Estimating the open biomass burning emissions in Central and Eastern China from 2003 to 2015 based on satellite observation

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Abstract. Open biomass burning (OBB) has significant impacts on air pollution, climate change and potential human health. OBB has raised wide attention but with little focus on the annual variation of pollutant emission. Central and Eastern China (CEC) is one of the most polluted regions in China. This study aims to provide a state-of-the-art estimation of the pollutant emissions from OBB in CEC from 2003 to 2015, by adopting the satellite observation dataset (the burned area product (MCD64Al) and the active fire product (MCD14 ML)), local biomass data (updated biomass loading data and high-resolution vegetation data) and local emission factors. The successful adoption of double satellite dataset for long term estimation of pollutants from OBB with a high spatial resolution can support the assessing of OBB on regional air-quality, especially for harvest periods or dry seasons. It is also useful to evaluate the effects of annual OBB management policies in different regions. Here, monthly emissions of pollutants were estimated and allocated into a 1×1 km spatial grid for four types of OBB including grassland, shrubland, forest and cropland. From 2003 to 2015, the emissions from forest, shrubland and grassland fire burning held annual fluctuation whereas the emissions from crop straw burning steadily increased. The cumulative

30 emissions of organic carbon (OC), elemental carbon (EC), methane (CH_4), nitric oxide (NO_x), non-methane volatile

31 organic compounds (NMVOCs), sulfur dioxide (SO_2), ammonia (NH_3), carbon monoxide (CO), carbon dioxide

32 (CO_2) and fine particles ($PM_{2.5}$) were 3.64×10^3, 2.87×10^2, 3.05×10^3, 1.82×10^3, 6.4×10^3, 2.12×10^2, 4.67×10^2,

33 4.59×10^4, 9.39×10^5 and 4.13×10^3 Gg in these years, respectively. Crop straw burning was the largest contributor

34 for all pollutant emissions, by 84%-96%. For the forest, shrubland and grassland fire burning, forest fire burning

35 emissions contributed the most and emissions from grassland fire was negligible due to few grass coverage in this

36 region. High pollutant emissions concentrated in the connection area of Shandong, Henan, Jiangsu and Anhui, with

37 emission intensity higher than 100 ton per square kilometers, which was related to the frequent agricultural

38 activities in these regions. Peak emission of pollutants occurred in summer and autumn harvest periods including

39 May, June, September and October, at which ~50% of the whole pollutants emission were emitted in these months .

40 This study highlights the importance in controlling the crop straw burning emissions. From December to March,

41 the crop residue burning emissions decreased, while the emissions from forest, shrubland and grassland exhibited

42 their highest values, leading to another small peak emissions of pollutants. Obvious regional differences in seasonal

43 variations of OBB were observed due to different local biomass types and environmental conditions. Rural

44 population, agricultural output, economic levels, local burning habits, social customs and management policies

45 were all influence factors for OBB emissions.

47 **1. Introduction**

48 Open biomass burning (OBB), which includes forest, shrubland, grassland and crop residue fire burning (van

49 der Werf et al., 2010; Qiu et al., 2016), is one of the most important sources for gaseous and particulate matter (PM)

50 especially for fine particulate particles ($PM_{2.5}$) and associated carbonaceous aerosols (elemental carbon (EC) and

51 organic carbon (OC)) (Zha, 2013; Yan et al., 2014; Zong et al., 2016; Zhou et al., 2017). Previous studies have

52 shown that the OBB contributed to approximately 40% of the annual average submicron EC emission and 65% of

53 primary OC emission globally (Bond et al., 2013), and contributed more than 45% of $PM_{2.5}$ concentration on days

54 of heavy air pollution (Deng, 2011). The pollutants with high emission amounts from OBB posed significant

55 impacts on regional and global climate change, air quality and human health (Seiler and Crutzen, 1980; Crutzen

56 and Andreae, 1990; Andreae and Merlet, 2001; Bond et al., 2004; Akagi et al., 2011; Zhang et al., 2016).

57 From 1970s (Crutzen et al., 1979), emission estimation of biomass burning has been a research hot topic from

58 global (Seiler and Crutzen et al., 1980; Levine, 1995; Liousse et al., 1995; Bond et al., 2004; Randerson et al., 2012;

59 Kaiser et al., 2012) to regional scale (Yevich and Logan, 2003; Chang et al., 2010; Liousse et al., 2010; Li et al.,

2017). China is suffering from severe air pollution with hundred millions of open biomass burned each year (Zhang et al., 2015). The quantitative estimation of pollutants emission for the whole China (Streets et al., 2003; Tian et al., 2002; Cao et al., 2005; Zhou et al., 2017) or a certain region (Liu et al., 2015; Zhou et al., 2015; Jin et al., 2017) is also a vital practice, which is the base for assessing the impact of OBB on air regional quality deterioration. The Central and Eastern China (CEC), including the Central China (Hunan, Henan and Hubei) and the Eastern China (part of the North Plain of China (Shandong), the Yangtze River delta (YRD, including Zhejiang, Jiangsu, Anhui and Shanghai) and part of the Pan-Pearl River delta (Fujian and Jiangxi)) (Figure 1), is an area with plenty of vegetation coverage (as listed in Figure S1 of Supplementary File). Yin et al (2017) have indicated that the crop residue fire burning in summer harvest time can lead to the increase of $PM_{2.5}$ concentration in China's middle-east region. As one of the most heavily polluted regions in China (Chang et al., 2009; Fu et al., 2013), many large cities are included in this region, such as Nanjing, Wuhan, Shanghai and Hangzhou. Former studies have highlighted the role of OBB on worsening air quality regionally or at megacities, especially for crop residue burning at harvest periods (Yamaji et al., 2010; Zhu et al., 2010; Yin et al., 2011; Huang et al., 2012b; Su et al., 2012; Cheng et al., 2014; Zhou et al., 2016; Zhang et al., 2017).

Previous studies mainly focused on crop residue burning emissions with relatively low spatial and temporal resolution (Yamaji et al., 2010; Huang et al., 2012b), which may limit its adoption in air quality modeling to give an accurate result. An accurate estimation of monthly emissions from OBB with a long timescale and high spatial resolution is still limited. It should be noted that, the OBB activities owned spatial-temporal variation properties and have changed greatly during the last two decades in China, especially for forestland fire burning (Huang et al., 2011) and crop residue burning, considering the implementation of related policies (Table S1 and Table S2). As a big agricultural country, the Chinese government has placed a high priority on environmental pollution prevention caused by OBB. From 1965 to 2015, 51 management documents for crop straw have been formulated and 34 documents were intensively issued after 2008 (Chen et al., 2016). Up to now, few studies have accurately estimated the biomass burning emissions in a long time period (Fu et al., 2013; Cheng et al., 2014). The role of the pollution prevention policies on the spatial-temporal variation of pollutants emitted needs to be better clarified.

In addition, most previous studies have adopted the top-down method (Seiler and Crutzen et al., 1980) to estimate the OBB emission by national or provincial statistical data and then the total emission amounts of pollutants were re-allocated in grids by population, land cover area, or even equal sharing, which is one of the key reasons for the high uncertainties of OBB emission inventories (Streets et al., 2003; Klimont and Streets., 2007; Gadde et al., 2009; He et al., 2013; Zhou et al., 2015; Zhou et al., 2017). Quantitative estimation of biomass

burning was highly improved by the satellite observations of fire burned area or active burning fires (Freitas et al., 2005; Wooster et al., 2005; Roy et al., 2008; Giglio et al., 2008; Roy et al., 2008; Reid et al., 2009; Sofiev et al., 2009; Giglio et al., 2010; Liousse et al., 2010; Huang et al., 2012; Li et al., 2016). The improvement of spatial-temporal distribution evolution was achieved by active fire products (e.g., the AVHRR fire count product (Setzer and Pereira, 1991), MODIS active fire satellite products (Cooke et al., 1996) and VIRS fire count product (Ito et al., 2007)). The burned area detection was improved by burned area products (e.g., GBA2000 product (Ito and Penner, 2004; Korontzi, 2005), MODIS burned area dataset (Ito et al., 2007) and Global Fire Emissions Database (GFED) (Randerson et al., 2012)). However, satellite observation also exhibited weakness in estimating fire burning emissions (Duncan et al., 2003; He et al., 2015). One is the burned area product, which provides fire burned areas of the whole month. It is limited by the lower pixel resolutions. The size of many small burn scars is below the detection limit of these products (Eva and Lambin, 1998; Laris, 2005; McCarty et al., 2009; Roy and Boschetti, 2009). Therefore, the contribution of small fires to fire burned area and corresponding fire burning emissions are still poorly understood (Randerson et al., 2012). The other is the active fire product, which can provides information on small fire locations, occurrence time and small fire burned area (Prins and Menzel, 1992; Giglio et al., 2006; Chuvieco et al., 2008; Roberts et al., 2009; Aragao and Shimabukuro, 2010; Bowman et al., 2011; Lin et al., 2012; Arino et al., 2012). The uncertainty of fire detection is mainly due to the limitation of satellite overpass periods. To reduce the uncertainty of emission estimation by satellite products, the combination of two satellite dataset has been proved to be an effective practice recently (Qiu et al., 2016).

The lack of local biomass data (biomass loading data and vegetation speciation data) and local emission factors could introduce uncertainty in emission estimates. Currently, local biomass loading data need to be updated and accurately measured. Local high spatial-resolution vegetation speciation data has been rarely adopted in OBB estimations. Meanwhile, a lot of researches about OBB have used the same emission factors for pollutants emitted from OBB without considering the various biomass species and combustion conditions (Andela et al., 2013; Giglio et al., 2013). All these should be considered and improved in the establishment of OBB emission inventory.

In this study, the multiple satellite data (MCD14 ML and MCD64Al), local high spatial-resolution of vegetation speciation data, updated local biomass loading data, local emission factors and survey results were used to estimate multi-year OBB emissions from 2003 to 2015 in CEC. High spatial-temporal resolution of emission allocation was achieved. The possible driving factors like local habits, social customs, rural population, economic level, agricultural production, energy and pollution control policies which may impact the spatial distribution and temporal variation of OBB emissions were explored. They have been overlooked in previous studies (Song et al.,

120 2009; Chen et al., 2013; Shi et al., 2015). The results here will provide scientific evidence for policy making on

121 controlling OBB emission and modeling its regional impact on air quality, climate and human health. The methods

122 are also helpful for other regions for OBB emission estimation.

123 **2. Methods**

124 **2.1 Estimation of burned areas**

125   OBB emissions in CEC were initially estimated based on the local biomass data (biomass loading data and

126 vegetation speciation data), satellite burned area data (Figure S2 and Figure 2) and emission factors. Fire burning

127 emission amount was calculated by the following equation (Wiedinmyer et al., 2011; Shi et al, 2015).

128 $$E_{i,x,t} = \sum_{j=1}^{n} BA_{x,t} \times CE_x \times BL_x \times EF_{i,j} \tag{1}$$

129   where j stands the different aggregated vegetation types; i stands for different pollutant species; $E_{i,x,t}$ is the

130 emission amount of pollutant i in location x and month t; $BA_{x,t}$ is the total burned area (km^2) of aggregated

131 vegetation class in location x and month t; CE_x is defined as the combustion efficiency in location x; BL_x is the

132 biomass fuel loading (kg) in location x; $EF_{i,j}$ is the emission factor of pollutant specie i for vegetation type j.

