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"Annual emissions of air toxics emitted from crop residue open burning in Southeast Asia over the period of 2010–2015"

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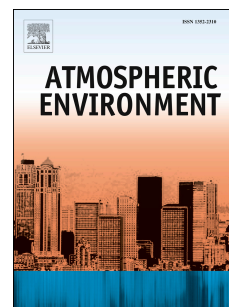Nguyen Thi Kim Oanh, Didin Agustian Permadi, Philip Hopke, Kirk Smith, Nguyen Phan Dong, Anh Nguyet Dang

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1 **Annual emissions of air toxics emitted from crop residue open burning in**

2 **Southeast Asia over the period of 2010 – 2015**

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16

17 **Abstract**

18 Southeast Asia (SEA) has large agricultural crop production and huge amounts of crop

19 residues generated annually are commonly burned in the field to quickly clear land for the

20 next crop planting. This study developed annual emission inventory for crop residue open

21 burning (CROB) covering 17 emission species/groups for 10 SEA countries during 2010-

22 2015, illustrated with relative contributions by country and by crop type. The fractions of

23 crop residue subjected to open burning (OB), a large source of uncertainty in the activity

24 data, compiled from surveys in SEA were significantly higher than those suggested in

25 international databases. Emission factors for rice and maize residue OB were obtained from

26 field experiments conducted in Thailand. The best estimates of the annual emissions averaged

27 over 6 years, of air toxics were: 32 Gg of polycyclic aromatic hydrocarbons, 0.03 Gg organo-

28 chlorinated pesticides, 292 Gg total chlorines, and 94 g I-TEQ dioxins. Emissions of $PM_{2.5}$,

29 BC and OC, in Tg yr^{-1}, were respectively 1.8, 0.08 and 0.8. The coefficients of variation of

30 annual emissions during the period were relatively small (2.6-8.6% depending on species) but

31 still showed an increasing trend that reflected the changes in production of major crops

32 during the period. Regionally, CROB shared 10-43% of the total biomass open burning

33 emissions but varying with country: by far dominant in Vietnam and Philippines, and much

34 less dominant in Indonesia, Myanmar, and Thailand. Rice straw open burning was the most

35 dominant (19-97%) in the total CROB emissions of the 8 considered crops. The spatial

36 distributions of annual emissions (0.1^{o} x 0.1^{o}) showed higher emission intensity over the

37 areas cultivated with rice and sugarcane, while higher monthly emissions coincided with

38 major harvesting periods in the dry season. The obtained EI data can be further used for air

39 quality modeling to assess effects of CROB emission and to promote non-OB alternatives in

40 the region.

43   **I.   Introduction**

44   Southeast Asia (SEA) is a dynamic region with fast growing economy and population. Most

45   of the countries in SEA are agrarian with economic development based largely on the

46   agricultural sector. The region also houses 3 countries among the world's top ten rice

47   exporters in 2015 (WTE, 2016). To ensure the food security for more than 600 million people

48   in the region and to meet the export demand, agricultural production has been intensified and

49   that has been accompanied by the generation of a huge quantity of crop residues annually.

50   Crop residue open burning (CROB) is viewed by regional farmers as the cheapest and fastest

51   way to clear land for the next crop and hence, has been increasingly practiced for decades

52   (Kanabkaew and Kim Oanh, 2011). Traditional slash and burn shifting cultivation (SBS) is

53   still practiced in several countries in the region such as Indonesia (Ketterings et al., 1999;

54   Murdiyarso et al., 2005) and some other SEA countries (Li et al., 2014). SBS is commonly

55   believed to enrich the soil but heat from burning may also damage soil structure and remove

56   the surface humic organic matter (Sanchez et al., 2005) while at the same time, huge

57   quantities of agro-residue biomass are wasted.

58   Several alternative options to reuse the crop residues (i.e. mushroom growing, ploughing for

59   on-site degradation, cooking fuel, animal feed, etc.) are available, but these are getting less

60   practiced as farmers get wealthier. There are still practical problems to sustain business

61   models that incorporate sufficient incentives to encourage farmers to stop open burning (Kim

62   Oanh et al., 2013). Awareness raising focusing on the negative impacts of CROB,

63   specifically the effects of smoke on human health, is necessary to encourage farmers to use

64   non-open burning alternatives for the crop residue management. This approach in turn needs

65 reliable information of the amount of toxic air pollutants released annually from this activity

66 in every country of the region.

67

68 Presently, the CROB impacts are often overlooked in many SEA countries and normally gain

69 less concern from the society as compared to the catastrophic SEA transboundary haze

70 caused by forest fires. By nature, CROB is the low temperature combustion of the vegetation

71 hence would release large quantities of products of incomplete combustion (PIC) which are

72 toxic air pollutants, such as particulate matter (PM), black carbon (BC), organic carbon (OC),

73 carbon monoxide (CO) and volatile organic compounds (VOCs). Certain amounts of nitrogen

74 oxides (NO_x) and sulfur oxides (SOx) are also released along with key greenhouse gases

75 (GHGs) like methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) although the

76 released CO_2 is believed to be taken up by the next season's crop growth. In addition to the

77 common emission species listed above, a range of semi-VOCs including the persistent

78 organic pollutants, such as polychlorinated dibenzo-p-dioxins and dibenzofurans

79 (PCDD/PCDFs, here referred to as dioxins for short), polychlorinated biphenyls (PCBs), and

80 polycyclic aromatic hydrocarbons (PAHs) are also emitted from the biomass burning

81 (Estrellan and Iino, 2010). CROB also emits considerable amount of chlorine compounds

82 with atmospheric lifetime varying from a day to several years that may catalytically affect

83 tropospheric ozone concentrations (Burklin et al. 2002) and stratospheric ozone destruction

84 (Khalil, 1999; Lobert et al., 1999). Therefore, it is important to comprehensively quantify the

85 CROB emissions and thereby provide necessary scientific basis to promote the environment-

86 friendly crop residue management practices in the SEA countries.

87

88 Previous emission inventory (EI) studies of CROB for SEA differ by the approaches used for

89 the emission estimation (i.e. statistical data vs. satellite data), scale (i.e. country based,

4

90 regional or global), and level of detail provided in the emissions database (i.e. species

91 coverage, temporal and spatial information). The global databases so far provide only

92 preliminary estimates of CROB emissions using the aggregate amount of crop residues burnt

93 in the open field of the developing and developed countries, respectively (Seiler and Crutzen,

94 1980; Hao and Liu, 1994). Further refined EI databases were also prepared by using the

95 available country specific information to some extent (Yevich and Logan, 2003; Andreae and

96 Merlet, 2001; Akagi et al., 2011). More up-to-date global EI for CROB is provided by the

97 Emission Database for Global Atmospheric Research (EDGAR) v4.3.1 for the base year of

98 2014 and with the spatial resolution of 0.5° and 0.1° using international crop statistics.

99 Published regional EI databases, e.g. Streets et al. (2003) at 0.5° x 0.5° for all of Asia, and

100 Shi and Yamaguchi (2014) at 0.01° x 0.01° for SEA, did not include dioxins and PAHs. The

101 national CROB EI databases for Thailand and Indonesia developed using the national

102 statistics and local survey results (Kanabkaew and Kim Oanh, 2011; Permadi et al., 2013)

103 provided more detailed temporal (monthly) and spatial emissions (district/provincial) but also

104 did not include these toxic semi-VOC. Gadde et al. (2009) estimated the national annual

105 emissions from rice straw (RS) open burning for India, Thailand and Philippines, roughly

106 included annual emissions of dioxins and PAHs but without spatial and temporal

107 distributions. These semi-VOC emissions are included in a few existing global studies, such

108 as dioxins in Brzuzy and Hites (1996) and UNEP (1999) or PAHs in Zhang and Tao (2009),

109 but the emissions specifically for CROB have not been explicitly identified. None of these

110 databases included emissions of reactive chlorine species from CROB. The global inventory

111 of reactive chlorine compounds was only reported in the "Reactive Chlorine Emissions

112 Inventory (RCEI)" within the "Global Emissions Inventory Activity" (Lobert et al., 1999).

113 For urban ozone air quality, reactive chlorine compounds may be important as they can

114 catalytically enhance the tropospheric ozone formation (Burklin et al., 2002).

115

116 Therefore, the SEA CROB emissions should be updated to more recent base years with

117 consideration on the inter-annual variation and semi-VOC species. The EI should be based

118 more on local survey data regarding crop practices and available emission factors (EFs)

119 relevant for the region. In addition, the temporal variations of CROB emissions should be

120 characterized as it is particularly important because of variations in local agricultural

121 practices in SEA and the distinct dry and wet seasons. Local surveys would provide specific

122 information to estimate the actual amounts of the residue from different crop types subjected

123 to open burning (OB) and the common burning practices that strongly affect the EFs. For

124 example, the use of satellite-derived fire counts in some existing EI databases for CROB

125 emissions would not fully capture CROB emissions in SEA because the burning is done

126 mainly in the late afternoon (Kanabkaew and Kim Oanh, 2011; Permadi and Kim Oanh,

127 2013) and occurs sporadically with short durations, i.e. about 1 hour (Kim Oanh et al., 2011),

128 while the Moderate Resolution Imaging Spectroradiometer (MODIS) of Terra and Aqua

129 satellite provides only snapshots of the region at 10.30 AM and 13.30 PM local standard time

130 (LST).

