ne	ne	31	ne	ne
$PM_{2.5}$	6.5–40.3 (16.9)	87–627 (330)	1.5–36 (10.5)	ne	ne	ne	ne	28.3	310	6.5
NH_3	0.9–5.9 (2.4)	98–299 (159)	0.15–3.4 (1.0)	58.2	94.7	88.5	7.6	5.1	57	19.6
BC	0.5–2.9 (1.2)	12.8–68.8 (22)	0.1–2.4 (0.7)	ne	ne	44.9	4.0	0.5	19	0.38
OC	3.7–23.3 (9.7)	49.3–251.8 (132)	0.8–19.4 (5.6)	ne	ne	354	19.2	4.6	160	3.0
CH_4	4.8–29 (12.3)	228–721 (382)	1.0–24 (6.9)	515	200	463	15.7	5.5	380	5.3
CO_2	1141–7539 (3083)	22,354–136,387 (52,614)	230–5340 (1550)	620,000	ne	107,535	8832	1492	57,000	1141
N_2O	0.2–1.1 (0.4)	1.8–5.8 (3.0)	0.02–0.5 (0.16)	15.2	5.26	ne	ne	ne	6.9	0.1

Note: values presented in the brackets are best estimates.

[a] The Emission Database for Global Atmospheric Research (EDGAR) reported the emissions from forest fire and crop residue OB of GHGs for base year of 2007 and other species for 2005. http://edgar.jrc.ec.europa.eu/index.php%23.

[b] The CGRER (Streets et al., 2003) specifically reported emission of Indonesian forest fire and crop residue OB in the base year of 2000 (no update for 2006 EI database).

[c] Song et al. (2010) reported only the emission from forest fire for the base year of 2007.

[d] The Global Fire Emission Database version 3 (GFED 3). http://www.falw.vu/~gwerf/GFED/GFED3/tables/.

estimate for the peat soil burning which was not included in our EI estimates. The difference between these EI might be partly caused by the different activity data used. We used the standard MODIS MCD45A1 burned area with bi-directional reflectance algorithm (Roy et al., 2005) which is similar to Song et al. (2010) while GFED 3 used MODIS burned area maps derived from direct broadcast (DB) mapping algorithm (Giglio et al., 2009). Different ρ_m (t ha^{-1}) data selection may also explain this discrepancy since we use reported local measurements data of ρ_m which are generally lower than modeled ρ_m values used by GFED 3.

To investigate the inter-annual variation of forest fires in Indonesia, the accumulated hotspots were taken from MODIS active fire count for 9 years (2001–2009) and presented in Fig. S4, SI. The lowest number of 30,000 hotspots was observed in 2007 as compared to the highest number of over 160,000 in 2006. In fact, lower numbers of hotspots were observed during 2007–2009 as compared to the previous years (2001–2006). The period of 2007–2009 was affected by the La Niña, the cold phase of the El Niño Southern Oscillation (ENSO) climate pattern (Fig. S5, SI) which in turns affected the rainfall intensity. The precipitation amount (averaged over more than 60 stations in Java, Kalimantan and Sumatra) was high during 2007–2009, as also seen in Fig. S4, SI. This may be a major reason for less fire events in 2007 hence the emission from forest fires in this year was likely to be lower than a normal year. Future studies should be conducted the EI for a number of years to obtain representative EI for the country.

Significant differences are also observed for the crop residue OB emission among the cited works which are most likely due to the differences in EFs, activity data used, and base year of the estimates. Our emission estimates were higher as compared to GFED 3 for all species but comparable to EDGAR especially for the GHGs (CO_2, CH_4, and N_2O). CGRER EI shows lower estimates than ours for most pollutants which were likely due to the significant difference in the selected fraction burned in the fields (B), i.e. we used B values in the range of 0.3–0.9 as compared to the single B value of 0.17 selected by CGRER for all crops. GFED 3 produced extreme low estimates which may be related to the method used in their study for the fire activity and fuel load. Incorporation of MODIS burn scars data to estimate burn area for crop residue OB in GFED 3 may underestimate the area since sporadic small fires (common for crop residue OB) cannot be readily detected by MODIS MCD45A1. In addition, the GFED 3 used fuel load data produced from a biogeochemical model hence the discrepancy is expected (Van der Werf et al., 2010).