133   MODIS burned area product (MCD64AL: http://modis-fire.umd.edu/) and MODIS active fire product (MCD14

134 ML: https://earthdata.nasa.gov/faq#ed-firms-faq) were combined to obtain accurate open biomass burned area data.

135 MCD64Al had a 500 m spatial resolution and monthly temporal resolution, which could accurately detect the

136 burning area at 500 m pixel. A much lower pixel resolution burning was difficult to detect by this satellite.

137 Therefore, we used MODIS active fire product MCD14 ML as a supplemental tool to obtain the small fire burned

138 area. The active fire detection method based on thermal anomalies could detect fires as low as 1/20 of a pixel. We

139 resampled the two fire products data into 1 km×1 km grid. The total burned area in each grid cell was estimated by

140 the following equation (Randerson et al., 2012).

141 $$BA_{total(i,t,j)} = BA_{MCD64AL(i,t,j)} + BA_{sf(i,t,j)} \tag{2}$$

142   where $BA_{total(i,t,j)}$ is the total fire burned area in grid cell i, month t and aggregated vegetation class j;

143 $BA_{MCD64AL(i,t,j)}$ is the MCD64AL burned area in grid cell i, month t and aggregated vegetation class j; $BA_{sf(i,t,j)}$ is the

144 small fire burned area in grid cell i, month t and aggregated vegetation class j.

145      $BA_{MCD64AL(i,t,j)}$ was directly detected from MCD64AL product. MCD14ML active fire points in each grid

146 included two parts: active fires points with or near MCD64A1 burned area (FC_{in}) and active fires outside the

147 MCD64AL burning area (FC_{out}). $BA_{sf(i,t,j)}$ was the burned area of FC_{out}. The $BA_{sf(i,t,j)}$ was used as supplement. Due

148 to the active fire product existed as the fire points and could not directly obtain the burned area data, the burned

149   area of small fire was estimated based on the following method (Randerson et al., 2012).

150    $$BA_{sf\,(i,\,t,\,j)} = FC_{out\,(i,\,t,\,j)} \times \alpha_{(r,\,s,\,j)} \times \gamma_{(r,\,s,\,j)} \tag{3}$$

151   where $BA_{sf(i,t,j)}$ is the small fire burned area of F_{out} in grid cell i, month t and aggregated vegetation class j;

152    $FC_{out(i,t,j)}$ is the total number of MCD14 ML active fires outside of the burned area in grid cell i, month t and

153   aggregated vegetation class j; α is the ratio of $BA_{MCD64A1}$ to F_{in} and α is equal to the value of surrounding grid cell

154   if $BA_{MCD64A1}$ is equal to 0; γ is an additional unit less scalar which indicates the difference between F_{in} and F_{out}

155   and γ is assumed equal to 1 in this research; r denotes the burning region; s indicates the burning period.

156

157   **2.2 Biomass fuel loading**

158   For forestland, most previous studies used the forest biomass loading data from Fang et al (1996). The forest

159   biomass loading data in recent years need to be updated. In this study, the forest loading data between 2003 and

160   2008 was collected from Fang et al (1996). From 2008-2015, the forest loading data was calculated based on the 8th

161   Chinese National Forest Resource Inventory (Xu, 2014). The forest biomass density data (Table 1) was estimated

162   by the following equation:

163    $$B_{i,\,r} = T_{i,\,r} / A_{i,\,r} \tag{4}$$

164   where i stands for different forest species (broadleaf forest, coniferous forest and mixed forest); r means each

165   province; $B_{i,r}$ is the biomass density of forest specie i in province r; $T_{i,r}$ means the total biomass of forest specie i in

166   province r; $A_{i,r}$ denotes the total area of forest specie i in province r.

167   The total biomass of different forest species was calculated based on the forest stock volume method as

168   follows (Fang et al., 1996):

169    $$T_{i,\,r} = \sum_{j=1}^{n} E_{j,\,r} = \sum_{j=1}^{n} (aV_{j,\,r} + b) \tag{5}$$

170   where j stands for different tree types of forest specie i; $E_{j,r}$ means the biomass of different tree type j in

171   province r; $V_{j,r}$ indicates the forest stock volume of different tree type j in province r; a and b are set as correlation

172   coefficient.

173   The correlation coefficient "a" and "b" for different tree types were derived from previous studies (Fang et al.,

174   1996; Tian et al., 2011; Lu et al., 2012; Li et al., 2014; Wang et al., 2014; Wen et al., 2014) (Table 2). $A_{j,r}$ and $V_{j,r}$

175   was collected from the 8th Chinese National Forest Continuous Inventory. As shown in Table 1, the forest biomass

176   density in recent years has changed a lot, which highlighted the importance of the updation for improving the

177 emission estimation.

178 For grassland and shrubland, local biomass density data were collected (Pu et al, 2004; Hu et al, 2006)in Table

179 1. To determine the accurate provincial amounts of crop residue burning, we gathered the production of different

180 species of crops from the China Statistical Yearbook (NBSC, 2003-2015). Detailed data of crop residue to

181 production ratio (dry matter) were collected from local statistical data (Table 3) and the updated data for crop straw

182 burned ratio were derived from survey results (Table 4). Using the updated biomass data, the accuracy of the

183 estimation of OBB emission is expected to be improved.

184 **2.3 Combustion efficiency**

185 In previous studies (Wang et al., 2008; Tian et al., 2011), the combustion efficiency (CE) of OBB was mainly

186 set as a constant, which may bias the emission estimation. To improve the accuracy, for cropland, the CE was set as

187 0.68 for soya bean and 0.93 for other types (Koopmans and Koppejan, 1997; Wang and Zhang, 2008; Zhang et al.,

188 2011). For forest, shrubland and grassland, the CE of fires at each grid cell was assumed as a function of forest

189 cover of corresponding grid cell (Ito et al, 2004; Wiedinmyer et al, 2006). If areas with tree coverage exceeding

190 60%, the CE for woody and herbaceous cover was set as 0.3 and 0.9, respectively; the CE was set as 0 and 0.98 for

191 woody and herbaceous cover with tree coverage less than 40%; for 40-60% tree cover of fires, the CE was defined

192 as 0.3 for woody fuels and the calculation of herbaceous areas was referred to the following equation:

193
$$CE_s = e^{-0.13 \times TB} \tag{6}$$

194 where TB stands for the percent tree cover for fires in each grid cell.

195 It should be noted that though we improved the selection of CE values for different biomass burning types by

196 reviewing literatures, the CE value should not be a constant during burning and the pollution emissions were not

197 uniform in different burning phase, such as smoldering (Kondo et al., 2011) and flaming burning (Burling et al.,

198 2010). Emission inventory in this research and currently published papers (Wang and Zhang, 2008; Zhang et al.,

199 2011; Lu et al., 2011) were estimated for a long time period or a whole year with the timescale as month, instead of

200 hour. Therefore, the CE values used here reflected the average biomass burning condition. In the future, for

201 researches on developing emission inventory with hourly or daily resolution, corresponding high time-resolution

202 activity data and emission factors for different burning stages should be considered.

203 **2.4 Emission Factors**

204 Emission factors (EFs) of different OBB were summarized in Table 5. EFs for cropland burning were mainly

205 collected from previous researches carried out in CEC (Tang et al., 2014). As the lack of EFs research on some crop

species conducted in CEC and forest, grassland and shrubland conducted in China, EFs were collected from previous researches (Cao et al., 2008; Wang et al., 2008; Akagi et al., 2011; He et al., 2015). In addition, some emission factors measured by our research group in CEC were included in this study.

2.5 Spatial and temporal allocation

In order to estimate high spatial resolution of OBB emission in CEC, a high resolution vegetation map (1:1 000 000) (Figure S1) together with the burned area of every open biomass species was used. All the data were relocated into a 1 km×1 km grid to identify and estimate spatial variations of OBB emission. The monthly distribution of OBB emissions were estimated based on the monthly burned area of different vegetation cover types.

The emission in t-th grid was calculated by the following equation:

$$E_{t,j} = BA_{t,j} / BA_{i,j} \times E_{i,j} \tag{7}$$

Where j means different biomass species; i denotes different provinces; $E_{t,j}$ is the emission of different biomass specie j in t-th grid; $BA_{t,j}$ is the burned area in t-th grid cell; $BA_{i,j}$ is the total burn area of different vegetation types in province i; $E_{i,j}$ is the total emission amounts from OBB in province i.

2.6 Other factors influencing OBB emission

Several detailed statistics data in the NBSC were collected, such as rural population, per capita net income of rural residents, agricultural output and forestry output in each province and each year. They may impact the OBB emission. Correlation analysis between the OBB emissions and these influencing factors were conducted. Rural population data in 2003, 2004 and 2010 were lack as the detailed data was not reported in NBSC.

2.7 Uncertainty analysis

The Monte Carlo method together with the crystal software was used to evaluate the estimation uncertainty quantitatively for all the pollutants. Pollutant emissions were estimated from 20,000 Monte Carlo simulations with a 95% coincidence interval.

3. Results and Discussion

3.1 Accumulated pollutants emission from OBB in CEC

Table 6 presented the cumulative OBB emission amounts during 2003-2015 and multi-year emissions of different provinces were detailedly listed in Table S3. By the end of 2015, the cumulative emissions of OC, EC, CH_4, NO_x, NMVOCs, SO_2, NH_3, CO, CO_2 and $PM_{2.5}$ were 3.64×10^3, 2.87×10^2, 3.05×10^3, 1.82×10^3, 6.4×10^3, 2.12×10^2, 4.67×10^2, 4.59×10^4, 9.39×10^5 and 4.13×10^3 Gg, respectively. For better revealing the spatial-temporal

235   variation of OBB emissions, the $PM_{2.5}$ variation was detailedly discussed as an example. From 2013 to 2015, the

236   highest emission amounts of $PM_{2.5}$ were found in Henan and Shandong, accounting for 27.93% and 24.35% of the

237   total emission amounts, respectively. The lowest emission appeared in Zhejiang and Shanghai, which only

238   contributed for 4.05% and 0.43%. For other provinces, Hunan, Hubei, Fujian, Anhui, Jiangxi and Jiangsu accounted

239   from 5.52% to 10.13% of the whole emission.

240   The contributions of different biomass burning types for various pollutants were shown in Figure 3a. Cropland

241   burning contributed the most emission for all the pollutants, by84%-96%. The forest fire exhibited higher emission

242   of NH_3, SO_2, NMVOCs and $PM_{2.5}$, accounting for 12%, 11%, 7% and 5% of corresponding total emission,

243   respectively. As shown in Figure 3b, for cropland, wheat, corn and rice straw burning were the top three emission

244   source types for all the pollutants. Corn straw burning contributed the most to SO_2 (48%), NO_x (37%), NMVOCs

245   (33%), CO (32%) and CO_2 (28%) emission. Highest contributions of EC (45%), OC (33%) and CH_4 (32%) from

246   rice straw burning was found, while wheat straw burning contributed the most (31%) to $PM_{2.5}$ emission.