131

132 This study considers the emissions from crop residue open/field burning in SEA with a focus

133 on emissions of trace gases, PM, semi-VOC species of PAHs, dioxins and chlorinated

134 pesticides (OCPs), reactive chlorines (5 compounds) and GHGs. The EI was done for 10 SEA

135 countries for each year over a 6-year period (2010 – 2015), incorporating country specific

136 activity data (local surveys) and available regional specific EFs. The EI results are presented

137 as the low, high and best estimates to include the uncertainty range. Further, monthly

138 emissions and the gridded emissions with a resolution of 0.1° x 0.1° were prepared which can

139 be further used for three-dimensional regional air quality modeling to assess the impacts of

6

140   current CROB emissions and emission reduction measures on the air quality, human health

141   and environment. Our annual emission results for CROB in SEA (SEA CROB) are

142   comparatively analyzed with the forest fires data taken from Global Fire Emission Database

143   version 4 (GFED4) (van der Werf et al., 2010) to reveal the relative importance of the

144   sources.

145   **2. Methodology**

146   *2.1 Emissions calculations*

147   The EI was developed following the common approach for this source type (Shrestha et al.,

148   2013; Hao and Liu, 1994). Accordingly, the annual emission from burning of crop residues

149   was calculated using Equation 1.

150
$$E_{m,k} = \sum_{m,k} M_k \times \eta_k \times EF_{m,k} \qquad (1)$$

151   Where,

152    $E_{m,k}$ = Emission (mass amount yr^{-1}) of emission specie m and crop residue type k biomass;

153   M_k = Amount of biomass of crop residue type k that is subjected to OB per year (mass per

154   year);

155   η_k = Burning efficiency of residue of crop type k (fraction, 0-1);

156    $EF_{m,k}$ = Emission factor of specie m from open burning of crop residue type k biomass (with

157   consistent unit).

158

159   The main parameter of M_k in Equation 1 was estimated using Equation 2.

160
$$M_k = P_k \times S_k \times D_k \times B_k \qquad (2)$$

161   Where,

162   P_k = Crop production for crop type k (mass per year);

163   S_k = Specific residue-to-production ratio for crop type k;

164   D_k = Dry matter-to-crop residue ratio (fraction, 0-1);

7

165   B_k = Fraction of dry matter of crop residue type k that is subjected to open burning (0-1).

166

167   To have good estimates for M_k, representative values of these parameters are required that in

168   turn need to be generated by well-designed local surveys.

169

170   *2.2   Activity data collection*

171   In this study, the annual M_k amounts in SEA were estimated for 8 main crop types (rice,

172   maize, soybean, potato, sweet potato, groundnut, sugarcane, and cassava) that commonly

173   have residues subjected to OB. Wheat straw OB was not included as wheat production was

174   not popular in SEA, e.g. only a small amount cultivated in northern Thailand for the beverage

175   industry (FAO Statistics, 2015). The parameters required to calculate M_k (Equation 2) were

176   gathered from surveys conducted for several years by the air quality research group at the

177   Asian Institute of Technology (AIT) supplemented by relevant published information

178   (SUMERNET, 2017; Tipayarom and Kim Oanh, 2007).

179

180   Among the parameters included in Equation 2, the annual crop production information (P_k)

181   was the most readily available. The P_k data for Thailand and Indonesia during the period

182   from 2010 to 2015 were obtained from the national statistical reports for each of 33 provinces

183   of Indonesia (BPS, 2016) and 76 provinces of Thailand (OAE, 2016). For other SEA

184   countries, the national production data for the period of 2010-2014 were taken from the Food

185   and Agriculture Organization (FAO) database (http://www.fao.org/faostat/en/#home). The

186   2015 data were extracted from the Association of Southeast Asian Nation (ASEAN) Food

187   Security   Information   System   (AFSIS):   Agricultural   Commodity   Outlook   2015

188   (http://www.afsisnc.org/publications/archive/2016). Table S1, supplementary information

189   (SI) presents the annual average production data over the study period for the selected crops

190　in 10 SEA countries. Brunei was reported to have only three types of crops (rice, cassava, and

191　sweet potato) while most other SEA countries have all 8 included crop types. The CROB

192　emissions from Singapore were assumed to be negligible as the country has only a small

193　agricultural production, and also due to the fact that open burning is strictly prohibited in the

194　country (Environmental Protection and Management Act, Cap. 94A). As seen from Table S1,

195　rice production dominated the annual average crop production in SEA during the period (204

196　Tg yr^{-1}) followed by sugarcane (162 Tg yr^{-1}), cassava (65 Tg yr^{-1}), and maize (38 Tg yr^{-1}).

197　The major rice producers are Indonesia (70 Tg yr^{-1}) followed by Vietnam (43 Tg yr^{-1}),

198　Thailand (34 Tg yr^{-1}) and Myanmar (28 Tg yr^{-1}). Except for the Philippines, SEA countries

199　generally have rice production rates following the country population that primarily reflects

200　the domestic consumption needs. The SEA total annual average production of 8 crops

201　amounted at 486 Tg yr^{-1} and was mainly contributed by Indonesia (148 Tg yr^{-1}), Thailand

202　(134 Tg yr^{-1}), Vietnam (77 Tg yr^{-1}) and the Philippines (55 Tg yr^{-1}).

203

204　It was more challenging to obtain country representative values for other parameters required

205　for the calculation of M_k. These included the residue-to-production ratio (S_k), the dry matter

206　to crop residue ratio (D_k), and the fraction of dry matter residue of different crops subjected to

207　open burning (B_k). The latter is in fact the largest source of uncertainty in the M_k calculation

208　because this B_k value depends mainly on the local specific agricultural practices and the

209　harvesting time (in wet or dry periods) in a country. In some countries, such as Vietnam, the

210　OB of rice crop residue happens both on-site in paddy field and off-site in villages. Thus,

211　both should be included in the estimation of B_k. A wide range of values for this B_k parameter

212　has been found in the global/regional EI reports. IPCC (2006) suggested a value of 0.25 to be

213　used for developing countries and <0.10 for developed countries, while Streets et al. (2003)

214　suggested a value of 0.25 for South Asian countries and 0.17 for the remaining countries in

9

215 the region. Information on B_k, especially for RS, available from local surveys in some

216 countries is included in Table 1 showing significantly higher values (0.17-0.90) than those

217 suggested in the international databases. Specifically, the B_k values relevant for SEA vary

218 with crop cycles, i.e. higher in the dry and lower in the wet season (Table 1).

219 In our study, significant efforts were made to select the appropriate ranges to be used for the

220 emission calculations (Table S2, SI). For example, for RS in Thailand, the B_k values were

221 different for different parts of the country and strongly varied with season. In the central part

222 of Thailand and for crops harvested in the dry season, we used the B_k value of 0.9 obtained

223 from the AIT survey results by Tipayarom and Kim Oanh (2007) and SUMERNET (2017),

224 the Sustainable Mekong Research Network rice straw co-benefits project (unpublished data

225 as of 2018), while for crops harvested in the wet season, B_k value is typically 0.25

226 (SUMERNET, 2017). Our surveys (SUMERNET, 2017) were conducted in selected

227 important agricultural areas in Thailand, Vietnam and Cambodia through a face-to-face

228 interview with farmers. For other countries, the sources of information are presented in the

229 footnote of Table 1.

230

231 Table S2 presents a summary of the values of the parameters used in the M_k calculation. The

232 country specific values of S_k and D_k, mainly available for rice, maize, sugarcane, and

233 potatoes, are those reported by the local surveys extracted from relevant studies in Thailand

234 and other SEA countries. For other crop types, we relied on the values for Asian countries

235 compiled by Koopman and Koppejan (1998) and Yevich and Logan (2003). For the countries

236 in SEA where no survey data were available, we considered the similarity in the cultivated

237 crop variants and geographical location to assign appropriate S_k and D_k. For example, the

238 values obtained for Indonesia were also used for Malaysia, Brunei, and East Timor while

239 those obtained for Thailand were also used for other countries in the Mainland Southeast

10

240   Asia. The information on the combustion efficiency of crop residues (η_k), i.e. the fraction

241   oxidized per total amount of crop residue biomass subjected to open burning (biomass

242   loading), was not readily available at the country level. For RS and maize residue, results of

243   the field measurements conducted in Thailand by Kim Oanh et al. (2011) and Athiwat (2016),

244   respectively, were used for all SEA countries. For other crop types, the relevant values

245   reported in the international data sources were used following the same approach applied in

246   previous studies (Permadi and Kim Oanh, 2013; Kanabkaew and Kim Oanh, 2011).