In general, the crop residue OB emission was the most significant compared to the forest fires and MSW OB in the country. This suggests that a suitable strategy to mitigate this emission source should be implemented, especially with the projected increase of the crop residue field burning activities accompanied by the increased production rate and better living conditions of farmers.

The data on the MSW OB for Indonesia have not been reported in any published works for comparison. The EI of MSW OB produced by this study is an innovative contribution to the national EI. Although, the MSW OB emission was estimated for urban areas only, this source contributed considerably, about 0.7–7% varying with species, to the national total OB emission (Fig. 1). This emphasizes the need for an improved integrated MSW management as in the near term this source emission is expected to increase along with the rapid urbanization, specifically the growth of peri-urban population which surpasses the MSW collection service development.

3.2. Spatial emission distribution

Forest fire: The spatial distribution of the annual emission of each species was determined and as a way of example the distribution of BC from OB sources is presented in Fig. 2a. The high forest fire emissions were seen concentrated in Java (due to primary and secondary forest fires), Bali and Nusa Tenggara Islands (due to savanna fires). There were also the grids with high emission scattered in other provinces (marked with circles in Fig. 2a). For example, in the Central Kalimantan province, there was a single grid with the highest emission BC intensity of 6–18 t km^{-2} y^{-1} at the south border line which appeared to be linked to the peatland swamp forest fire. Another grid also with the same highest emission range was observed in a province of 'Lampung' located in the southern part of Sumatra. This appeared to be consistent with the burned area mapping of MODIS MCD45A1 showing more burning in Java Island than in other Islands (Fig. 2a).

Crop residue: The highest emission intensity from crop residue OB was seen in East Java and South Sumatra which are well known major agricultural areas in Indonesia. Relatively high emissions