247   In Figure 4, except for Fujian, cropland burning emission was the largest contributor to$PM_{2.5}$ emission, with

248   the contributions ranging from 75.25% (Jiangxi) to almost 100% (Shanghai). The higher rural agglomeration,

249   abundant crop production and more crop residue burning activities in these provinces can explain the higher

250   contributions. Shanghai is one of the most developed cities in China. The highest contribution of cropland burning

251   is not related with its high levels of agricultural activities, but is due to the lack of emissions from other open

252   biomass burning sources. Highest contribution from the forest fire burning and shrubland fire burning were found

253   in Fujian as 45.29% and in Jiangxi as 23.95%, respectively. For forest fire burning, the southern provinces (Fujian,

254   Zhejiang, Jiangxi, Hunan, Hubei and Anhui) exhibited higher values, varying from 3.66% (Hubei) to 38.3% (Fujian)

255   and for shrubland fire burning, the contributions varied from 1.5% (Hubei) to 7.23% (Zhejiang). The relative high

256   emission contributions of forest and shrubland fire burning in the southern provinces can be explained by the large

257   forest and shrubland coverage, frequent human forestry activities, low precipitation and dry weather in spring and

258   winter (Cao et al., 2015), which may easily lead to forest and shurbland fires. While for the northern provinces

259   (Shandong, Henan and Jiangsu), the contributions ranged around 0.76%-1.97%, which can be neglected. $PM_{2.5}$

260   emission from grassland in CEC was negligible with the following provinces holding higher contributions: Jiangxi

261   (0.8%), Hunan (0.25%), Fujian (0.11%) and Anhui (0.1%).

262   From Figure 5, emissions from wheat and corn straw burning mainly concentrated in Shandong and Henan

263   (totally accounting for 82% and 78% of the whole emissions, respectively) and the rice straw burning exhibited

264   higher concentrations in Hunan, Jiangxi and Hubei provinces, by 25%, 18% and 16%, respectively. The total

contributions of rapeseed, cotton, potato and peanut straw burning to the $PM_{2.5}$ emission were relatively small, accounting for 21%-24% of the total emissions. Most emissions from cotton, peanut and potato straw burning located in Shandong (totally accounting for 35%, 35% and 20%) and Henan (totally accounting for 19%, 40% and 15%). Hubei (32%) and Hunan (31%) were the major provinces for rapeseed straw burning emissions. In addition, emissions from soya bean, sugar cane, tobacco, sesame and sugar beet straw burning were negligible, which never exceeded 1% of total crop residue burning emission in this study.

3.2 Temporal variation and spatial distribution for OBB emissions in CEC

3.2.1 Yearly variation

Multi-year emissions of OBB from 2003 to 2015 in CEC were shown in Figure 6. The multi-year variation of OBB emissions for various pollutants was similar (Figure 6).

The increase of crops residue burning dominated the significant growth of OBB emission. Pollutants emitted from OBB all increased obviously from 2003 to 2008. Then with the adoption of strict control policies (Table S1 in Supplement), the growth of crops residue burning emission gradually slow down. The forest, shrubland and grassland fire burning were related to weather conditions and human activities. Their emissions were difficult to predict and control and existed random yearly variation. Therefore, we discussed the multi-year variation during 2003-2015 instead of the overall trend for the whole period (Figure S3). Take $PM_{2.5}$ as example, emission exhibited clearly increasing trend from 2003 (256 Gg) to 2008 (353 Gg) and then decreased in the following two years to 322 Gg. After 2010, there existed higher (2011, 2013 and 2015) and lower values (2010, 2012 and 2014) alternately. The values in 2011, 2013 and 2015 all did not exceed the peak values in 2008.

Emissions from forest, shrubland and grassland fire burning have an obvious trend of declining from 2003 to 2006 and rising from 2006 to 2008. Peak emissions for $PM_{2.5}$ from forest, shrubland and grassland fire burning were found in 2008, as 49 Gg, 8.9 Gg and 0.7 Gg, respectively. In 2008, intensive policies for utilization of straw energy (Table S1) and strengthening the forestry fires prevention (Table S2) were published, which effectively limited the emissions from forest and shrubland fire burning as Figure 7a shown. Obvious decreasing was found from 2008 to 2010, down to 19 Gg, 4.8 Gg and 0.24 Gg, respectively. Then they exhibited inter-annual oscillation from 2010 to 2015, with higher emission in 2011, 2013 and 2015 and lower emission in 2012 and 2014 (Jin et al., 2017a). The multi-year tendency for forest, shrubland and grassland fire burning were mainly affected by the variations in climate, management measures and other human forcing. It can also conclude that the yearly fluctuation of pollutants from OBB was mainly impacted by the emission of forest, shrubland and grassland fire burning, but not the crop residue burning.

295   The emission of PM$_{2.5}$ from crop residue burning exhibited quite different yearly variation trend with other

296   three types of biomass burning, which gradually increased from 2003 (228 Gg) to 2015 (323 Gg), by 29%. The

297   increase of crop residue production can primarily explain the increasing of pollutant emission. Meanwhile, as

298   shown in Figure S6 and Table S1, the controlling of pollutants from crop residue burning in China started from

299   1965s. In 2000, the law for prevention of air pollution was published. Then in 2003, the regulations on straw

300   banning and comprehensive utilization were released. In Figure 6, we found that the emission of PM$_{2.5}$ from crop

301   residue burning significantly increased from 2003 (228 Gg) to 2008 (294 Gg), due to the increase of crops

302   production and deficiency of strict control policies in this period (Table S1). Although emissions from forest,

303   shrubland and grassland fire burning fluctuated markedly during this period, the obvious increase of crops residue

304   burning dominated the total growth of OBB emission from 2003 to 2008 as their higher emission amounts. From

305   2008 to 2015, strict policies were developed to improve the straw energy utilization and reduce the air pollution

306   raised by its burning. However, it has to say, the policies may not be well implemented, with the annual averaged

307   increasing amounts of 7.3 Gg for PM$_{2.5}$. From Figure 7b, the large contributions to PM$_{2.5}$ (22%-28% and 29%-33%)

308   and increasing trends for corn straw burning and wheat straw burning could be found, which should be further

309   focused. The contribution of rice straw burning has slightly decreased in research period, by about 19% . Other

310   types of biomass totally accounted for averaged 25% of PM$_{2.5}$ emission and all exhibited slightly increasing trend

311   from 2003 to 2015, by about 21%-29%.

312   Figure 8 showed that the crop residue burning emission in Henan, Shandong, Anhui, Jiangsu, Hubei, Hunan

313   and Jiangxi exhibited obvious increasing trends, which suggested the importance of crop residue burning control in

314   these provinces. For Fujian and Zhejiang, no obvious increase for cropland burning emission was found, implying

315   that the emission has been well controlled in these years. It should be noted that in Fujian and Zhejiang, the main

316   crop is rice. While in other provinces, the main crops are corn and wheat especially for northern provinces. To

317   conclude, pollutants emitted from crop straw burning (wheat, corn and rice) are still now the key sources for air

318   pollution, in view of its increasing emission trend. The randomness of burning activities and corresponding

319   widespread and scattered distribution make it difficult to control them. The wheat and corn emissions at northern

320   provinces and rice burning emissions at southern provinces should be controlled specially in the future.

321   In Figure 8, the PM$_{2.5}$ emission from crop residue burning exhibited higher amounts for Henan and Shandong

322   province in 2015, as 100 Gg and 82 Gg, respectively, which are 200%-1200% times of those for other provinces.

323   As the main source regions for air pollution of Yangtze River Delta (YRD) and Beijing-Tijin-Hebei (BTH) region

324   (Fu et al., 2013; Zhou et al., 2015), the enforced and effective control of crop residue burning in the two provinces

325   at summer and autumn harvest periods are important for improving the air quality of these regions.

326   **3.2.2 Monthly distribution**

327   The monthly $PM_{2.5}$ emission variation of different OBB in CEC was shown in Figure 9a. $PM_{2.5}$ emission held

328 higher amounts in May and June (90.4 Gg-179.3 Gg), followed by December to March of next year (32.2 Gg-127.3

329 Gg) and September-October (8.2 Gg-89.2 Gg), and was lowest during July-August (14.3 Gg-65.9 Gg). As the

330 emission amounts of cropland fire burning was one or two magnitude higher than other three types of biomass

331 burning, the monthly variation of total $PM_{2.5}$ emission was dominantly controlled by the crop residue fire burning

332 (Zhang et al., 2016). The periods with highest $PM_{2.5}$ emissions were the summer and autumn harvest times, when

333 the burning activities are more frequent. The peak of open biomass fire burning occurred in May and June, totally

334 accounted for 42% of the whole $PM_{2.5}$ emission in 2003-2015, which is caused by the harvest and open residue

335 burning of winter wheat, especially in Henan, Shandong, Jiangsu and Anhui (Figure 9b). Large amounts of wheat

336 straw were burned after the harvest to increase the soil fertility and prepare for following corn cultivation (Levine

337 et al., 1995). The small peak of open biomass burning emission in September to October (totally accounted for

338 13.82% of the whole $PM_{2.5}$ emission in 2003-2015) can be attributed to the burning of corn straw after corn harvest.

339 Though the open biomass burning was strictly forbidden in recent years, scattered burning activities still existed in

340 these regions. As shown in Figure S4, the $PM_{2.5}$ emissions in CEC and major agricultural provinces during harvest

341 time have shown a rapid decline in recent years, in accordance with the change tendency of burned area due to

342 increased government management. Considering of the yearly increasing fact of crops straw burning, it is worth

343 noting that fire burning out of harvest season as a way of circumventing governmental polices needs to be well

344 regulated. From December to February, the crop residue burning emission decreased to the lowest level in the

345 whole year (18.9% of the whole $PM_{2.5}$ emission in 2003-2015). However, the emissions of $PM_{2.5}$ from forest,

346 shrubland and grassland burning achieved peak values from December to March, being 67% of that in 2003-2015.

347   Figure 10 clearly listed the monthly average emissions of $PM_{2.5}$ from OBB in different provinces. These

348 provinces were classified based on the correlation between their monthly emissions of 2003-2015. Henan,

349 Shandong, Anhui and Jiangsu provinces (R^2 higher than 0.92, P<0.01), as one of the largest and contiguous wheat

350 planting areas in China (Fang et al., 2014), have two crop rotations. The highest monthly emissions were observed

351 for winter wheat harvesting (sown in October and harvested from May to June) and corn harvesting (sown in

352 middle June and harvested from September to October). A large proportion of crop straw were always burnt

353 directly after the crop harvest (MEPC, 2015). For Hubei province, agricultural emissions fluctuated over the period

354 from February to October with several peaks due to that different crop species matured in succession. In Jiangxi,

355 Fujian and Hunan (R^2 higher than 0.9, P<0.01), the largest monthly emissions were observed with forest and

356 shrubland fire burning during the time between December and March, which is the dry season in these provinces

357 (Li et al., 2014; Li et al., 2015). While in other months, the emissions were limited. For Shanghai and Zhejiang (R^2

358 = 0.7, P<0.01), lowest levels of $PM_{2.5}$ emission were found, with peak values occurring in summer and autumn

359 harvest periods. Obvious two peaks were found for April-May and July-August periods, which may reflect the rice

360 harvesting at these times. To sum up, the regional differences of monthly $PM_{2.5}$ emissions from OBB were mainly

361 caused by the different biomass burning types and times as well as corresponding environmental conditions.