247

248   Table S2 provides the range and the most probable values of the parameters used for the M_k

249   calculation. The "best estimates" of the inventory species were produced using the most

250   probable values given in the brackets (if more than one value is presented) while the lower

251   and upper values given in the range were used to calculate the low and high emissions

252   estimates, respectively, as further detailed in Section 2.4. Note that, due to lack of

253   information, we did not include the inter-annual variations for S_k, D_k, η_k and B_k during the

254   study period. The most significant change with time is expected for B_k because it strongly

255   depends on the local practice and, in principle, on the regulation enforcement, e.g. banning

256   CROB. However, during the reported period, there were no significant regulations and/or

257   technological intervention to substantially reduce the CROB activity in the region. There was

258   no main infrastructure development that could induce a fast change in the agricultural waste

259   management practice in SEA. For example, there was no drastic development to enhance off-

260   site uses of rice straw and other crop residues to cut down the B_k values.

261

262   *2.3 Emission factors*

263   The available EFs were scrutinized to select the most relevant value for a specific crop for the

264   calculation of the best emission estimates in a country. Accordingly, EFs produced by

11

265   measurement in the country were used for the best estimates. If not available, corresponding

266   values reported for other Asian countries were applied. The compilation of EFs for different

267   species and crop types used in this study is given in Table S3, SI (data sources are included in

268   Text box S1, SI). The upper and higher values in the EF range given in Table S3 were used to

269   calculate the low and high emission estimate, respectively. When the EF data were not

270   available, we used the corresponding values reported for combined crops provided in

271   Andreae and Merlet (2001) that are specified under the column "others" in Table S3.

272

273   Kim Oanh et al. (2011) reported that depending on the harvesting method, RS field burning

274   can be practiced as "spread burning" or "pile burning" and these two practices produce

275   significantly different EFs. Therefore, information on local harvesting methods i.e. by

276   traditional (manual) or mechanical (combine harvester), was gathered, so that the most

277   appropriate EFs could be applied. In Thailand and Southern Vietnam, the mechanical

278   harvesting was common. In northern Vietnam, manual harvesting was still prevalent, mainly

279   due to the small size of paddy field. Likewise, in Indonesia, mechanical harvesting was

280   common on the Java Island (6 provinces) whereas manual harvesting was practiced in smaller

281   islands. In Cambodia, mechanical harvesting was also most common, i.e. >90% for rice crops

282   (SUMERNET, 2017). In Malaysia and Brunei, we assumed only mechanical harvesting

283   method while for the Philippines, manual harvesting was considered for the hilly areas and

284   mechanical for the rest (Javier, 2009). For other countries (Myanmar, Lao PDR and East

285   Timor), it was assumed that manual harvesting was still common. The EFs were selected for

286   the rice straw OB (RSOB) in the countries, depending on the harvesting method, i.e. the

287   "spread burning" EFs were applied for mechanical harvesting and "pile burning" EFs were

288   used for manual harvesting areas. Accordingly, the EFs of PM (PM_{10} and $PM_{2.5}$), trace gases

289   (NO_2, SO_2, and CO), PAHs (16 US EPA priority compounds), OCPs (16 compounds), and

290   GHGs (CO_2 and CH_4) obtained from the RS spread field burning measurements in Thailand

291   (Kim Oanh et al., 2011; Kim Oanh et al., 2015) were used for the places with mechanical

292   harvesting. The EFs of CO, CO_2, CH_4, NO_2, SO_2, $PM_{2.5}$ and BC for maize residue field

293   burning also relied on the AIT field burning experiments in Thailand (Athiwat, 2016;

294   Phitsuca, 2016). For Indonesia, the EFs were generated by RS field burning experiments in

295   the country (Christian et al., 2003). The EFs for other crops were obtained from Asian and

296   international studies (Textbox S1, SI) that have been compiled in the Atmospheric Brown

297   Cloud Emission Inventory Manual (ABC EIM) (Shrestha et al., 2013).

298

299   Less EF data were available for PAHs hence the values obtained from RS open burning field

300   experiments for 16 PAHs in both particulate and gaseous phases (Kim Oanh et al., 2011; Kim

301   Oanh et al., 2015) were used for the best estimates while those from a RS burning study in

302   China (Zhang et al., 2011) were included in the EFs range. Jenkins et al. (1996) also provided

303   EFs of 19 PAHs in the PM phase for several types of crop residues, and the estimated value

304   for 16 PAHs is 80 mg kg^{-1} of RS, which is higher but still in the range with the EF for the PM

305   PAHs used in this EI, 34 mg kg^{-1} of RS (Kim Oanh et al., 2011). For other types of crops,

306   only limited information of EFs for PAHs, i.e. PM_{10}-bound PAHs for maize (Wiriya et al.,

307   2015) was available for SEA. Hence, the EFs measured in China, both PM and gaseous

308   phases (Zhang et al., 2011) for maize, and the United States for sugarcane (Hall et al., 2012)

309   were used. The EFs for combined agricultural residues provided by Andreae and Merlet

310   (2001) were used for the rest of crops types. However, only a single EF value of PAHs (25

311   mg kg^{-1} of biomass) estimated based on the laboratory studies is provided in Andreae and

312   Merlet (2001). This EF in fact may be low compared to the measured values, e.g. Jenkins et

313   al. (1996) reported the EFs for corn stover of 270 mg kg^{-1} (estimated for 16 PAHs, only PM

314   phase). Thus, the need for relevant local measurement data of EFs is further evident.

13

315

316 The experimentally derived EFs for dioxins were not available for RS in any SEA countries.

317 It was thus necessary to use the value reported by Gullet and Touati (2003) for RS (0.54 ng

318 International Toxic Equivalent, ng I-TEQ kg^{-1}), for the best emission estimate. Crop type

319 specific EFs for dioxins measured outside SEA are also available for maize residue burning,

320 i.e. 0.24 ng I-TEQ kg^{-1}, from a study in China (Zhang et al., 2011) hence this value was used

321 for our best emission estimate. Likewise, we used the dioxins EFs for sugarcane open burning

322 of 1.6 ng I-TEQ kg^{-1} reported by Black et al. (2011). For other crop types, the aggregate EF

323 provided in UNEP toolkit (UNEP, 2005) for "Agricultural residue burning in the field" of 0.5

324 ng I-TEQ kg^{-1} was used for the best estimate.

325

326 EFs of the OCPs are available only from the RS field burning experiments in Thailand (Kim

327 Oanh et al., 2015). The values were also used for rice straw OB in other SEA countries. The

328 EFs for reactive chlorine compounds, including CH_3Cl, CH_2Cl_2, $CHCl_3$ and CH_3CCl_3, and

329 particulate and inorganic chlorine for CROB were estimated from Burklin et al. (2002) using

330 the provided emission ratios of the respective chlorinated compounds to the EFs of CO.

331

332 *2.4 Range of the emission estimates*

333 In this study, the range of the emission estimates for different species (also referred to as the

334 emission uncertainty) was produced by incorporating the uncertainty of both activity data

335 and of available emission factors. Determination of the "best", "low" and "high" values for

336 the EFs and activity data followed the approach used previously in Kanabkaew and Kim

337 Oanh (2011) and Permadi and Kim Oanh (2013). For the activity data, the ranges of the

338 parameters used for M_k calculation and the range of burning efficiency η_k are given in Table

339 S2 while those for the EFs are detailed in Table S3. For the crop production (P_k), this study

340 assumed that the data taken from the various National Agencies or Ministerial Departments

341 had an uncertainty level of 5%, while for those collected from the international agencies, e.g.

342 the FAO statistics or other international agencies had a higher uncertainty, i.e. 10%,

343 following the approach of IPCC (2006). Specifically, to calculate the "best estimate" for the

344 emission of a specie, the most probable values of all parameters were used in Equations 1

345 and 2. The low and high emission estimates were calculated using the lower and upper

346 values of the ranges of the activity data and EFs, respectively.

347

348 *2.5 Spatial and temporal distribution*

349 Mapping of the spatial distributions of the SEA CROB annual emissions of different species

350 was done with the geographical information system (GIS). Crop cultivation land in SEA was

351 based on the land cover product provided by the Moderate Resolution Imaging

352 Spectroradiometer (MODIS), available at https://lpdaac.usgs.gov/dataset_discovery/modis

353 (Fig. S1, SI). The spatial distribution of the emissions was prepared with a grid resolution of

354 0.1º x 0.1º (~ 10 x 10 km^2) for the domain.

355

356 The monthly emissions for Indonesia, Thailand, and Vietnam were constructed using the

357 monthly production data, estimated biomass amount subjected to open burning, and crop

358 annual cycle for the year of 2015 following the same approach presented in the previous

359 studies (Kanabkaew and Kim Oanh, 2011; Permadi and Kim Oanh, 2013; Dong, 2013). For

360 other countries where no information on the monthly crop production was available, the daily

361 MODIS   MCD45A1   product

362 (https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mcd45a1) was used

363 together with the land use/land cover map to identify agricultural fires from other fires, e.g.

15

364   forest fires, and the monthly fractions of the agricultural fire hotspots out of the total annual

365   agricultural hotspots number were used for the monthly emission segregation.