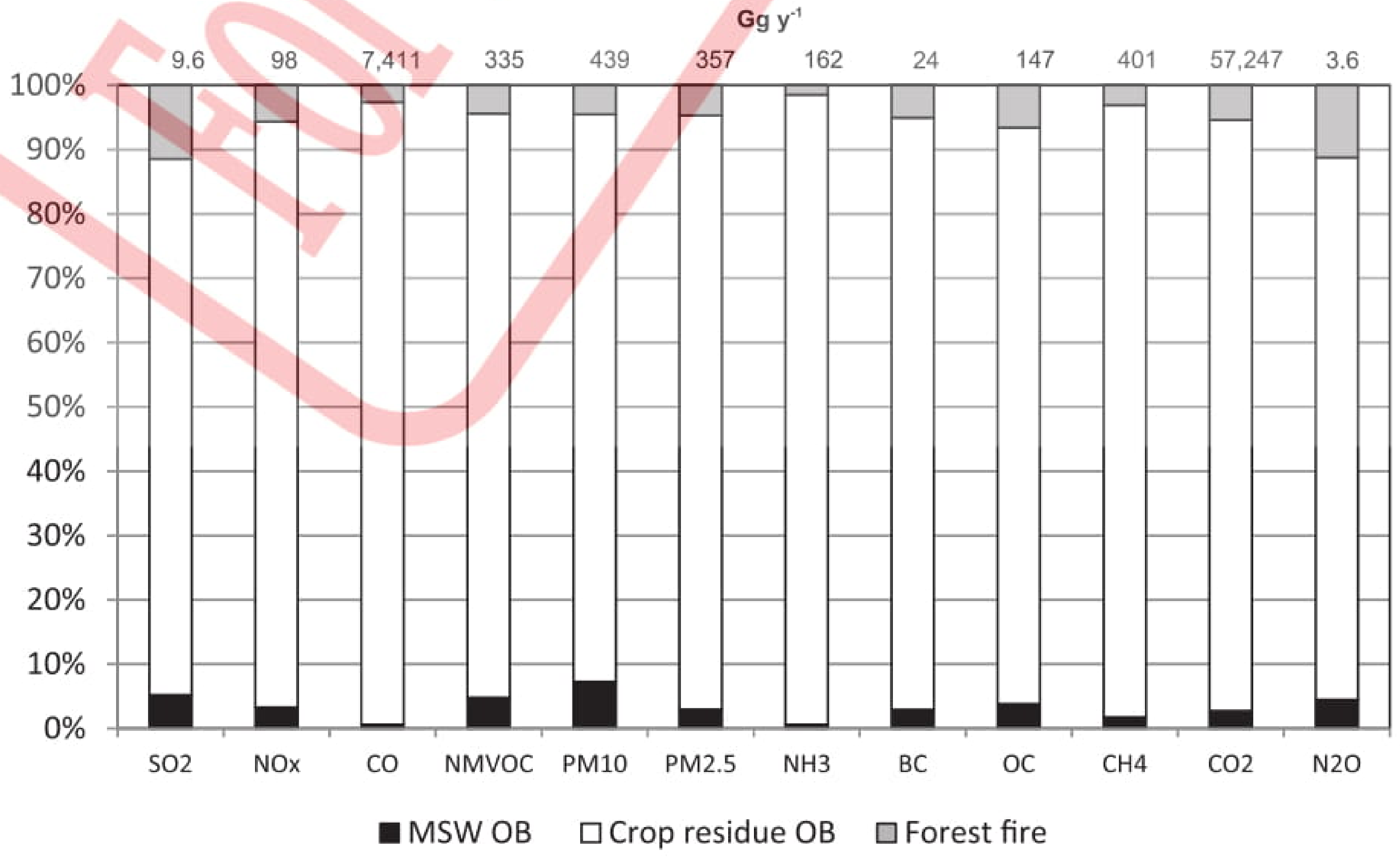

Fig. 1. Shares of the total biomass OB emission (%).