362 **3.2.3 Spatial distribution within 1 km×1 km of $PM_{2.5}$ emitted from OBB in CEC**

363 The spatial distribution of $PM_{2.5}$ emitted from OBB within 1 km×1 km resolution was mapped based on the

364 burned area and a high-resolution vegetation map (1:1 000000) in CEC. The multi-year averaged spatial

365 distributions of $PM_{2.5}$ emission were shown in Figure 11. It can be found that the OBB was widespread and

366 scattered. The average emissions intensity of $PM_{2.5}$ ranged from 0 to 15 tons per pixel in most provinces. The

367 variation range is mainly caused by the social-economic development level, rural population and agricultural

368 activities. The highest value in different provinces was all mainly raised by the cropland fire burning due to the

369 centralized burning in a relatively small area. Some pixels with high emissions exceeding more than 100 tons each

370 year were found in Henan, Shandong and Hunan. It can be attributed to the large amounts of crop straws in these

371 provinces. The pixels of high emission intensity more than 70 tons from crop straw burning were also found in

372 Hubei, Jiangsu and Anhui. For forest and shrubland fire burning, the high emission points (more than 30 tons per

373 pixel) were found in Fujian and Jiangxi. Lower emission intensities in Zhejiang (lower than 10 tons per pixel on

374 average) and Shanghai (lower than 7 tons on average) were mainly due to the highly developed economy and

375 limited agricultural activities (Su et al., 2012). In addition, northern Anhui and eastern Jiangsu featured high

376 emissions of OBB with a relatively lower intensity (lower than 15 tons per pixel on average), which may be due to

377 that the crop straw were burned in a large area in these regions.

378 Though the emission intensities varied in the past ten years, the areas with high emission amounts remain

379 similar. They were mainly located in the main agricultural areas in eastern Henan, southern Shandong, northern

380 Anhui, northern Jiangsu, eastern Hubei and northern Hunan. This result is in accordance with formers (Huang, et

381 al., 2012b). The junction regions of the four provinces (Henan, Shandong, Anhui and Jiangsu) should be paid more

382 attention, where the pollutants emission from OBB jointed together. This was similar to a recent research (Jin et al.,

383 2017b). This region belongs to HuangHuai Plain, with large area of cropland and low economic development levels.

384 The open burning activities and corresponding banning policies are both abundant in village scale. The game of

385 "cat and mouse" is frequently acted. More effective policies for guiding or helping farmers to utilize straw energy

386 rather than banning crop residue burning arbitrarily should be considered sincerely. In Zhejiang and Shanghai, OBB

387 emissions are sparsely scattered, due to the relatively developed economic level, scarce biomass sources and

388 limited agricultural activities. The recycling of crop straw faces many difficulties due in part to its high cost and the

389 relative low price of crop straw. Improving policies for effectively utilizing crop residue straw is also an important

390 challenge for the government.

391 Figure 12 highlights the spatial distribution of $PM_{2.5}$ emitted from OBB in different seasons of 2015.

392 Emissions were more concentrated in summer, followed by winter. In summer, the emission was concentrated in

393 the connection regions of Henan, Shandong, Anhui and Jiangsu, which is mainly raised by the crop residue burning

394 as discussed before. In winter, Jiangxi, Hunan and Fujian showed the higher emission intensities from forest and

395 shrubland burning.

3.3 The impact of social-economic factors on OBB emission

397 Emissions from OBB were found to be in line with the local burning habit, social customs, rural population,

398 local economic level, agricultural level and pollution controlling policies. Local burning habits have a great

399 influence on different types of OBB emissions. According to our survey, in agricultural provinces, such as Henan,

400 Shandong, Jiangsu and Anhui, people always burn crop straws in sowing and harvest seasons. Despite the strict

401 implementation of crop residue burning management policies, the burning habit is difficult to change in a short

402 time. Less crop residue production and crop burning activities are found in Jiangxi and Fujian, where people are

403 accustomed to use crop straw to feed draught animals and produce biogas instead of open burning directly.

404 Emission from crop residue burning is low. However, due to the rich forest and shrubland resources, wood is served

405 as the staple household fuel, which mainly comes from felling trees or collecting branches. These human activities

406 can lead to an increase of forest and shrubland fire burning, resulting in the elevated levels of corresponding

407 emission in these provinces.

408 Social customs also pose impact on OBB emissions. Biomass burning emissions in April can be enhanced by

409 human burning activities in the tomb-sweeping day. The tomb-sweeping day (often in April 4 or April 5) is a time

410 to memorize the death. People sweep graves and burn sacrifices by ignited straw, which can easily cause grass,

411 shrub and forest fires (Qiu et al., 2016). The fire points at the tomb-sweeping day in CEC occupied by 22%-38% of

412 the whole fire points in April in some years (Figure S5). The Chinese government has also introduced policies to

413 prevent forest, shrubland and grassland fires on tomb-sweeping day (Table S2). The wildfires caused by biomass

414 burning from late January to early February are partially related to the firework burning in the Spring Festival (Zuo,

415 2004). The firework burning activities for celebration and official sacrifices to ancestors in the Spring Festival

416 easily lead to grass, shrub and forest fires. All these activities can affect the emission levels and air quality in a

417 short time scale.

418   In order to understand the impact of the rural population, local economic level and agricultural level,

419 correlation analysis between $PM_{2.5}$ emissions from OBB and statistics data (rural population, per capita net income

420 of rural residents, agricultural output (crop straw burning) and forestry output (forest, shrubland and grassland

421 burning) in different provinces were conducted. Significant positive correlations were found between the rural

422 population, agricultural output and the $PM_{2.5}$ emissions from crops straw burning (R^2 higher than 0.58, P<0.01) for

423 the whole CEC (Figure 13a). According to our survey, the high rural population and agricultural output indicate that

424 agricultural activities are quite important in a certain region. With more crops residue produced, it can easily cause

425 high emissions from cropland fire burning. No significant correlations were found for $PM_{2.5}$ emission from crop

426 straw burning with the income of rural residents (Figure 15), which indicates that the rural economic level in

427 different regions in CEC have no relationship with the $PM_{2.5}$ emission. Then we calculated the correlations between

428 the change tendency of $PM_{2.5}$ emission from crops fire burning and the multi-year variation of other three

429 social-economic factors as Table 7 shown for different provinces. Significant positive correlations were found for

430 $PM_{2.5}$ emission with per capita income of rural residents and agricultural output (most R^2 higher than 0.59, P<0.01)

431 and negative correlation were found for $PM_{2.5}$ emission with rural population (most R^2 higher than 0.73, P<0.01)

432 except for the provinces of Shanghai, Zhejiang and Fujian, which are underdeveloped agricultural provinces. From

433 2003 to 2015, with the increase of agricultural outputs, more crop residue was produced. However, rapid economic

434 development and less rural population in each province lead to the popular of commercial energy and clean energy

435 in rural area. It decreased the demands in using crop residue as fuel. As a consequence, more crop residues were

436 directly burned in the agricultural field. But it was not suitable for Shanghai, Zhejiang and Fujian (most R^2 lower

437 than 0.19, P>0.05), which holds less crop residue production and high utilization efficiency of crop straws.

438   Positive correlations were also found between forestry output and $PM_{2.5}$ emission from forestland, shrubland

439 and grassland fire burning (R^2 =0.14, P<0.01) in the whole CEC (Figure 13b), which indicated that human forestry

440 activities played positive role on open fire burning (Yan et al., 2006). According to our survey, human forest

441 activities such as felling trees or picking up branches from trees can easily cause more forest and shrubland burning.

442 However, compared with the crops straw burning, no correlation was found between $PM_{2.5}$ emission and other

443 statistics data (the rural population and the per capita net income of rural residents) (Figure 13b and Table S4). It

444 may indicate that the forestry fire burning activities were not predominantly associated with the rural human living

activity. According to previous studies, forestry fire burning was affected by environmental conditions and human activities with environmental factors having a larger impact (Chen et al., 2013).

3.4 Comparison with others

Emission data from OBB in CEC during the past several years have been compared with other studies for the similar year (Table 8). Compared with the emissions derived from Wang et al. (2008) based on statistical data, the differences of OC, EC, CH_4, NO_x, NMVOCs, NH_3, CO_2 and CO emissions ranged from -41% to 12%. For SO_2 (121%) and $PM_{2.5}$ (288%) emission, the differences were relative high. All these differences were mainly caused by the selection of EFs. The EFs employed in Wang et al.(2008) were constant values for different biomass species. In addition, the crop residue to production ratio data and the burned ratio for various crop types were all specific to CEC in this study based on literatures and survey results, which increased the reliable of these data. Similarly, Huang et al. (2012) used the same EF_S of different crops straw burning for emission calculation. Compared with Wang et al. (2008) and Huang et al. (2012),,the estimate in our study is believed to be more accuracy. An obvious underestimation of $PM_{2.5}$ emission from crop straw burning were found in Jin et al. (2017), in which not all the crop species were considered.

The estimation based on satellite observation was prevalent recently. Compared to Zhou et al. (2017) who estimated the pollutant emission amounts from MODIS burned area product, the results in this study were much higher. The reason may be that when using a single satellite data set, pollutant emission can be underestimated due to that some actual fire activities could not be detected (van der Werf et al., 2010). The lower emission of CO_2, NMVOCs, SO_2 and NO_x in our study is due to the adoption of more accurate and suitable EFs values as those in a previous study (Tang et al, 2014). Our emission estimation of the pollutants is more similar to the results of Qiu et al. (2016), who also used multiple satellite products (MCD14 ML and MCD64Al) to estimate the OBB emissions of China in 2013, with the differences of the two studies ranging from -42% to 22%. For CH_4, NO_x, NMVOCs, NH_3 and CO_2, the differences were less than 10%. The reason for the differences is due to the use of updated local biomass data and EFs in this study. Therefore, the combination of multiple satellite products with local EFs data and updated local biomass data (updated forest loading data, the crop residue to production ratio data and the burned ratio for various crop types) are likely to have improved the estimation of pollutant emission from OBB effectively.

3.5 Uncertainty analysis

Emission uncertainties in this study were associated with the satellite fire products, biomass fuel loading data, combustion efficiency and emission factors. It is difficult to assess the uncertainty of the satellite-derived data for

475 burned land area (Hoelzemann et al., 2004, Chang et al., 2010). The estimation of fire burned area were proved to

476 be reliable by using the burned area product MCD64AL (Giglio et al., 2013) and active fire product MCD14ML

477 (Randerson et al., 2012). Although some active fires which burned out at 10:30 am-1:30 pm each day could not be

478 captured by MCD14ML, the burned area used in this study were more reliable due to the combination of multiple

479 satellite dataset (MCD64AL and MCD14ML). The uncertainties in this study were mainly caused by biomass

480 loading data, combustion efficiency and emission factors. These data were assumed to be normal distributions

481 (Zhao et al., 2011). The uncertainty of biomass loading data and combustion efficiency was estimated to be

482 approximately 50% (Shi et al., 2015) and the uncertainty of EFs of each pollutant mainly ranged from 0.03 to 0.85

483 (Table S5). The reliable of emission factors played the most important role in driving uncertainty. Considering all

484 these parameters, 20,000 Monte Carlo simulations were performed to evaluate the estimation uncertainty

485 quantitatively for pollutant emissions with 95% coincidence level. Table 9 showed the emission uncertainty for

486 different pollutants from 2003-2015. On average, the uncertainty of the estimated OC, EC, CH_4, NO_x, NMVOCs,

487 CO, SO_2, NH_3, CO_2 and $PM_{2.5}$ were (-30%, 30%), (-48%, 48%), (-20%, 20%), (-20%, 20%), (-45%, 45%), (-18%,

488 18%), (-45%, 45%), (-35%, 35%), (-3%, 3%) and (-36%, 36%), respectively.