366

367   **3**. **Results and discussion**

368   *3.1 Total residue biomass subjected to open burning*

369   The annual average M_k of all 8 crop types in SEA during this period was 152 Tg yr^{-1} of

370   which RS, sugarcane, maize, and "other residues" contributed 117, 15, 13, and 6.5 Tg yr^{-1},

371   respectively. The annual M_k values showed an increasing trend during the period of 2010-

372   2015 with the highest amount in 2015 of 160 Tg (Fig. 1) and the lowest in 2010 of 139 Tg.

373   Rice production in SEA increased during the period of 2010-2013 with an average growth of

374   5%, but dropped in 2014 and 2015, mainly caused by the reduction in the rice production in

375   Thailand. There was a sharp increase of sugarcane production in Thailand in 2012 of almost

376   63% that increased the total sugarcane production in SEA. The total crop production showed

377   an increasing trend during the period that was linearly correlated with the amount of M_k.

378   Country-wise, Indonesia contributed most significantly to the amount of crop residue open

379   burning annually, i.e. 36%, followed by Vietnam (21%), Myanmar (15%), Thailand (14.8%),

380   and the Philippines (9%) while the rest "other countries" had only small shares (Fig. S2, SI).

381

382   *3.2 Average annual emissions and inter-annual variations*

383   3.2.1 Annual emissions

384   The annual emissions from CROB in SEA during 2010-2015 are presented in Table 2. The

385   best estimates of the annual emissions averaged over 6-year period, from whole SEA CROB

386   for different species in Tg yr^{-1} were 12.5 CO; 0.36 NOx; 0.03 SO$_2$; 1.0 NMVOC; 0.5 NH$_3$;

387   2.0 PM$_{10}$; 1.8 PM$_{2.5}$, 0.08 BC, 0.8 OC; 190 CO$_2$; 0.56 CH$_4$; and 0.015 N$_2$O. The best

388   estimates of the annual average emission of PAHs was 32 Gg yr^{-1} while the benzo(a)pyrene

16

389 (B*a*P) emission alone was 0.16 Gg yr^{-1}. The annual emission of dioxins was 94 g I-TEQ yr^{-1},

390 while that of the total chlorines was 292 Gg yr^{-1} and of OCPs (from RS burning alone) was

391 0.03 Gg yr^{-1}. The best estimates of the total SEA CROB emissions produced in this study for

392 the base year of 2010 are compared with those presented in other global and regional

393 databases (Table S4 and Fig. S3, SI), i.e. EDGAR (2010) for 2010, Shi and Yamaguchi

394 (2014) as the average over 10 years (2001-2010), and GFED (2010) for 2010.

395

396 The EDGAR estimates were the highest of all 3 datasets for NOx, CO and PM (2-4 times

397 higher than ours) and SO$_2$ (6 times higher than ours), as seen in Fig. S3, SI. However, our

398 estimates were higher than EDGAR for NH$_3$ (1.7 times) and were similar for N$_2$O (Table S4,

399 SI). One of the important reasons for the EI results difference may have been the inclusion of

400 palm and other oil crops residue OB in the EDGAR database, but not in ours. Note that our

401 extracted data (not shown in Table S1) showed that the annual oil crop production in SEA

402 during 2010-2015 was 44 Tg yr^{-1} (26 Tg yr^{-1} in Indonesia and 13 Tg yr^{-1} in Malaysia) which

403 in fact was relatively small compared to rice or sugarcane production (Table S1, SI). Further,

404 the differences in the emission results between this study and other studies presented in Table

405 S4 and S5, SI are also caused by the differences in the values of parameters used to calculate

406 the amount of biomass burned and the EFs selected. The SEA CROB emission estimates

407 provided by Shi and Yamaguchi (2014) produced consistently lower results than our study

408 for all species despite their larger EI domain, i.e. including also southern China. The main

409 factor causing lower EI results by Shi and Yamaguchi (2014) was perhaps the lower B_k

410 values (0.10) for RS used in their study that substantially underestimated the M_k of RS for

411 example, i.e. by 5 times on average (Table 1). The difference in the number of crops

412 considered may also cause discrepancies in EI results, i.e. Shi and Yamaguchi (2014) focused

413 only on 4 main crop types of wheat, rice, maize and sugarcane, as compared to our 8 crops

17

414 (not including the wheat production as it was negligible in SEA) but the discrepancies may

415 not be as substantial (as caused by B_k values) because the three top contributors (rice, maize

416 and sugarcane) were considered in both studies. GFED had the lowest CROB emission rates

417 of all species as compared to others presented in Table S4 and visually in Fig. S3, SI and this

418 may be due to their underestimation of M_k amount based on the satellite data of the fire

419 hotspots. As mentioned above, agricultural fires in SEA are of small size, sporadic, and short

420 duration and mainly taken place in the late afternoon (Tipayarom and Kim Oanh, 2007).

421 Thus, these fires may not be adequately captured by the MODIS satellite, for example.

422

423 For the total chlorine emissions from SEA CROB, our result was 271 Gg yr^{-1} in 2010 for the

424 5 species. The result for 3 species of CH_3Cl, CH_2Cl_2, and $CHCl_3$ was 26 Gg yr^{-1} that is, as

425 expected, only a small fraction of the emission result from the whole Asia domain, for the

426 same species, reported by Lobert et al. (1999) of 307 Gg yr^{-1}. The SEA regional dioxins and

427 PAHs emissions from CROB are generally included but not explicitly presented in the global

428 EIs for dioxins (UNEP, 1999) and PAHs (Zhang et al., 2004) hence no relevant data are

429 available for comparison. The results of RS open burning emissions for Thailand and the

430 Philippines reported in Gadde et al. (2009) are not comparable to our results for the

431 Philippines specifically due a much higher B_k value used in their study as discussed above.

432 As a result, our M_k for this country of 8.6 Tg yr^{-1} for 2010 was 1.5 Tg yr^{-1} lower than the

433 value of Gadde et al. (2009) for 2007 (Table S5). However, our EI results for PAHs were

434 significantly higher (>10 times), mainly because of the large difference in EFs, i.e. we used

435 the EF of 264 mg kg^{-1} for 16 PAHs (both PM and gas phase) obtained from the field burning

436 experiments in Thailand while a much lower EF of 18.6 mg kg^{-1} was used in Gadde et al.

437 (2009).

438

439 Annual average SEA CROB emissions were compared with the results of the existing studies

440 for China and India. Our emission results were generally higher by 1.1-2.8 times, varying

441 with species, than those reported for China (Li et al., 2016) for 2012. SEA CROB emissions

442 were also 1.3-1.5 times higher than the emissions estimated for India by Jain et al. (2014) for

443 the year of 2008-2009. Given the larger population of China and India (above 1300 million in

444 each country) as compared to SEA population (about 640 million) the per capita emission for

445 SEA would be significantly higher than those for China and India. This further emphasizes

446 the importance of the CROB emissions on the air quality in the SEA region and the urgent

447 need for sustainable crop residue management.

448

449 3.2.2 Inter-annual variations of emissions

450 Annual SEA CROB emissions showed increasing trends for most species (Table 2).

451 Coefficient of variations (CV) were computed (the ratio of the standard deviation and mean)

452 that show a range of 2.6 – 8.6% depending on the species. This CV range represents relative

453 weak inter-annual variations owning to the relatively stable crop production rates and the

454 stable crop type composition hence less variation in the M_k values. These relatively small

455 inter-annual variations of SEA CROB emissions suggested that the average of decadal

456 historical emissions would still provide meaningful information for air quality management

457 purpose, e.g. for the regional air quality modeling. However, the variations in B_k values

458 should be incorporated, especially when major emission regulatory programs are being

459 promulgated, e.g. banning of open burning, that lead to substantial changes in the annual Mk

460 values.

461

462 3.2.3 Crop residue verse forest fires emissions

19

463   To roughly compare the magnitude of the SEA CROB emissions estimated in this study with

464   forest fire emissions, forest fire data from SEA in 2010 were extracted from the GFED

465   Version 3.1 (van der Werf et al., 2010) and presented in Table 3. The year 2010 was selected

466   because it represents the normal climate without strong El Niño/La Nina effects. The GFED

467   forest fire emissions included both above and below ground biomass (peat) burning. Overall,

468   the CROB emissions (covering 8 crop types) contributed 10-43%, depending on species, of

469   the total OB emissions (sum of CROB and forest fires) from the SEA region in 2010. The

470   contributions from CROB were relatively more significant (>30%) for toxic pollutants of

471     $PM_{2.5}$, OC and NH_3 and less significant (14-21%) for GHGs and the least (10%) for SO_2

472   (Table 3). The relative contributions of CROB to the total biomass open burning varied

473   widely between countries. The CROB contributed less in the countries having large forest

474   reserve areas with frequent forest fire events, i.e. 4-31%, depending on species, in Indonesia;

475   16-36% in Thailand; and 8-38% in Myanmar. For other SEA countries, the contributions of

476   CROB were higher than forest fires emissions, i.e. sharing 49-92% for Vietnam and 33-69%

477   for the Philippines. Current concern is more on regional massive forest fires as they normally

478   cause catastrophic haze transboundary events and are more visible on a scale that attract

479   intensive international attention. Alternatively, CROB emissions mainly occur in populated

480   areas and happen mostly in dry months when the air pollution levels in SEA countries are

481   normally high.   Therefore, they may cause significant local effects on health and the

482   environment. Specifically, substantial amounts of dioxins, PAHs, and OCPs along with large

483   quantities of toxic fine particles emitted annually from the crop residue field burning should

484   be of concern and be the focal point of raising awareness to stop CROB activity.