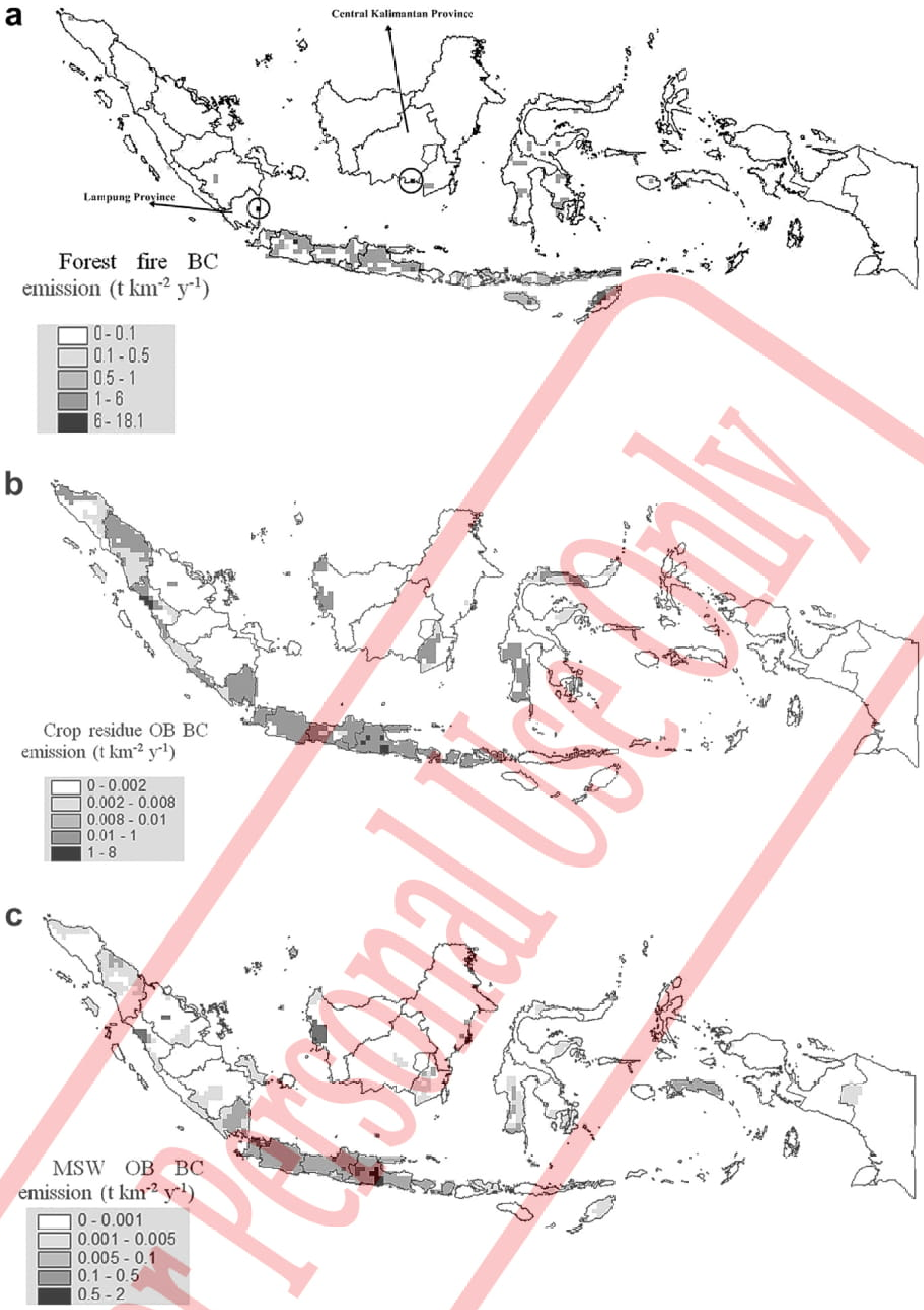

Fig. 2. Spatial distribution of BC annual emissions from; (a) forest fire, (b) crop residue and (c) MSW OB (0.25° resolution).

were also observed in North Sumatra, all parts of Java, Bali, West and South Kalimantan, North and South Sulawesi (Fig. 2b). Note that in Eastern part of Indonesia (Papua, Maluku, etc), lower emissions were estimated because rice is not a staple food in those areas. In fact, sago is a staple food in the area but with less production on the national scale as compared to rice. The 'agriculture clean production' initiative has been promoted recently, mostly in Java, to prevent the 'slash and burn' practice but it may take longer period to yield a drastic change (Makarim et al., 2007).

MSW: The MSW OB emissions were found the highest in big and populated urban areas in Java Island (Jakarta, Bandung, and Surabaya) and Sumatra (Padang and Medan), as seen in Fig. 2c, as compared to the rest of 300 districts in the country. As mentioned above, this study considered only MSW OB in urban areas which accounted for about 40% of the total national population. The peri-urban population was not included hence the emission was likely underestimated. A previous emission inventory conducted for two big cities (Bandung and Jakarta) revealed a significant contribution of MSW OB of (7–9% for NMVOC and 8–20% for total PM) to the city total anthropogenic emission (Soedomo and Irsyad, 1992).

3.3. Temporal emission distribution

Monthly fractions, averaged for the country, of OB emissions are shown in Fig. 3. It is clearly seen that peak burning emissions occur during the dry season (August–October). The temporal pattern of crop residue OB emission was estimated using the plantation and harvesting periods in different districts and the types of crops. For example, the rice crop plantation period is mainly during October–March while the harvesting period occurs between April and July