489   Compared with previous studies, the uncertainty was improved in our study due to the datasets used here were

490 better and more suitable. The reliable multiple satellites could better obtain burned area data. The local EFs data,

491 updated forest loading data, the adoption of local crop residue to production ratio data and the crop residue burned

492 ratio data based on survey results improved the emission estimation of forestry and cropland burning as they could

493 better reflect the actual situation in this region. Compared with the constant combustion efficiency in previous

494 researches, the activity combustion efficiency data could also reduce the uncertainty as they could more accurately

495 reflect the actual combustion conditions (Chen et al., 2013) Therefore, due to the adoption of multiple satellite

496 products, updated local biomass data and local emission factors, the uncertainty ranges of different pollutant

497 emissions were narrowed and reliable in this study, which could better reflect the real emission.

498 **4 Conclusions**

499   In this study, a combination of the burned area product (MCD64Al) with the active fire product (MCD14 ML),

500 as well as local high resolution vegetation speciation data, updated local biomass data, local emission factors and

501 survey results were used to estimate the pollutant emissions from open burning in Central and Eastern China (CEC)

502 from 2003 to 2015. The emission from crop residue, forest, shrubland and grassland fire burning were considered.

503   Crop residue burning was the major source type for pollutant emissions, followed by forest and shrubland fire

504 burning. The grassland fire burning emissions were negligible in CEC. For cropland, the fire burning was mainly

concentrated in agricultural provinces, such as Henan and Shandong. For forest and shrubland, the fire burning was mainly concentrated in Fujian, Jiangxi and Hunan provinces, with abundant forest resources. Wheat, corn and rice straw were the major three types of crop straws for pollutant emission. Wheat and corn straw burning dominated in Shangdong and Henan and the rice straw burning dominated in Hunan, Jiangxi and Hubei provinces. For various pollutant emissions, corn straw burning was the largest contributor to SO_2, NO_x, CO, NMVOCs, CO_2, NH_3. OC, EC and CH_4 emission was mainly produced by rice straw burning. Wheat straw burning was the largest contributor to $PM_{2.5}$. The spatial distribution of open biomass residue burning in different years was similar. The high emissions were mainly found in the major agricultural areas in eastern Henan, southern Shandong, northern Anhui, northern Jiangsu, eastern Hubei and northern Hunan, due to their abundant agricultural cultivated areas and low straw utilization efficiency.

From 2003 to 2015, the multi-year tendency of opening biomass residue burning emission for various pollutants was similar. Emissions from crop straw burning continued to increase, due to the gradual increase of crop residue production. While emissions from forest, shrubland and grassland fire burning exhibited yearly fluctuations, which was mainly influenced by the environmental conditions, management measures and other human driving factors. Monthly distributions revealed that the pollutant emissions were at the highest levels in May and June, with the lowest emissions in July and August. The high emissions in May, June and October were mainly caused by crop straw burning in sowing and harvest times. It is worth noting that the fire burning activities at harvest season need to be regulated continuously by local governments and emissions from forest and shrubland burning accounted for the vast majority of total emissions in December to March should also be paid attention. The emission of crop residue burning was associated with the rural population, agricultural output and economic levels while the environmental conditions play an important role in the emissions from forestland, shrubland and grassland fire burning.

The estimation of mulit-year open biomass burning emissions by satellite data in this study will provide an objective and creditable evidences for assessing the role of pollution prevention policies on open burning activities issued in the last decade. The high-spatial (1×1 km) resolution emission inventory in month scale is also useful in modeling regional air quality and human health risks in the future.

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539 **References**

540 Akagi, S. K., Yokelson, R. J., Wiedinmyer, C., Alvarado, M. J., Reid, J. S., Karl, T., Crounse, J. D. and Wennberg, P.

541   O.: Emission factors for open and domestic biomass burning for use in atmospheric models, Atmos. Chem.

542   Phys., 11(9), 4039-4072, doi:10.5194/acp-11-4039-2011, 2011.

543 Andreae, M. O. and Rosenfeld, D.: Aerosol-cloud precipitation interactions. Part 1, The nature and sources of

544   cloud-active aerosols, Earth Sci. Rev., 89, 13–41, doi:10.1016/j.earscirev.2008.03.001, 2008.

545 Andela, N., Schultz, M., Van, der W., Van Leeuwen, T. T., Kaiser, J. W., Wooster, M. J., Heil, A. and Remy, S.:

546   Assessment of the Global Fire Assimilation System (GFASv1), MACC-II Deliverable D_31.2, 2013.

547 Andreae, M. O. and Merlet, P: Emission of trace gases and aerosols from biomass burning, Global Biogeochem.

548   Cy., 15(4), 955-966, 2001.

549 Ao, H. J., Zou, Y. B., Shen, J. B., Peng, S. B., Tang, Q. Y. and Feng, Y. h.: Effects of fertilizer-N application for

550   double early rice on the yield, nitrogen use efficiency and soil nitrogen content of double rice, Plant Nutr. Fert.

551   Sci., 13(5), 772-780, 2007 (in Chinese).

552 Aragao, L. E. O. C. and Shimabukuro, Y. E.: The Incidence of Fire in Amazonian Forests with Implications for

553   REDD, Science, 328(5983), 1275-1278, doi:10.1126/science.1186925, 2010.

554 Arino, O., Casadio, S. and Serpe, D.: Global night-time fire season timing and fire count trends using the ATSR

555   instrument series, Remote. Sens. Environ., 116, 226-238, doi:10.1016/j.rse.2011.05.025, 2012.

556 Bond, T. C.: A technology-based global inventory of black and organic carbon emissions from combustion, J.

557   Geophys. Res., 109(D14), doi:10.1029/2003JD003697, 2004.

558 Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S.,

559   Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M.,

560   Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S. K., Hopke, P. K., Jacobson, M. Z.,

561   Kaiser, J. W., Klimont, Z., Lohmann, U., Schwarz, J. P., Shindell, D., Storelvmo, T., Warren, S. G. and Zender,

562   C. S.: Bounding the role of black carbon in the climate system: A scientific assessment: black carbon in the

563   climate system, J. Geophys. Res. Atmos., 118 (11), 5380-5552, doi:10.1002/jgrd.50171, 2013.

564 Bowman, D. M. J. S., Balch, J., Artaxo, P., Bond, W. J., Cochrane, M. A., D'Antonio, C. M., DeFries, R., Johnston,

565   F. H., Keeley, J. E., Krawchuk, M. A., Kull, C. A., Mack, M., Moritz, M. A., Pyne, S., Roos, C. I., Scott, A. C.,

566   Sodhi, N. S. and Swetnam, T. W.: The human dimension of fire regimes on Earth: The human dimension of

567   fire regimes on Earth, J. Biogeogr., 38 (12), 2223-2236, doi:10.1111/j.1365-2699.2011.02595.x, 2011.

568 Burling, I. R., Yokelson, R. J., Griffith, D. W. T., Johnson, T. J., Veres, P., Roberts, J. M., Warneke, C., Urbanski, S.

569   P., Reardon, J., Weise, D. R., Hao, W. M. and de Gouw, J.: Laboratory measurements of trace gas emissions

570   from biomass burning of fuel types from the southeastern and southwestern United States, Atmos. Chem.

571   Phys., 10(22), 11115-11130, doi:10.5194/acp-10-11115-2010, 2010.

572 Cao, G. L., Zhang, X. Y., Wang, D. and Deng, F. C.: Inventory of Atmospheric Pollutants Discharged from Biomass

573   Burning in China Continent, China Environ. Sci., 25, 389-393, 2005 (in Chinese).

574 Cao, G. L., Zhang, X. Y., Gong, S. L. and Zheng, F. C.: Investigation on emission factors of particulate matter and

575   gaseous pollutants from crop residue burning, J. Environ. Sci., 20 (1), 50-55, 2008.

576 Chang, D. and Song, Y.: Estimates of biomass burning emissions in tropical Asia based on satellite-derived data,

577   Atmos. Chem. Phys., 10(5), 2335-2351, doi:10.5194/acp-10-2335-2010, 2010.

578 Chang, D., Song, Y. and Liu, B.: Visibility trends in six megacities in China 1973-2007, Atmos. Res., 94(2),

579   161-167, doi:10.1016/j.atmosres.2009.05.006, 2009.

580 Chen, C., Wang, H., Zhang, W., Hu, D., Chen, L. and Wang, X.: High-resolution inventory of mercury emissions

581   from biomass burning in China for 2000-2010 and a projection for 2020: Mercury emission from biomass

582   burning, J. Geophys. Res. Atmos., 118(21), 12, 248-12, 256, doi: 10.1002/2013JD019734, 2013.

583 Chen, C. L., Yang, Y. and Xie, G. H.: Study of the development of crop straw management policy in China, J.

584   China Agric. Univ., 21, 1-11, 2016 (in Chinese).

585 Chen, H. F., Lin, R. Y., Liang, Y. Y., Zheng, L. D., Liang, K. J. and Lin, W. X.: Dry-matter accumulation and

586   transportation in first-rice crop of early rice-ratoon rice under different cultivation patterns, Chin. J. Eco.

587   Agric., 16(1), 129-133, 2008 (in Chinese).

588 Cheng, Z., Wang, S., Fu, X., Watson, J. G., Jiang, J., Fu, Q., Chen, C., Xu, B., Yu, J., Chow, J. C. and Hao, J.:

589   Impact of biomass burning on haze pollution in the Yangtze River delta, China: a case study in summer 2011,

590   Atmos. Chem. Phys., 14(9), 4573-4585, doi:10.5194/acp-14-4573-2014, 2014.

591 Chuvieco, E., Giglio, L. and Justice, C.: Global characterization of fire activity: toward defining fire regimes from

592   Earth observation data, Global Change Biol, 14(7), 1488-1502, doi:10.1111/j.1365-2486.2008.01585.x, 2008.

593 Cooke, W. F., Koffi, B. and Grégoire, J. M.: Seasonality of vegetation fires in Africa from remote sensing data and

594   application to a global chemistry model, J. Geophys. Res. Atmos., 101(D15), 21051-21066, 1996.

595   Crutzen, P. J. and Andreae, M. O.: Biomass burning in the tropics: impact on atmospheric chemistry and

596   biogeochemical cycles, Science, 250, 1669-1678, 1990.

597   Crutzen, P. J., Heidt, L. E., Krasnec, J. P., Pollock, W. H. and Seiler, W.: Biomass burning as a source of

598   atmospheric gases CO, H_2, N_2O, NO, CH_3Cl and COS, Nature, 282, 253–256, doi:10.1038/282253a0, 1979.

599   Deng, C. R.: Identification of biomass burning source in aerosols and the formation mechanism of haze, PhD

600   dissertation, Fudan University, Shanghai, 2011 (in Chinese).

601   Duncan, B. N.: Interannual and seasonal variability of biomass burning emissions constrained by satellite

602   observations, J. Geophys. Res., 108(D2), doi:10.1029/2002JD002378, 2003.

603   EPD: Guide for compiling atmospheric pollutant emission inventory for biomass burning, Environmental

604   Protection Department, available at: http://www.zhb.gov.cn/gkml/hbb/bgg/201501/t20150107_293955.htm,

605   2014 (in Chinese).

606   Fang, J. Y., Liu, G. H. and Xu, S. L.: Biomass and net production of forest vegetation in China, Acta. Eco. Sin.,

607   16(5), 497-508, 1996 (in Chinese).