485

486   *3.3 Emission shares by country and by crop type*

20

487 The emissions by country (Fig. 2) show that Indonesia was the dominant contributor to the

488 total SEA CROB emissions of all species, i.e. 33-42%, followed by Vietnam (15-25%),

489 Myanmar (11-23%), Thailand (7-21%), the Philippines (8-12%) and Cambodia (1-2%). The

490 remaining 4 countries had relatively low emission shares, collectively of 0 – 6 %, namely 0.5-

491 5% from Laos, 0.3-0.9% from Malaysia, and 0.06-0.2% from both East Timor and Brunei.

492 The emission rates are explained by the country crop production rates that in turn are linked

493 to population (domestic use), export quantity, and the amount of crop residues generated as

494 well as residue management practices (B_k values). The high emissions in the top 4 countries

495 (Indonesia, Vietnam, Myanmar and Thailand) were mainly due to the large crop production

496 coupled with the high fractions of crop residues subjected to open burning. As noted earlier,

497 this study did not cover palm oil plantation OB that is likely to be important in some

498 countries, e.g. Indonesia and Malaysia being the world top two palm oil producers and to

499 some extent Thailand (World Growth, 2011). Without consideration of palm oil production,

500 the CROB emissions from Malaysia were only a small fraction in the SEA CROB emissions

501 because the country had only a small production of the 8 included crops. Future studies

502 should focus on the open burning emissions from various types of oil crops to provide a more

503 complete view of CROB emissions in all SEA countries.

504 Contributions of different types of crops to the total CROB emissions of different species are

505 presented in Fig. 3. Rice straw OB contributed dominantly to the total CROB emissions,

506 sharing 19-97% (varying by species) followed by maize (2-78%), sugarcane (0.4 – 26%)

507 while the rest of 5 crop types had only small shares (0-4.4%). Sugarcane residue open

508 burning was high in Thailand due to the extensive plantations to provide raw material for the

509 sugar industry in the country that is known as the world second largest sugar exporter

510 (Sornpoon et al., 2012).

511

21

512 *3.4 Range of the emission estimates*

513 Figure 4 presents the best emission estimate for different species (shown as bars) for 2015

514 with the vertical lines indicating the high and low estimates, respectively. The vertical lines

515 shown in Fig. 4 do not show the standard deviation of the best estimate but the emission

516 ranges which are linked to the relative difference between the low and the best estimates

517 [(Low-Best)/Best], % negative) and that between the best and the high emission estimates

518 (%, positive). Average uncertainty range of the emissions estimates for all species was -79 to

519 +256%, with the lowest range for NMVOC (-68 to +235%) and the highest for BC (-72 to

520 +323%). A wide range of EFs found in the literature for BC from CROB contributed to this

521 large range of the emission estimates.

522

523 *3.5 Spatial and temporal distributions of SEA CROB emissions*

524 Using the MODIS land cover product for SEA (Fig. S2, SI), the spatial distributions of the

525 annual emissions for year 2015 are mapped using GIS technique for all considered species at

526 0.1° x 0.1° (about 10 x 10 km^2) resolution. The gridded emission maps for PM$_{2.5}$, BC, PAHs

527 and dioxins are presented in Fig. 5, in t yr^{-1} grid^{-1} in black and white. The corresponding color

528 figure is given in Fig. S4 while the maps for other species are presented in Fig. S5, SI. As

529 expected, higher emissions are shown over the agricultural land areas. For example, in

530 Indonesia, a higher emission intensity was seen over western and eastern Java that are known

531 as the rice production hubs in the country and over the Sumatra Island where maize and

532 paddy plantations are concentrated. In Thailand, emissions were higher in the central (rice)

533 and northeastern regions (rice and sugarcane) (Chetthamrongchai et al. 2001). In Vietnam,

534 higher emissions are seen in the Mekong River delta, Red River delta and the central coastal

535 region, where agricultural crop production, especially rice, is intensive.

536

537 Monthly emission profiles are presented in Fig. 6 for different SEA countries. The monthly

538 emission variations were constructed using information on the harvesting periods of different

539 types of crops (related to *Bk* values in dry or wet season) in a year. In Indonesia, higher

540 emissions were during August – October period which is in the dry season and follow the

541 major rice harvesting time (August – September). For Thailand, the major crop residue

542 burning emissions occurred also during the dry season (October – April) with peaks in

543 November-December coinciding with the harvesting period of the rice crop. In Vietnam,

544 emissions are clearly shown in three periods following the harvesting of 3 rice crops with the

545 highest peaks in February – March followed by May - June and August - October. Higher

546 emissions in February – March were mainly the effects of the dry season harvesting time in

547 the central and southern Vietnam, while May – June peaks were mostly caused by the

548 harvesting in the northern Vietnam. In Myanmar, similar to Thailand, the emissions peaked

549 during the period of November – December coinciding with the rice crop harvesting time.

550 The peak emission was found during August - October in Malaysia while that in the

551 Philippines was during July - September. The total temporal variations were determined by

552 the variations of different crop types, however due to its dominance in the emissions the rice

553 straw open burning activity also dominated the monthly profiles of the SEA CROB

554 emissions. As a way of example, the monthly EC emissions over SEA is given in Fig. S6, SI

555 which closely follow the monthly emission fractions of the rice straw OB (Fig. S7, SI).

556

557 A good correlation between ambient air pollution levels and the CROB activities in SEA was

558 reported in previous studies. Tipayarom and Kim Oanh (2007) showed higher levels of CO

559 and PM_{10} during the RS burning period in Pathumthani, a sub-urban area of Bangkok,

560 Thailand, and the linear regression between the monthly pollutant levels and the monthly

561 MODIS hotspot counts over the area had R^2 of 0.56 for CO and 0.77 for PM_{10}. Klinmalee

23

562 (2008) reported significantly higher levels of PAHs (in both PM and gas phases) in the

563 RSOB area of Pathumthani during the dry season (400 ng m^{-3} for 16 PAHs excluding

564 naphthalene) as compared to the levels measured during non-RSOB period of 10-40 ng m^{-3}

565 while the levels found in a national park in both seasons were only 1-2 ng m^{-3}. The air

566 quality measurements thus confirmed the seasonal effects of CROB emissions especially in

567 the areas of intensive CROB.

568

569 The gridded SEA CROB emissions with the monthly distributions can be further used in the

570 modeling studies to simulate the base case and various emission reduction scenarios, e.g.

571 implementation of non-burning alternatives and/or a ban on CROB, to assess the impact on

572 air quality and regional climate.

573

574 **4. Conclusions**

575

576 The annual average quantity of crop residue biomass subjected to open burning in SEA

577 during 2010-2015 was 152 Tg yr^{-1}. An increasing trend in the annual emissions was observed

578 during the 2010-2015 period but the inter-annual variations were relatively small, 2.6% -

579 8.6% varying with species. The best estimates of annual average SEA CROB emissions over

580 the period in Tg were: 12.5 CO; 0.36 NOx; 0.03 SO$_2$; 1.0 NMVOC; 0.5 NH$_3$; 2.0 PM$_{10}$; 1.8

581 PM$_{2.5}$, 0.08 BC, 0.8 OC; 190 CO$_2$; 0.56 CH$_4$; and 0.015 N$_2$O. The annual average emissions

582 of toxic pollutants, in Gg yr^{-1}, were 32 PAHs (0.16 for BaP alone), 292 total chlorines and

583 0.03 OCPs. The annual emission of dioxins was estimated at 94 g I-TEQ yr^{-1}. On average, the

584 lower and higher emission estimates were between -79% to 256% of the respective species

585 best estimates. BC had the highest uncertainty range due to a wide range of the available EFs

586 reported in literature. The EI data for CROB in SEA available in literature showed significant

587   discrepancies for some species that could be explained by the difference in the methodology

588   (top-down or bottom up), inclusion of the local specific detail (e.g. B_k values and harvesting

589   methods), and EF selection.

590

591   Indonesia was the top contributor to the total SEA CROB emissions (33-42%) followed by

592   Vietnam (15-25%), Myanmar (11-23%), Thailand (7-21%), and the Philippines (8-12%).

593   Rice straw open burning contributed dominantly to the total SEA CROB emissions (19-97%)

594   followed by maize (2-78%), sugarcane (0.4 – 26%) while the rest five crops had small shares

595   (0-4.4%). The top three contributing crops should therefore be of priority for implementation

596   of alternative non-burning measures.