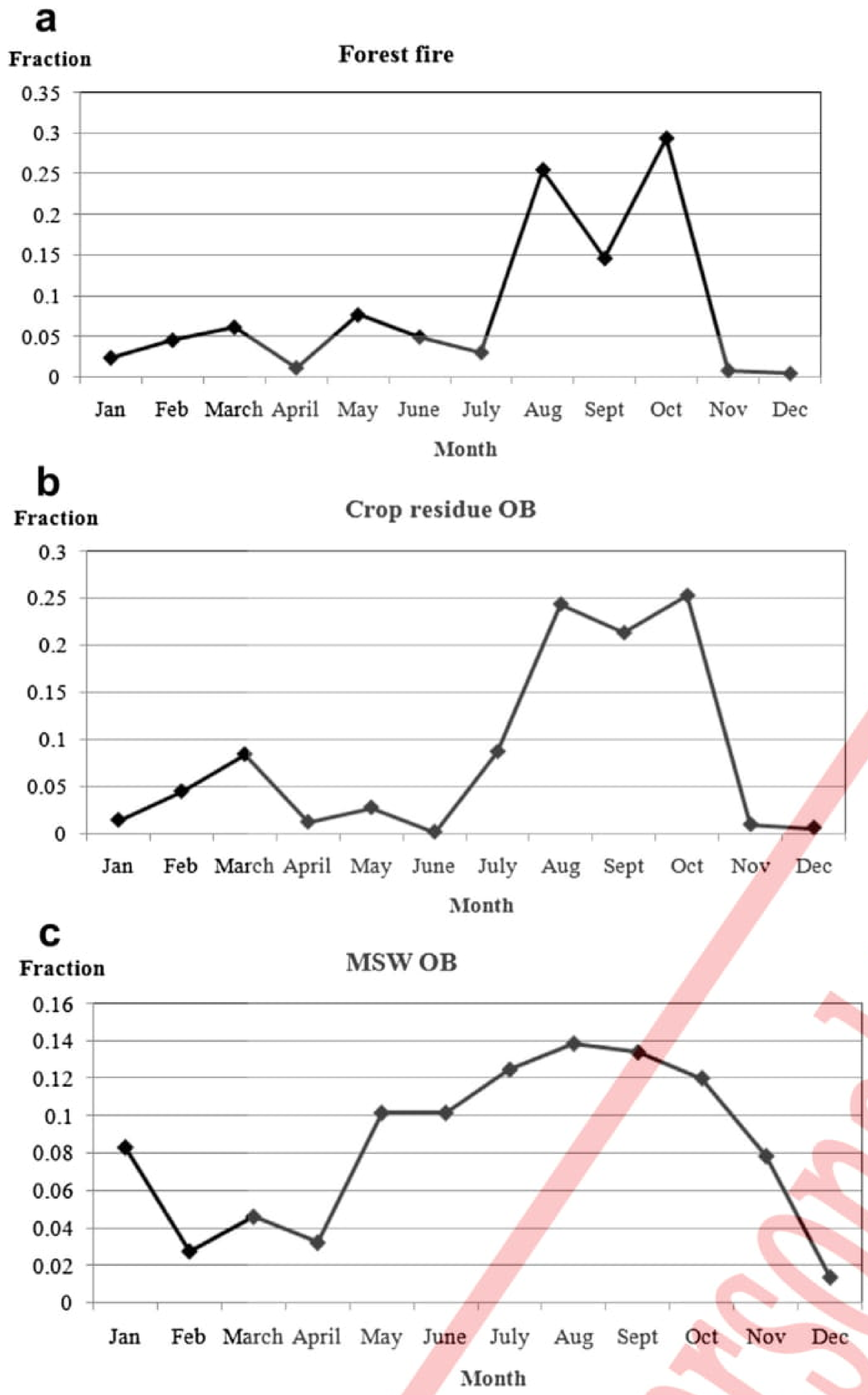

Fig. 3. Monthly variation factor of emissions from; (a) forest fire, (b) crop residue and (c) MSW OB.

(MOA, 2008). The August–September is considered as a critical period where most of rice straw field burning occurs during the preparation for the next crop plantation. This is also seen in our monthly emission profile with peak values shown during August–October. Using the non-rainy days as a proxy for the distribution the country average profile (Fig. 3c) for MSW OB emissions shows high emissions during July–October, i.e. during the dry season.

3.4. *Contribution to the global biomass open burning GWP*

GWP of GHGs and short-lived climate forcers emitted from the Indonesian biomass OB in 2007 relative to CO_2 is presented in Table 2. The assessment includes both the GWP of warming agents (i.e. GHGs, NO_x, NMVOC, CO, BC with positive forcing) and cooling agents (OC and SO_2 with negative forcing). The total GWP of warming agents estimated from the country biomass OB in 2007 was around 190 (20 year horizon) and 95 (100 year horizon) Tg CO_2 equivalents while the net GWP was 110 (20 year) and 73 (100 year) Tg CO_2 equivalents. Note that GWP for BC alone is around 41 (20 year) and 11.5 (100 year) Tg CO_2 equivalents, i.e. 12–21% of the total positive forcing, which is the third most important warming agent after CO_2 (30–60%, 57 Tg) and CO (8–18%, 17–53 Tg). The GWP of global biomass OB estimated using the data extracted from GFED 3 for 2007 (GHGs, NO_x, NMVOC, CO, SO_2, BC, and OC) (Table 2) was around 9820 (20 year) and 7861 (100 year) Tg CO_2 equivalents. The contribution from the Indonesian biomass OB was around 0.9–1.1% for both time horizons.