608   Fang, S., Qi, Y., Han, G., Zhou, G. and Cammarano, D.: Meteorological drought trend in winter and spring from

609   1961 to 2010 and its possible impacts on wheat in wheat planting area of China, Sci. Agric. Sin., 47(9),

610   1754-1763, 2014 (in Chinese).

611   Freitas, S. R., Longo, K. M., Dias, M. A. F. S., Dias, P. L. S., Chatfield, R., Prins, E., Artaxo, P., Grell, G. A. and

612   Recuero, F. S.: Monitoring the transport of biomass burning emissions in South America, Environ. Fluid.

613   Mech., 5(1-2), 135-167, 2005.

614   Fu, X., Wang, S., Zhao, B., Xing, J., Cheng, Z., Liu, H. and Hao, J.: Emission inventory of primary pollutants and

615   chemical speciation in 2010 for the Yangtze River Delta region, China, Atmos. Environ., 70, 39-50,

616   doi:10.1016/j.atmosenv.2012.12.034, 2013.

617   Gadde, B., Bonnet, S., Menke, C. and Garivait, S.: Air pollutant emissions from rice straw open field burning in

618   India, Thailand and the Philippines, Environ. Pollut., 157(5), 1554-1558, doi:10.1016/j.envpol.2009.01.004,

619   2009.

620   Giglio, L., Csiszar, I. and Justice, C. O.: Global distribution and seasonality of active fires as observed with the

621   Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) sensors: Global fire distribution

622   and seasonality, J. Geophys. Res. Biogeo., 111(G2), doi:10.1029/2005JG000142, 2006.

623   Giglio, L., Randerson, J. T. and van der Werf, G. R.: Analysis of daily, monthly, and annual burned area using the

624   fourth-generation global fire emissions database (GFED4): ANALYSIS OF BURNED AREA, J. Geophys. Res.

625   Biogeo., 118(1), 317-328, doi:10.1002/jgrg.20042, 2013.

626   He, M., Wang, X. R., Han, L., Feng, X. Q. and Mao, X.: Emission Inventory of Crop Residues Field Burning and

627   Its Temporal and Spatial Distribution in Sichuan Province, Environ. Sci., 36, 1208-1216, 2015 (in Chinese).

628   He, M., Zheng, J., Yin, S. S. and Zhang, Y.: Trends, Temporal and spatial characteristics, and uncertainties in

629   biomass burning emissions in the Pearl River Delta, China, Atmos. Environ., 45(24), 4051-4059, 2011.

630   Hoelzemann, J. J., Schultz, M. G., Brasseur, G. P., Granier, C. and Simon, M.: Global Wildland Fire Emission

631   Model (GWEM): Evaluating the use of global area burnt satellite data, J. Geophys. Res. Atmos., 109, D14S04

632   doi:10.1029/2003JD003666, 2004.

633   Hu, H. F., Wang, Z. H., Liu, G. H. and Fu, B. J.: Vegetation carbon storage of major shrublands in China, Chin. J.

634   Plant Ecol., 30, 539–544, 2006 (in Chinese).

635   Huang, X., Li, M., Friedli, H. R., Song, Y., Chang, D. and Zhu, L.: Mercury Emissions from Biomass Burning in

636   China, Environ. Sci. Technol., 45(21), 9442-9448, doi: 10.1021/es202224e, 2011.

637   Huang, X., Li, M., Li, J. and Song, Y.: A high-resolution emission inventory of crop burning in fields in China

638   based   on   MODIS   Thermal   Anomalies/Fire   products,   Atmos.   Environ.,   50,   9-15,

639   doi:10.1016/j.atmosenv.2012.01.017, 2012a.

640   Huang, X., Song, Y., Li, M., Li, J. and Zhu, T.: Harvest season, high polluted season in East China, Environ. Res.

641   Lett., 7(4), 044033, doi:10.1088/1748-9326/7/4/044033, 2012b.

642   Hugh, E. and Eric F, L.: Remote sensing of biomass burning in tropical regions: Sampling issues and multisensor

643   approach, 1998.

644   Ito, A.: Global estimates of biomass burning emissions based on satellite imagery for the year 2000, J. Geophys.

645   Res., 109(D14), doi: 10.1029/2003JD004423, 2004.

646   Ito, A. and Akimoto, H.: Seasonal and interannual variations in CO and BC emissions from OBB in Southern

647   Africa   during   1998-2005:   seasonal   CO/BC   emissions,   Global   Biogeochem.   Cy.,   21(2),   doi:

648   10.1029/2006GB002848, 2007.

649   Jin, Q. F., Ma, X. Q., A., Wang, W. H., Yang, S. Y. and Guo, F. T.: Temporal and spatial dynamics of pollutants

650   emission from forest fires in Fujian during 2000-2010, China Environ. Sci., 37, 476-485, 2017a (in Chinese).

651   Jin, Q. F., Ma, X. Q., A., Wang, W. H., Yang, S. Y. and Guo, F. T.: Temporal and spatial variations of $PM_{2.5}$

652   emissions from crop straw burning in eastern China during 2000—2014, Acta. Sci. Circum., 37, 460-468,

653   2017b (in Chinese).

654   Kaiser, J. W., Benedetti, A., Detmers, R., Heil, A., Morcrette, J. J., Schultz, M. G., Van,   der W., Wooster, M. J.

655   and Xu, W.: Assimilation of FRP observations for global fire emission estimation in MACC-II, in EGU

656   general assembly conference, p. 10521., 2012a.

657 Kaiser, J. W., Heil, A., Andreae, M. O., Benedetti, A., Chubarova, N., Jones, L., Morcrette, J.-J., Razinger, M.,

658   Schultz, M. G., Suttie, M. and van der Werf, G. R.: Biomass burning emissions estimated with a global fire

659   assimilation system based on observed fire radiative power, Biogeosciences, 9(1), 527-554,

660   doi:10.5194/bg-9-527-2012, 2012b.

661 Klimont, Z. and Streets, D.: Emission inventories and projections for assessing hemispheric or intercontinental

662   transport, Hemispheric Transport of Air Pollution, 2007.

663 Kondo, Y., Matsui, H., Moteki, N., Sahu, L., Takegawa, N., Kajino, M., Zhao, Y., Cubison, M. J., Jimenez, J. L.,

664   Vay, S., Diskin, G. S., Anderson, B., Wisthaler, A., Mikoviny, T., Fuelberg, H. E., Blake, D. R., Huey, G.,

665   Weinheimer, A. J., Knapp, D. J. and Brune, W. H.: Emissions of black carbon, organic, and inorganic aerosols

666   from biomass burning in North America and Asia in 2008, J. Geophys. Res. Atmos., 116(D8),

667   doi:10.1029/2010JD015152, 2011.

668 Koopmans, A. and Koppejan, J.: Agricultural and Forest Residues-Generation, Utilization and Availability, 6, 1997.

669 Laris, P. S.: Spatiotemporal problems with detecting and mapping mosaic fire regimes with coarse-resolution

670   satellite data in savanna environments, Remote. Sens. Environ., 99(4), 412-424, doi:10.1016/j.rse.2005.09.012,

671   2005.

672 Lei, E., Tang, Q. Y., Luo, H. B. and Chen, L. J.: Comparison of late maturing spring maize varieties in paddy field

673   and its correlation analysis, Crop. Res., 23(1), 24-29, 2009 (in Chinese).

674 Levine, J. S., Iii, W. R. C., Jr, D. R. C. and Winstead, E. L.: A driver for global change, Environ. Sci. Technol.,

675   1995.

676 Li, C., Hu, Y., Zhang, F., Chen, J., Ma, Z., Ye, X., Yang, X., Wang, L., Tang, X., Zhang, R., Mu, M., Wang, G., Kan,

677   H., Wang, X. and Mellouki, A.: Multi-pollutant emissions from the burning of major agricultural residues in

678   China and the related health-economic effects, Atmos. Chem. Phys., 17(8), 4957-4988,

679   doi:10.5194/acp-17-4957-2017, 2017.

680 Li, H. K., Lei, Y. C. and Zeng, W. S.: Forest carbon storage in China estimated using forestry inventory data, Sci.

681   Silv. Sin., 47, 7-12, 2011 (in Chinese).

682 Li, J., Li, Y., Bo, Y. and Xie, S.: High-resolution historical emission inventories of crop residue burning in fields in

683   China for the period 1990-2013, Atmos. Environ., 138, 152-161, doi:10.1016/j.atmosenv.2016.05.002, 2016.

684 Li, L., Liu, W. D., Zou, D. S. and Liu, F.: The correlation between main characteristics and pod yield in peanut

685   genotypes under natural waterlogging stress, Chin. J. Oil Crop Sci., 30(1), 62-70, 2008 (in Chinese).

686   Li, S. M., Yang C. Q., Wang, H. N. and Ge, L. Q.: Carbon storage of forest stands in Shandong Province estimated

687   by forestry inventory data, Chin. J. Appl. Ecol., 25(8), 2215–2220, 2014 (in Chinese).

688   Li, X. H., Wang, S. X., Duan, L., Hao, J., Li, C., Chen, Y. S. and Yang, L.: Particulate and trace gas emissions from

689   open burning of wheat straw and corn stover in China, Environ. Sci. Technol., 41, 6052–6058, doi:

690   10.1021/es0705137, 2007.

691   Li, Y. P., Wang, J. S., Li Y. H., Wang, S. P. and Sha, S.: Study of the sustainability of droughts in China, Journal of

692   Glaciology and Geocryology, 36, 1131-1142, 2014 (in Chinese).

693   Li, W. J., ZUO J. Q., Song, Y. L., Liu, J. P., LI,   Y., Shen, Y. Y.. and Li, J. X.: Changes in spatio-temporal

694   distribution of drought/flood disaster in Southern China under global climate warming, Meteor, Mon., 3,

695   261-271, 2015 (in Chinese).

696   Lin, H. W., Jin, Y. F., Giglio, L., Foley, J. A. and Randerson, J. T.: Evaluating greenhouse gas emissions inventories

697   for agricultural burning using satellite observations of active fires, Ecol. Appl., 22(4), 1345-1364, 2012.

698   Liousse, C., Devaux, C., Dulac, F. and Cachier, H.: Aging of savanna biomass burning aerosols: Consequences on

699   their optical properties, J. Atmos. Chem., 22(1-2), 1-17, 1995.

700   Liousse, C., Guillaume, B., Grégoire, J. M., Mallet, M., Galy, C., Pont, V., Akpo, A., Bedou, M., Castéra, P.,

701   Dungall, L., Gardrat, E., Granier, C., Konaré, A., Malavelle, F., Mariscal, A., Mieville, A., Rosset, R., Serça,

702   D., Solmon, F., Tummon, F., Assamoi, E., Yoboué, V. and Van Velthoven, P.: Updated African biomass burning

703   emission inventories in the framework of the AMMA-IDAF program, with an evaluation of combustion

704   aerosols, Atmos. Chem. Phys., 10(19), 9631-9646, doi:10.5194/acp-10-9631-2010, 2010.

705   Liu, D. M., Liu, Q., Rong, X. M., Peng, J. W., Xie, G. X., Zhang, Y. P. and Song, H. X.: Influences of

706   photosynthesis and dry matter accumulation of different oilseed rape cultivars on nitrogen use efficiency,

707   Hunan Agric. Sci., 34(9), 29-31, 2010 (in Chinese).

708   Liu, M., Song, Y., Yao, H., Kang, Y., Li, M., Huang, X. and Hu, M.: Estimating emissions from agricultural fires in

709   the North China Plain based on MODIS fire radiative power, Atmos. Environ., 112, 326-334,

710   doi:10.1016/j.atmosenv.2015.04.058, 2015.