597

598   The CROB emissions contributed 10-43% of the total OB emissions (sum of CROB and

599   forest fires) in SEA in 2010 but varied widely with country. Forest fire emissions dominated

600   in Indonesia (69-96%), Thailand (64-84%) and Myanmar (62-92%) but CROB emissions

601   dominated in Vietnam (49-92%) and the Philippines (33-69%). The adverse local effects of

602   the CROB emissions on human health and the environment should not be overlooked as these

603   emissions occur in populated areas and mainly in the dry season when the air pollution levels

604   in SEA are significantly higher than other times of the year. The spatial distributions of the

605   SEA CROB emissions showed higher intensity over the agricultural areas where rice and

606   sugarcane were mainly cultivated. Monthly emissions profiles varied by country and were

607   affected by the local agricultural practices (harvesting times for different crop types) and

608   seasons (dry or wet).

609   The emission data produced in this study, with spatial and temporal distributions, could be

610   used for air quality modeling studies to assess the effects of current and future emissions on

611   the ambient air quality. It is suggested that multi-year average of past emissions can be used

612   for air quality modeling data due to relatively small inter-annual variations of CROB

613   emissions. Future studies should also include other types of oil crops that are commonly

614   cultivated in some countries of the region. Locally measured EFs are required to improve the

615   SEA CROB emission inventory results. Health effects of the CROB emissions should be

616   quantified to provide a driving force for elimination of this open burning activity and to

617   promote non-open burning alternatives for the sustainable agricultural waste management.

618

629

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Table caption

Table 1 Values of B_k for rice straw in SEA countries compiled from available survey results

Table 2 Annual SEA CROB emissions in the period of 2010-2015, Tg yr^{-1} (if not otherwise specified)

Table 3 SEA CROB vs. forest fire emissions in 2010, Tg yr^{-1}, in brackets are the percentage CROB contribution to the total biomass

open burning

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Table 1
Values of B_k for rice straw in SEA countries compiled from available survey results

Country	Region	Compiled B_k values	
		Dry season	Wet season
Thailand	Central	0.90[a]	0.25[c]
	South	0.30[b]	0.25[c]
	Others	0.48[a]	0.25[c]
Vietnam	North	0.77[d]	0.54[f]
	Central	0.59[e]	0.54[f]
	South	0.70[f]	0.54[f]
Indonesia	Java Island	0.43[g]	0.31[i]
	Others	0.75[h]	0.50[i]
Philippines	Whole country	0.71[j]	0.57[j]
Cambodia	Whole country	0.17[k]	0.17[k]
Malaysia	Whole country	0.43[l]	0.31[l]
Myanmar[m]	Whole country	0.77	0.54
Lao PDR[m]	Whole country	0.17	0.17
East Timor[m]	Whole country	0.43	0.31
Brunei[m]	Whole country	0.43	0.31
SEA range and most probable value (in brackets)		0.17-0.9 (0.51)	

Remarks:
[a] Tipayarom and Kim Oanh (2007) and DEDE (2007)
[b] Cheewaphongphan and Savitri Garivait (2013);
[c] SUMERNET (2017), unpublished data;
[d] Dong et al. (2013), local survey data in Northern Vietnam;
[e] SUMERNET (2017), unpublished survey data in central Vietnam;
[f] Tran et al. (2014), survey in Mekong Delta provinces of Vietnam;
[g] Sasongko et al. (2004), survey for rice straw in Java, Indonesia (used also for East Timor);
[h] Makarim et al. (2007), survey in Sumatera, Kalimantan and Sulawesi, Indonesia (also used for Malaysia and Brunei);
[i] Hafidawati (2017), personal communication regarding the survey results conducted in West Java during rainy season;
[j] Launio et al. (2013), surveys in the several areas in Philippines;
[k] SUMERNET (2017), unpublished survey data in Prey Veng Province, Cambodia;
[l] Rosmiza et al. (2014), estimated using the rice straw data in Kedah, Malaysia;
[m] No country specific data available hence data from neighboring countries were used.

Table 2
Annual SEA CROB emissions in the period of 2010-2015, Tg yr^{-1} (if not otherwise specified)

Species	Annual emissions						
	2010	2011	2012	2013	2014	2015	Average (CV,%)[b]
CO	11.65	12.18	12.73	12.79	12.81	12.94	12.5±0.46 (3.6%)
NOx	0.33	0.34	0.37	0.37	0.38	0.38	0.36±0.02 (5.6%)
SO$_2$	0.0279	0.0287	0.0327	0.0327	0.0333	0.0341	0.0315 ±0.002 (7.5%)
NMVOC	0.95	1.00	1.04	1.05	1.05	1.07	1.03±0.04 (3.8%)
NH$_3$	0.48	0.50	0.52	0.52	0.52	0.52	0.51±0.02 (3.1%)
PM$_{10}$	1.87	1.91	1.97	1.99	2.00	2.02	1.96 ±0.05 (2.6%)
PM$_{2.5}$	1.71	1.73	1.79	1.80	1.82	1.84	1.78±0.05 (2.6%)
BC	0.074	0.076	0.084	0.084	0.085	0.087	0.082±0.005 (5.8%)
OC	0.81	0.81	0.84	0.84	0.85	0.86	0.83±0.02 (2.6%)
CO$_2$	172	178	195	196	198	202	190±11 (5.8%)
CH$_4$	0.52	0.55	0.56	0.57	0.56	0.57	0.56±0.02 (3.1%)
N$_2$O	0.0139	0.0144	0.0155	0.0156	0.0157	0.016	0.0152±0.0008 (5.1%)
PAHs (Gg yr^{-1})	30.0	31.6	32.3	32.6	32.4	32.1	31.8±0.09 (2.7%)
BaP (Gg yr^{-1})	0.143	0.159	0.166	0.167	0.168	0.184	0.164±0.012 (7.6%)
Dioxin (g I-TEQ yr^{-1})	82	82	98	98	100	102	94±8.1 (8.6%)
OCPs (Gg yr^{-1}), RSOB	0.025	0.0264	0.0269	0.0272	0.027	0.0266	0.027±0.007 (2.6%)
Total chlorine (Gg yr^{-1})[a]	271	284	296	298	298	302	292±10.6 (3.6%)

Note: [a] Sum of five listed species in Table S3: CH_3Cl, CH_2Cl_2, $CHCl_3$, CH_3CCl_3, particulate and inorganic Cl.
[b] in brackets, CV is the coefficient of variation (SD/average), in %; OCPs are estimated for rice straw open burning only.

Table 3

SEA CROB vs. forest fire emissions in 2010, in Tg yr^{-1}, in brackets are the percentage CROB contribution to the total biomass open burning.

Species	Indonesia		Vietnam		Thailand		Philippines		Myanmar		SEA region		
	CROB	Forest	CROB	Forest	CROB	Forest	CROB	Forest	CROB	Forest	CROB	Forest	Total
CO	4.5(8)	50.4	2.5(76)	0.8	0.94(29)	2.3	0.96(52)	0.90	2.3(23)	7.7	11.6(24)	37.6	49.2
NOx	0.13(15)	0.7	0.07(76)	0.022	0.029(33)	0.057	0.032(59)	0.022	0.06(24)	0.193	0.329(26)	0.93	1.26
SO_2	0.01(4)	0.223	0.0058(49)	0.006	0.003(16)	0.015	0.003(33)	0.006	0.005(8)	0.054	0.028(10)	0.263	0.291
NMVOC	0.37(15)	2.2	0.21(81)	0.05	0.07(29)	0.17	0.08(53)	0.07	0.182(26)	0.52	0.95(27)	2.6	3.5
NH_3	0.19(31)	0.42	0.103(81)	0.024	0.038(29)	0.093	0.039(57)	0.029	0.096(45)	0.118	0.48(43)	0.64	1.1
PM_{10}	0.77(17)	3.78	0.31(74)	0.11	0.09(25)	0.29	0.19(63)	0.11	0.47(33)	0.96	1.9(29)	4.7	6.5
$PM_{2.5}$	0.7(20)	2.9	0.28(78)	0.080	0.084(29)	0.21	0.17(68)	0.08	0.43(38)	0.7	1.7(33)	3.4	5.15
BC	0.028(14)	0.178	0.015(75)	0.005	0.0072(36)	0.013	0.007(59)	0.005	0.014(24)	0.045	0.074(25)	0.22	0.29
OC	0.34(19)	1.4	0.12(74)	0.040	0.031(22)	0.11	0.089(69)	0.040	0.22(37)	0.37	0.81(31)	1.8	2.6
CO_2	65.2(11)	522	36.8(72)	14	16(29)	39	16.5(52)	15	32.1(19)	135	172(21)	655	827
CH_4	0.2(31)	0.45	0.11(69)	0.05	0.038(20)	0.15	0.041(41)	0.06	0.104(18)	0.47	0.52(18)	2.3	2.8
N_2O	0.053(8)	0.063	0.003(92)	0.0018	0.0012(21)	0.0047	0.001(41)	0.0018	0.0026(13)	0.017	0.014(14)	0.082	0.096

Note: Forest – forest fire emission from GFED4, http://www.globalfiredata.org/data.html.