3.5. *Uncertainty analysis*

The uncertainty presented here is the ratio (in percents) of the difference between the low or high estimate and the best estimate, respectively, to the best emission estimate. Thus, these whiskers shown in Fig. 4 for the EI uncertainty are the ranges and not the standard deviations. The average uncertainty of different species ranged from −67% to +164% for forest fire emission, −76% to +131% for crop residue and from −86% to 260% for MSW OB. Higher uncertainty for MSW OB was mainly a result of the high uncertainty of the activity data, especially P_{frac} (0.04–0.2) used to estimate the amount of MSW subjected to OB. For this source, all species had similar uncertainties because only a limited number of the EF and the variations between these available EFs were relatively small. For forest fires and crop residue OB, both the variations in EFs and activity data contributed significantly to the uncertainty range. CH_4 and SO_2 emissions showed the largest uncertainty for the forest fire while BC had the largest uncertainty for the crop residue OB emission.

Table 2
Contribution of Indonesian biomass OB to the global biomass OB GWP.

Species	This study (Indonesia), Gg y^{-1}			Global estimate, Gg y^{-1}		
	Emission (Gg y^{-1})	CO_2 equivalent (20 year)	CO_2 equivalent (100 year)	Emission (Gg y^{-1})[a]	CO_2 equivalent (20 year)	CO_2 equivalent (100 year)
Global warming agents						
CO_2	57,247	57,248	57,248	6,943,000	6,943,000	6,943,000
CH_4	401	28,886	10,030	17,520	1,261,440	438,000
N_2O	3.6	1029	545	891	257,499	136,323
BC	24	40,630	11,472	2156	3,449,600	991,760
NOx	98	4201	−2736	9831	186,789	−108,141
CO	7411	53,359	17,045	339,900	2,039,400	679,800
NMVOC	335	4686	1506	21,340	298,760	106,700
Sub total 1		190,039	95,111		14,436,488	9,187,442
Global cooling agents						
SO_2	9.6	−547	−154	2320	−324,800	−92,800
OC	147	−79,542	−22,095	17,880	−4,291,200	−1,233,720
Sub total 2		−80,089	−22,249		−4,616,000	−1,326,520
Total net GWP		109,950	72,862		9,820,488	7,860,922

[a] Global OB emissions for base year of 2007 were taken from GFED 3, http://www.falw.vu/~gwerf/GFED/GFED3/tables/.