711   Lu, J. L., Liang, S. L. and Liu, J.: Study on estimation of forest biomass and carbon storage of Shanxi Province,

712   Chin. Agric. Sci. Bull., (31), 51–56, 2012.

713   McCarty, J. L., Korontzi, S., Justice, C. O. and Loboda, T.: The spatial and temporal distribution of crop residue

714   burning   in   the   contiguous   United   States,   Sci.   Total.   Environ.,   407(21),   5701-5712,

715   doi:10.1016/j.scitotenv.2009.07.009, 2009.

716   MEPC: Ministry of Environmental Protection of China, Crop residue burning report, available at:

717   http://www.zhb.gov.cn/, 2015 (in Chinese).

718   NBSC (National Bureau of Statistics of China): China Statistical Yearbook 2004-2016, China Statistics Press,

719   Beijing, available at: http://www.stats.gov.cn/tjsj/ndsj/, 2003-2015 (in Chinese).

720   Prins, E. M. and Menzel, W. P.: Geostationary satellite detection of bio mass burning in South America, Int. J.

721   Remote. Sens., 13(15), 2783-2799, 1992.

722   Pu, S. L., Fang, J. Y., He, J. S. and Xiao, Y.: Spatial distribution of grassland biomass in China, Acta. Phyt. Sci.,

723   28(4), 491-498, 2004 (in Chinese).

724   Qiu, X., Duan, L., Chai, F., Wang, S., Yu, Q. and Wang, S.: Deriving high-resolution emission inventory of OBB in

725   China   based   on   satellite   observations,   Environ.   Sci.   Technol.,   50(21),   11779-11786,

726   doi:10.1021/acs.est.6b02705, 2016.

727   Randerson, J. T., Chen, Y., van der Werf, G. R., Rogers, B. M. and Morton, D. C.: Global burned area and biomass

728   burning emissions from small fires: burned area from small fires, J. Geophys. Res. Biogeo., 117(G4), n/a-n/a,

729   doi:10.1029/2012JG002128, 2012.

730   Reid, J. S., Hyer, E. J., Prins, E. M., Westphal, D. L., Zhang, J., Wang, J., Christopher, S. A., Curtis, C. A., Schmidt,

731   C. C., Eleuterio, D. P., Richardson, K. A. and Hoffman, J. P.: Global monitoring and forecasting of

732   biomass-burning smoke: Description of and lessons from the fire locating and modeling of burning emissions

733   (FLAMBE) program, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing,

734   2(3), 144-162, doi:10.1109/JSTARS.2009.2027443, 2009.

735   Roberts, G., Wooster, M. J. and Lagoudakis, E.: Annual and diurnal African biomass burning temporal dynamics,

736   Biogeosciences, 6(5), 849-866, 2009.

737   Roy, D. P., Ju, J., Lewis, P., Schaaf, C., Gao, F., Hansen, M. and Lindquist, E.: Multi-temporal MODIS-Landsat

738   data fusion for relative radiometric normalization, gap filling, and prediction of Landsat data, Remote Sens.

739   Environ., 112(6), 3112-3130, doi:10.1016/j.rse.2008.03.009, 2008.

740   Roy, D. P. and Boschetti, L.: Southern Africa Validation of the MODIS, L3JRC, and Glob Carbon Burned-Area

741   Products,   IEEE   Transactions   on   Geoscience   and   Remote   Sensing,   47(4),   1032-1044,

742   doi:10.1109/TGRS.2008.2009000, 2009.

743   Seiler, W. and Crutzen, P. J.: Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere

744   from biomass burning, Climatic Change, 2(3), 207-247, 1980.

745 Setzer, A. W. and Pereira, M. C.: Amazonia biomass burnings in 1987 and an estimate of their tropospheric

746   emissions, Ambio, 20(1), 19-22, 1991.

747 Shi, Y., Matsunaga, T., Saito, M., Yamaguchi, Y. and Chen, X.: Comparison of global inventories of CO_2 emissions

748   from biomass burning during 2002-2011 derived from multiple satellite products, Environ. Pollut., 206,

749   479-487, doi:10.1016/j.envpol.2015.08.009, 2015a.

750 Shi, Y., Matsunaga, T. and Yamaguchi, Y.: High-resolution mapping of biomass burning emissions in three tropical

751   regions, Environ. Sci. Technol., 49(18), 10806-10814, doi:10.1021/acs.est.5b01598, 2015b.

752 Sofiev, M., Vankevich, R., Lotjonen, M., Prank, M., Petukhov, V., Ermakova, T., Koskinen, J. and Kukkonen, J.: An

753   operational system for the assimilation of the satellite information on wild-land fires for the needs of air

754   quality modelling and forecasting, Atmos. Chem. Phys., 9(18), 6833-6847, doi: 10.5194/acp-9-6833-2009,

755   2009.

756 Song, Y., Liu, B., Miao, W., Chang, D. and Zhang, Y.: Spatiotemporal variation in nonagricultural open fire

757   emissions in China from 2000 to 2007: open fire emissions in China, Global Biogeochem. Cy., 23(2), n/a-n/a,

758   doi: 10.1029/2008GB003344, 2009.

759 Streets, D. G., Yarber, K. F., Woo, J. H. and Carmichael, G. R.: Biomass burning in Asia: Annual and seasonal

760   estimates and atmospheric emissions, Global Biogeochem. Cy., 17(4), n/a-n/a, doi:10.1029/2003GB002040,

761   2003.

762 Su, J. F., Zhu, B., Kang, H. Q., Wang, H. L. and Wang, T. J.: Applications of pollutants released form crop residues

763   at open burning in Yangtze River Delta Region in air quality model, Enviro. Sci., 33, 1418-1424, 2012 (in

764   Chinese).

765 Sun, J., Peng, H., Chen, J., Wang, X., Wei, M., Li, W., Yang, L., Zhang, Q., Wang, W. and Mellouki, A.: An

766   estimation of CO_2 emission via agricultural crop residue open field burning in China from 1996 to 2013, J.

767   Clean. Prod., 112, 2625-2631, doi:10.1016/j.jclepro.2015.09.112, 2016.

768 Tao, S.: Study on the Effect of crop production on the air quality in Wuhan, J. Residuals. Sci. Tech., 14(S1),

769   S41-S45, doi:10.12783/issn.1544-8053/14/S1/5, 2017.

770 Tang, X. B., Huang, C., Lou, S. R., Qiao, L. P., Wang, H. L., Zhou, M., Chen, M. H., Chen, C. H.,Wang, Q., Li, G.

771   L., Li, L., Huang, H. Y. and Zhang, G. F.: Emission factors and PM chemical composition study of biomass

772   burning in the Yangtze River Delta Region, Environ. Sci., 35, 1623–1632, 2014 (in Chinese).

773 Tang, Z. X., Xu, R, R. and Lan, X. L.: Breeding of a new peanut variety fuhua 3 and the physiological foundation

774   of high yield, Chin. Agric. Sci. Bull., 25(23), 232-237, 2009 (in Chinese).

775   Tian, H., Hao, J., Lu, Y. Q. and Zhou, Z.: Evaluation of SO_2 and NO_x emissions resulted from biomass fuels

776   utilization in China, Acta Scien. Circum., 22(2), 204-208, 2002 (in Chinese).

777   Tian, H., Zhao, D. and Wang, Y.: Emission inventories of atmospheric pollutants discharged from biomass burning

778   in China, Acta Scien. Circum., 31(2), 349-357, 2011 (in Chinese).

779   Tian, X. L., Xia, J., Xia, H. B. and Ni, J.: Forest biomass and its spatial pattern in Guizhou Province, Chinese J.

780   Appl. Ecol., 22(2), 287–297, 2014 (in Chinese).

781   van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries,

782   R. S., Jin, Y. and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna,

783   forest, agricultural, and peat fires (1997-2009), Atmos. Chem. Phys., 10(23), 11707-11735,

784   doi:10.5194/acp-10-11707-2010, 2010.

785   Wang, K. D. and Deng, L. Y.: Dynamics of forest vegetation carbon stock in Fujian Province based on national

786   forest inventories, J. Fujian For. Univ., 34(2), 145–151, 2014 (in Chinese).

787   Wang, S. X. and Zhang, C. Y.: Spatial and temporal distribution of air pollutant emissions from open burning of

788   crop residues in China, Science paper Online, 3, 329–333, 2008 (in Chinese).

789   Wen, X. R., Jiang, L. X., Liu, L., Lin, G. Z., Zheng, Y., Xie, X. J. and She, G. H.: Forest biomass, spatial

790   distribution analysis and productivity estimation in Jiangsu Province, J. Northwest. For. Univ., 29(1), 36–40,

791   2014 (in Chinese).

792   Wiedinmyer, C., Quayle, B., Geron, C., Belote, A., McKenzie, D., Zhang, X., O'Neill, S. and Wynne, K. K.:

793   Estimating emissions from fires in North America for air quality modeling, Atmos. Environ., 40(19),

794   3419-3432, doi:10.1016/j.atmosenv.2006.02.010, 2006.

795   Wiedinmyer, C., Akagi, S. K., Yokelson, R. J. and Emmons, L. K.: The Fire INventory from NCAR (FINN) - a high

796   resolution global model to estimate the emissions from open burning, Geosci. Model. Dev. Discuss., 3(4),

797   625-641, 2011.

798   Wooster, M. J., Roberts, G., Perry, G. L. W. and Kaufman, Y. J.: Retrieval of biomass combustion rates and totals

799   from fire radiative power observations: FRP derivation and calibration relationships between biomass

800   consumption and fire radiative energy release, J. Geophys. Res., 110 (D24), doi: 10.1029/2005JD006318,

801   2005.

802   Xie, G. H., Han, D. Q., Wang, X. Y. and Lv, R. H.: Harvest index and residue factor of cereal crops in China, J.

803   China Agric. Univ., 16(1), 1-8, 2011a (in Chinese).

804   Xie, G. H., Wang, X. Y., Han, D. Q. and Xue, S.: Harvest index and residue factor of non-cereal crops in China, J.

805   China Agric. Univ., 16(1), 9-17, 2011b (in Chinese).

806   Xu, J. D.: The 8th forest resources inventory results and analysis in China, For. Econ, doi:
807   10.13843/j.cnki.lyjj.2014.03.002, 2014 (in Chinese).

808   Xue, X. P., Wang, J. G., Guo, W. Q., Chen, B. L., You, J. and Zhou, Z. G.: Effect of nitrogen applied levels on the
809   dynamics of biomass, nitrogen accumulation and nitrogen fertilization recovery rate of cotton after initial
810   flowering, Acta. Eco. Sin., 26(11), 3632-3640, 2006 (in Chinese).

811   Yamaji, K., Li, J., Uno, I., Kanaya, Y., Irie, H., Takigawa, M., Komazaki, Y., Pochanart, P., Liu, Y., Tanimoto, H.,
812   Ohara, T., Yan, X., Wang, Z. and Akimoto, H.: Impact of open crop residual burning on air quality over
813   Central Eastern China during the Mount Tai Experiment 2006 (MTX2006), Atmos. Chem. Phys., 10(15),
814   7353-7368, doi:10.5194/acp-10-7353-2010, 2010.