Figure caption

Fig. 1. Amount of crop residues subjected to open burning by type of crop, 2010-2015 (M_k, Tg yr^{-1})
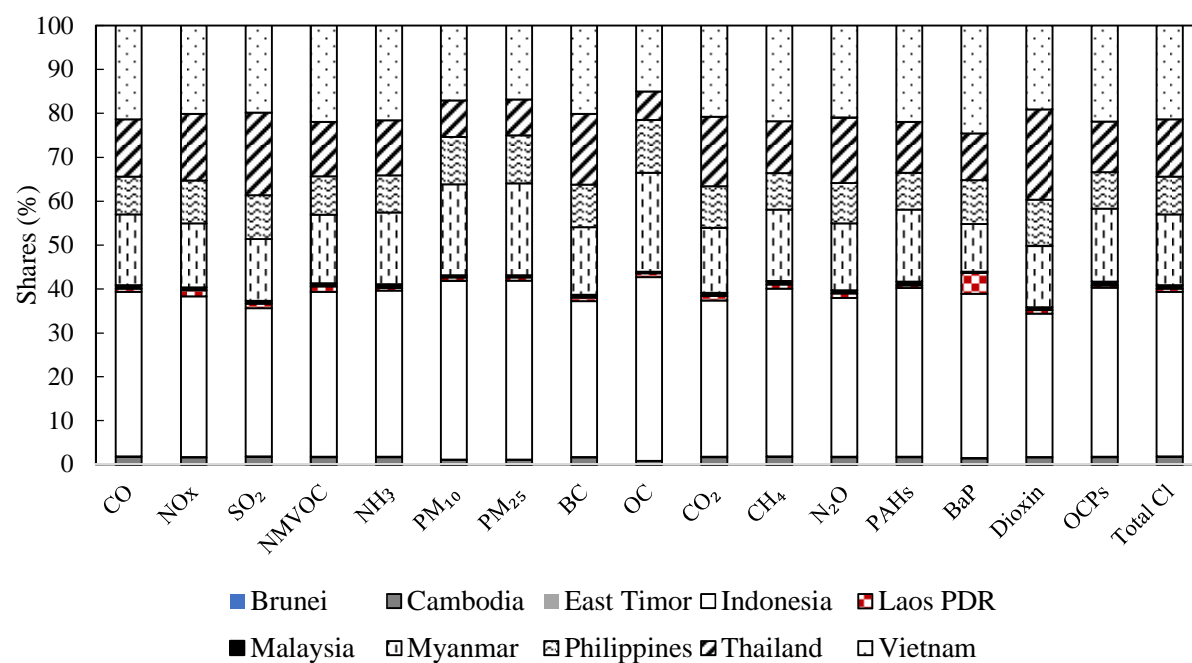
Fig. 2. Shares by country in the annual SEA CROB emissions of different species, averaged over 2010-2015 (refer to Table 2 for the total annual emissions)
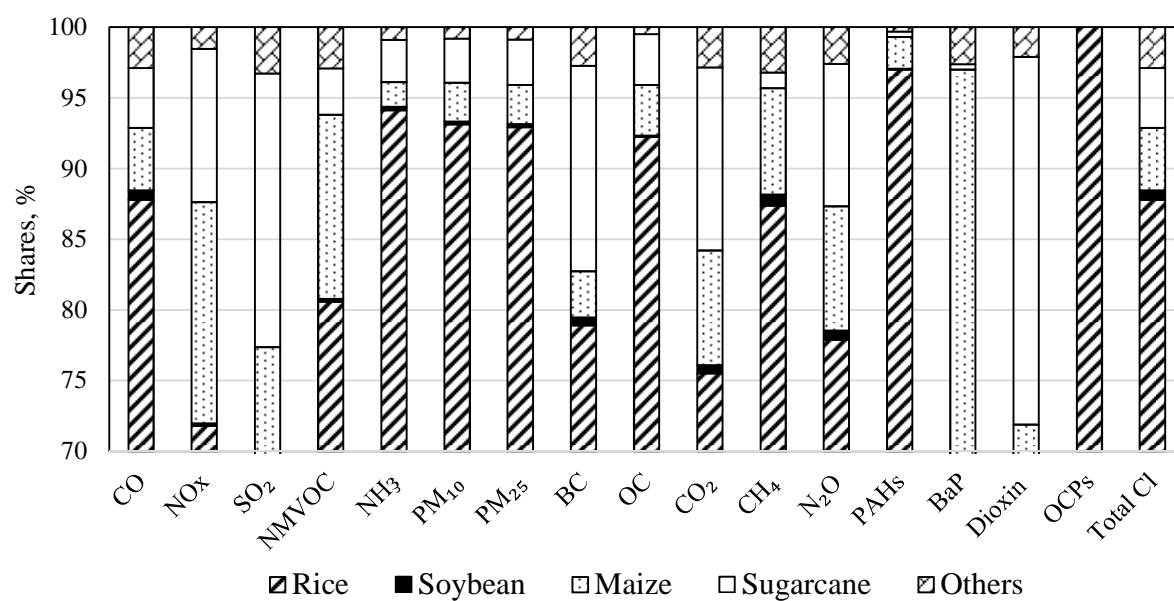
Fig. 3. Total annual emissions of different species and shares by crop types, averaged over 2010-2015 (refer to Table 2 for the total annual emissions)
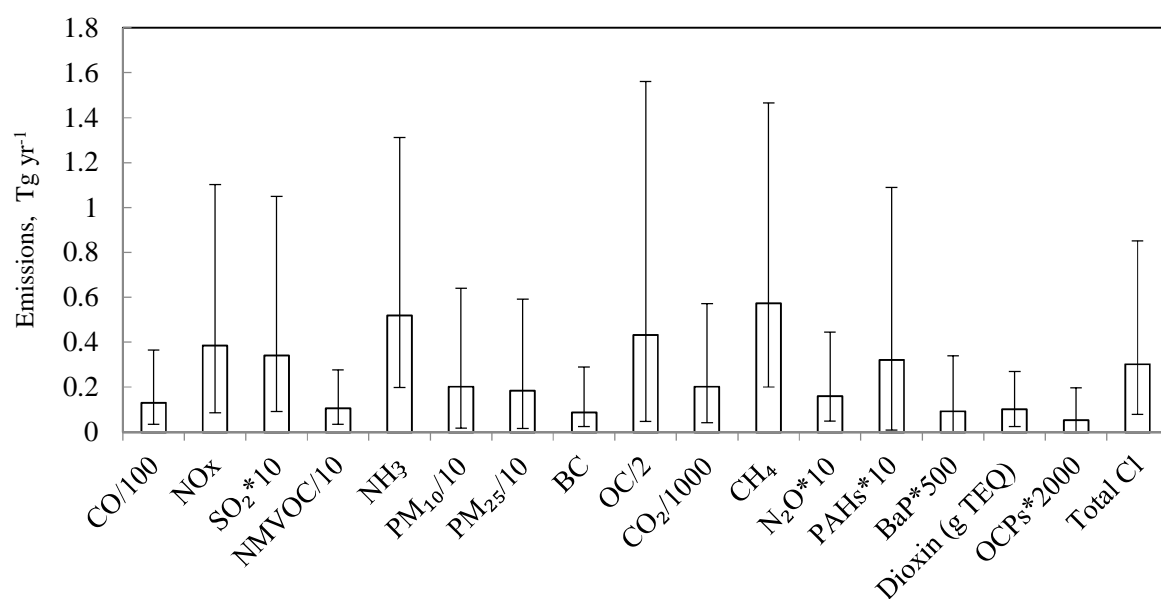
Fig. 4. SEA CROB emissions during 2015 showing with low, best and high emission estimates of different species

Fig. 5. Gridded SEA CROB emissions in t yr^{-1} $grid^{-1}$, if not otherwise specified, with grid resolution of 0.1º x 0.1º, 2015 for selected species (colorful version is in Fig. S4, SI)

Fig. 6. Monthly fractions of CROB emissions from different countries in SEA, 2015
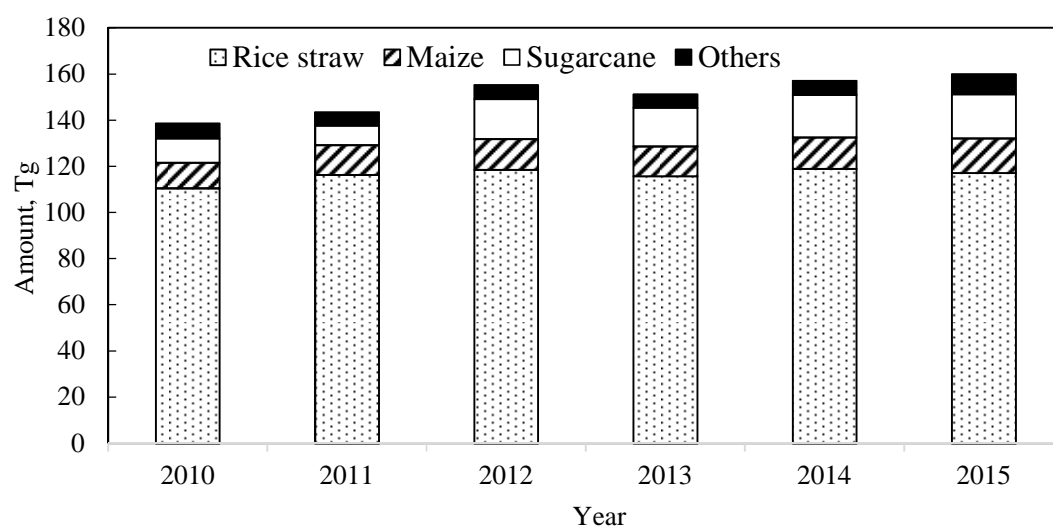
Fig. 1. SEA total amount of crop residues subjected to open burning annually by type of crop (M_k, Tg yr^{-1})

Fig. 2. Shares by country in the annual SEA CROB emissions of different species, averaged over 2010-2015 (refer to Table 2 for the total annual emissions)

Fig. 3. Total annual emissions of different species and shares by crop types, averaged over

2010-2015 (refer to Table 2 for the total annual emissions)

Note: OCPs were estimated only for RSOB.