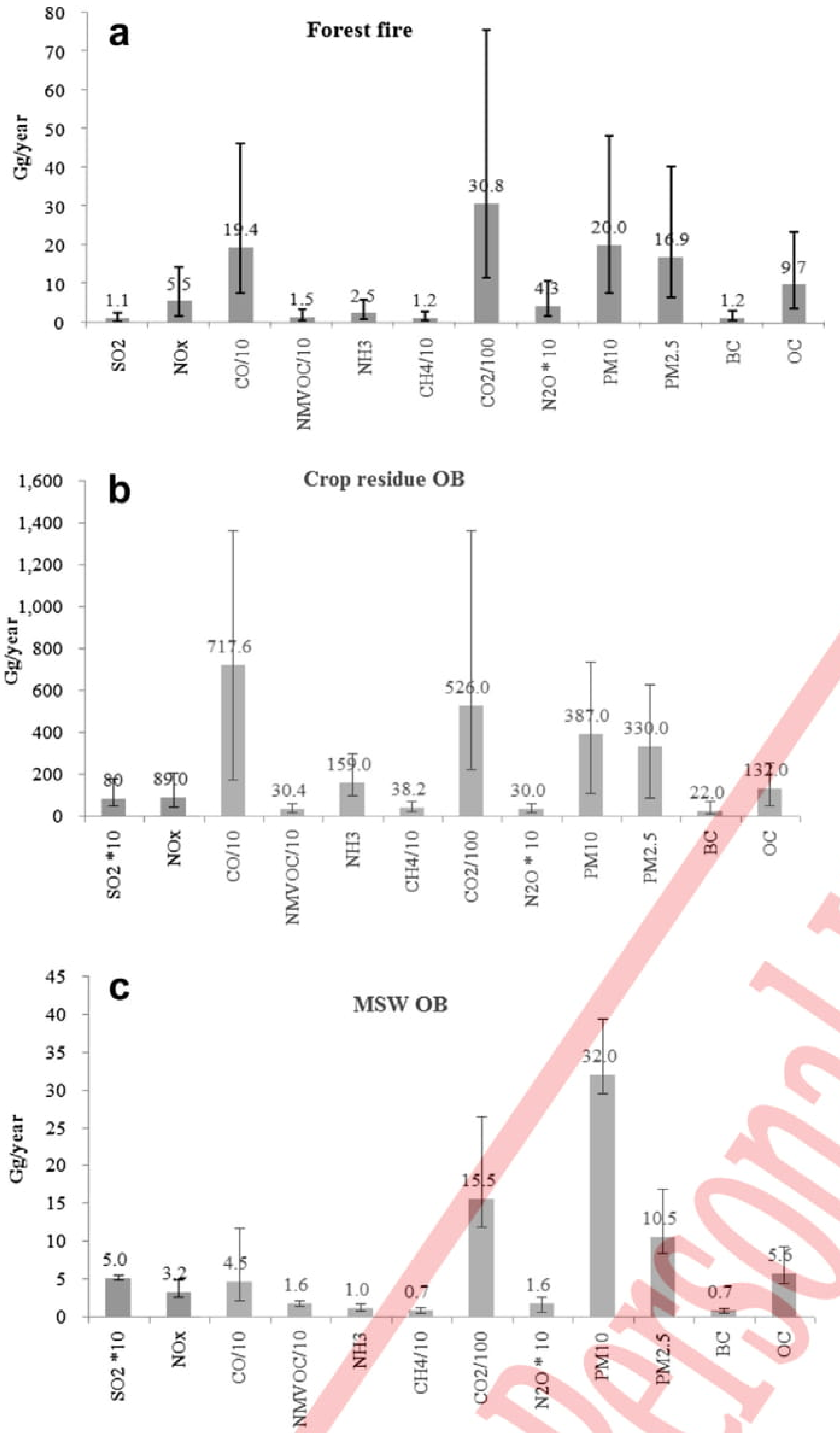

Fig. 4. Uncertainty estimates for different species emitted from; (a) forest fire, (b) crop residue, and (c) MSW OB.

4. Conclusions

The largest OB air pollution emission contribution was from crop residue followed by forest fire and the lowest was from MSW. Year to year fluctuations in the forest fire events were likely high reflecting the *El Niño – La Niña* weather patterns. Majority (85–90%) of the estimated total forest fire emission was associated with secondary forest and peatland swamp forest fires. Over 80% of total crop residue OB emission was from rice straw. Open burning of MSW was practiced most intensively (88%) at the generation sites which was due to the inadequate MSW waste collection in large urban areas in Indonesia.

The total net GWP of warming species from biomass OB in the country constituted about 0.9–1.1% of that from the global biomass OB. BC released from OB was the third most important warming agent, contributed 21% (20 year horizon) and 12% (100 year horizon) of the total global warming forcing as compared to 30 and 60%, respectively, by CO_2 emission. The large amount of air pollution emitted from the biomass OB and associated high GWP suggest a good potential for air quality improvement and climate benefit through the OB reduction. Non-burning alternatives for crop waste and better MSW management can efficiently minimize this OB emission source and bring in co-benefits. Minimization of forest fire emission requires a consolidated approach involving several actors through an integrated forest management.

Overall, the relative uncertainty of EI ranges from −86% to +260% for all species with the highest uncertainties found for BC. However, there were strong seasonal variations in the emission from OB with higher values observed in dry months of August–October. Based on the MODIS active fire analysis results, the number of forest fire events in 2007 was the lowest during the period of 2001–2009 hence our emission estimation for forest fires may be lower than the period average.

Our results provide a step forward for the national EI for Indonesia which may be used for the general air quality management but more specifically for 3D modeling purposes. This EI should be further improved incorporating more relevant EFs and more accurate activity data, and regularly updated to reflect the recent changes in the emission sources. In particular, emission from peat soil burning should be incorporated in the future analysis. Measurements of EF for local sources should be conducted, especially for MSW OB emission. A survey may be necessary to be conducted to provide a better estimate of amount of MSW in all typical urban, semi-urban and rural areas in the country.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2012.10.016.

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