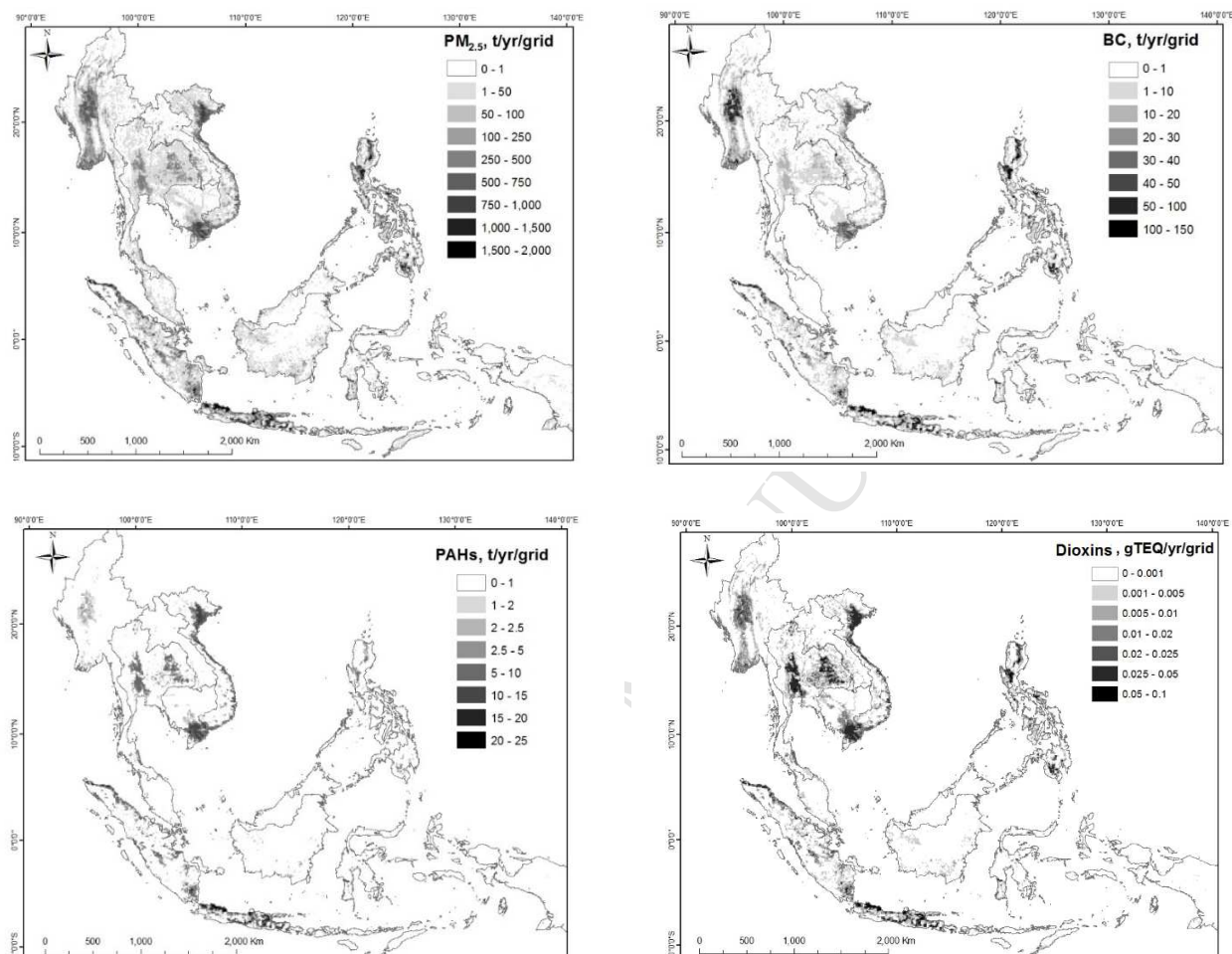**Fig. 4.** SEA CROB emissions during 2015 showing with low, best and high emission estimates of different species

Fig. 5. Gridded SEA CROB emissions in t yr^{-1} grid^{-1}, if not otherwise specified, with grid resolution of 0.1° x 0.1°, 2015 for selected species (colorful version is in Fig. S4, SI)
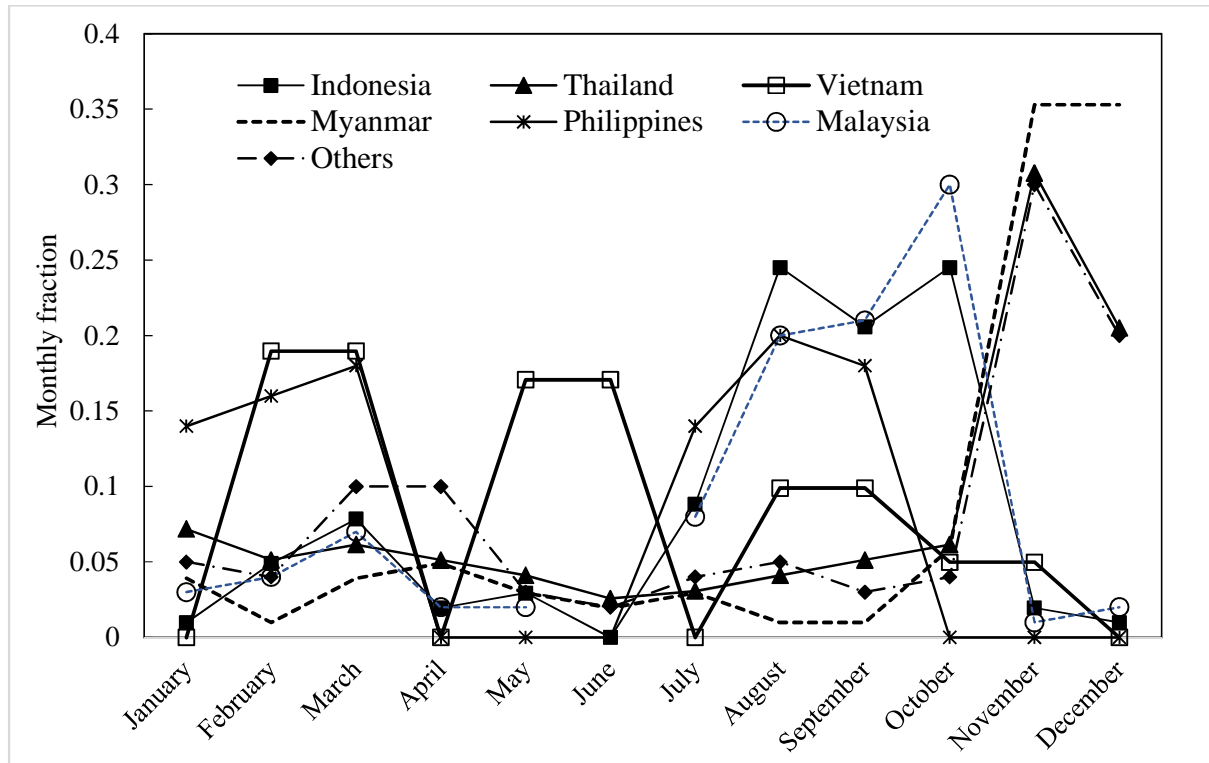
Fig. 6. Monthly fractions of CROB emissions from different countries in SEA, 2015

Note: This figure was constructed based on monthly crop production and harvesting time

compiled for the countries. The sum of the monthly fractions over the year (January –

December) is 1.0 for each country.

Highlights

- Emission inventory for air toxics from crop residue open burning (CROB) in Southeast Asia
- Fractions of residue subjected to open burning *(B$_k$)* compiled from local surveys
- Minimal inter-annual fluctuations in emissions over the 2010-2015 period
- Rice, maize and sugarcane residue open burning was major emitters
- CROB emissions contributed more than forest fires in Vietnam and Philippines