815   Yan, X., Ohara, T. and Akimoto, H.: Bottom-up estimate of biomass burning in mainland China, Atmos. Environ.,
816   40(27), 5262-5273, doi:10.1016/j.atmosenv.2006.04.040, 2006.

817   Yan, W. L., Liu, D. Y., Sun Y., Wei, J. S. and Pu, M. J.: Analysis of the sustained fog and haze event resulting from
818   crop burning residue in Jiangsu province, Climatic Environ. Res., 19, 237-247, 2014 (in Chinese).

819   Yevich, R. and Logan, J. A.: An assessment of biofuel use and burning of agricultural waste in the developing
820   world, Global Biogeochem. Cy., 17(4), doi:10.1029/2002GB001952, 2003.

821   Yin, S., Wang, X., Xiao, Y., Tani, H., Zhong, G. and Sun, Z.: Study on spatial distribution of crop residue burning
822   and $PM_{2.5}$ change in China, Environ. Pollut., 220, 204-221, doi:10.1016/j.envpol.2016.09.040, 2017.

823   Yu, L. X., Zhang, J. H., Liu, L. Q., Chen, Q. Q., Zhou, Y., Wang, X. G., Xia, S. B. and Bie, S.: Study on high yield
824   mechanism of hybrid cotton, Hubei Agric. Sci., 48(9), 2084-2086, 2009 (in Chinese).

825   Zeng, J. M., Cui, K. H., Huang, J. L., He, F. and Peng, S. B. : Responses of physio-biochemical properties to
826   N-fertilizer application and its relationship with nitrogen use efficiency in rice, Acta Agron. Sin., 33(7),
827   1168-1176, 2007 (in Chinese).

828   Zha, S.: Agricultural fires and their potential impacts on regional air quality over China, Aerosol Air Qual. Res.,
829   13(3), 992-1001, 2013.

830   Zhang, H., Hu, D., Chen, J., Ye, X., Wang, S. X., Hao, J. M., Wang, L., Zhang, R. and An, Z.: Particle size
831   distribution and polycyclic aromatic hydrocarbons emissions from agricultural crop residue burning, Environ.
832   Sci. Technol., 45(13), 5477-5482, doi:10.1021/es1037904, 2011.

833   Zhang, H., Wang, S., Hao, J., Wang, X., Wang, S., Chai, F. and Li, M.: Air pollution and control action in Beijing, J.
834   Clean. Prod., 112, 1519-1527, doi:10.1016/j.jclepro.2015.04.092, 2016.

835 Zhang, H. F., Ye, X. N., Cheng, T. T., Chen, J. M., Yang, X., Wang, L. and Zhang, R. Y.: A laboratory study of

836   agricultural crop residue combustion in China: Emission factors and emission inventory, Atmos. Environ., 42,

837   8432–8441, doi:10.1016/j.atmosenv.2008.08.015, 2008.

838 Zhang, L., Liu, Y. and Hao, L.: Contributions of open crop straw burning emissions to $PM_{2.5}$ concentrations in

839   China, Environ. Res. Lett., 11(1), 014014, doi:10.1088/1748-9326/11/1/014014, 2016.

840 Zhang, J., Cui, M., Fan, D., Zhang, D., Lian, H., Yin, Z. and Li, J.: Relationship between haze and acute

841   cardiovascular, cerebrovascular, and respiratory diseases in Beijing, Environ. Sci. Pollut. Res., 22(5),

842   3920-3925, doi:10.1007/s11356-014-3644-7, 2015.

843 Zhang, Y., Tang, L., Croteau, P. L., Favez, O., Sun, Y., Canagaratna, M. R., Wang, Z., Couvidat, F., Albinet, A.,

844   Zhang, H., Sciare, J., Prévôt, A. S. H., Jayne, J. T. and Worsnop, D. R.: Field characterization of the $PM_{2.5}$

845   aerosol chemical speciation monitor: insights into the composition, sources, and processes of fine particles in

846   eastern China, Atmos. Chem. Phys., 17(23), 14501-14517, doi:10.5194/acp-17-14501-2017, 2017.

847 Zhao, P. and Chen, F.: Short-term influences of straw and nitrogen cooperation on nitrogen use and soil nitrate

848   content in North Henan, J. China Agric. Univ., 13(4), 19-23, 2008 (in Chinese).

849 Zhou, Y., Cheng, S. Y, Lang, J., Chen, D. S., Zhao, B. B., Liu, C., Xu, R. and Li, T.: A comprehensive ammonia

850   emission inventory with high-resolution and its evaluation in the Beijing-Tianjin-Hebei (BTH) region, China,

851   Atmos. Environ., 106, 305-317, doi:10.1016/j.atmosenv.2015.01.069, 2015.

852 Zhou, Y., Yue, Y., Lan, L. I., Liu, M. and Zhou, T.: Analysis of a serious haze event resulting from crop residue

853   burning in Central Eastern Hubei, Climatic Environ. Res., 2016.

854 Zhou, Y., Xing, X., Lang, J., Chen, D., Cheng, S., Wei, L., Wei, X. and Liu, C.: A comprehensive biomass burning

855   emission inventory with high spatial and temporal resolution in China, Atmos. Chem. Phys., 17(4), 2839-2864,

856   doi:10.5194/acp-17-2839-2017, 2017.

857 Zhu, B., Su, J. F., Han, Z. W., Y, C and Wang, T. J.: Analysis of a serious air pollution event resulting from crop

858   residue burning over Nanjing and surrounding regions, China Environ. Sci., 30(5), 585-592, 2010.

859 Zhu, L. J., Wang, G. Y. and Zhang, Y. L.: Spatial and temporal distribution of crop straw resources in Yangtze River

860   Delta area, Guizhou Agric. Sci., 45(4), 138-142, 2017 (in Chinese)

861 Zong, Z., Wang, X., Tian, C., Chen, Y., Qu, L., Ji, L., Zhi, G., Li, J. and Zhang, G.: Source apportionment of $PM_{2.5}$

862   at a regional background site in North China using PMF linked with radiocarbon analysis: insight into the

863   contribution of biomass burning, Atmos. Chem. Phys., 16(17), 11249-11265, doi:10.5194/acp-16-11249-2016,

864   2016.

865 Zou, J., Lu, J. W., Liao, Z. W., Gong, X. M., Wang, H., Zhou, Y. G. and Zhou, H.: Study on response of rapeseed to

866   boron application and critical level of soil available B in Hubei province, Sci. Agric. Sin., 41(3), 752-759,

867   2008 (in Chinese).

868 Zuo, Z. G.: The cause and prevention of forest fire in forest area of Southern China, Land Greening, 2004 (in

869   Chinese).

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Table 1. Forest, shrubland and grassland biomass fuel loading (kt km^{-2}) in each province.

Province	Forest (2003-2008)[a]	Forest (2009-2015)[*]	Shrubland[b]	Grassland[c]
Shandong	4.26	2.95	6.94	0.78
Henan	5.66	4.16	6.94	0.77
Anhui	6.32	3.61	12.2	0.77
Jiangsu	4.7	2.64	6.86	0.72
Hubei	5.34	3.28	7.87	0.88
Hunan	4.79	2.52	17.4	0.8
Jiangxi	4.75	3.08	18.5	0.76
Fujian	6.29	5.91	18.9	0.85
Zhejiang	3.51	3.11	18.4	0.86
Shanghai	6.09	2.99	6.86	0.93

References: [a] Fang et al. (1996); [b] Pu et al. (2004); [c] Hu et al. (2006); [*] This study.

Table 2. Parameters of linear regression model for biomass and stock volume of dominant tree species.

Tree species	a	b	Tree species	a	b
Larix	0.967[a]	5.7598[a]	Cinnamomum camphora	1.0357[a]	8.0591[a]
Pinus koraiensis	0.5185[a]	18.22[a]	Phoebe	1.0357[a]	8.0591[a]
Pinus sylvestris var. mongolica	1.11[a]		Elm	0.7564[f]	8.3013[f]
Pinus densiflora	1.0945[b]	2.004[b]	Robinia	0.7564[a]	8.3103[a]
Pinus thunbergii parl	0.5168[b]	33.237[b]	Schima superba	0.76[e]	8.31[e]
Chinese pine	0.7554[a]	5.0928[a]	Sweetgum	0.76[e]	8.31[e]
Pinus armandi	0.5856[a]	18.7435[a]	Other hard broad leaf	0.7564[b]	8.3103[b]
Pinus massoniana	0.52[a]		Tilia	0.7975[b]	0.4204[b]
Pinus yunnanensis	0.52[a]		Sassafras	1.0357[a]	8.0591[a]
Pinus kesiya var. langbiamensis	0.510[b]	1.045[b]	Populus	0.4754[a]	30.603[a]
Pinus densata	0.5168[b]	33.237[b]	Salix	0.4754[c]	30.6034[c]
Foreign pine	0.5168	33.2378	Paulownia	0.8956[d]	0.0048[d]
Pinus elliottii	0.51[e]	1.05[e]	Eucalyptus	0.7893[a]	6.9306[a]
Pinus taeda	0.5168[f]	33.2378[f]	Rich acacia	0.4754[a]	30.60[a]
Mount huangshan pine	0.5168[f]	33.2378[f]	Casuarina equisetifolia	0.7441[b]	3.2377[b]
Joe pine	0.5168[f]	33.237[f]	Melia azedarach	0.4754[b]	30.603[b]
Other pine	0.5168[a]	33.2378[a]	Other soft broad leaf	0.4754[b]	30.603[b]
Cunninghamia lanceolata	0.399[a]	22.54[a]	Coniferous mixed	0.5168[f]	33.2378[f]
Cryptomeria fortunei	0.4158[a]	41.3318[a]	Broad-leaved mixed	0.8392[b]	9.4157[b]
Metasequoia	0.4158[a]	41.3318[a]	Coniferous and broad-leaved mixed	0.7143[b]	16.9154[b]
Taxodium ascendens	0.399[a]	22.541[a]	Betula	0.9644[a]	0.8485[a]
Abies	0.4642[a]	47.499	White birch	0.9644[a]	0.8485[a]
Picea	0.4642[a]	47.499[a]	Betula costata	0.9644[a]	0.8485[a]
Tsuga	0.4158[a]	41.3318[a]	Water, beard and yellow	0.7975[b]	0.4202[b]
Keteleeria	0.4158	41.3318	Manchurian Ash	0.798[c]	0.42[c]
Cupressus	0.6129[a]	26.1451[a]	Juglans mandshurica	0.798[c]	0.42[c]
Yew	0.4642[b]	47.499[b]	Amur corktree	0.798[c]	0.42[c]
Other fir	0.399[a]	22.541[a]	Quercus	1.3288[a]	-3.8999[a]

References: [a] Fang et al. (1996); [b] Wen et al. (2014); [c] Lu et al. (2012); [d] Tian et al (2011); [e] Wang et al (2014); [f] Li et al. (2014).

Table 3. Detailed crop residue to production ratio data for each province

Province	Rice	Corn	Wheat	Cotton	Rapeseed	Soy bean	Sugar cane	Peanut	Potato	Sesame	Sugar beet	Tobacco
Anhui	1.09[a]	1[a]	1.12[a]	3.35[a]	2.98[a]	1.52[a]	0.34[a]	1.26[a]	0.53[a]	2.01[a]	0.37[a]	0.71[a]
Fujian	0.85[b]	1.04[c]	1.17[c]	2.91[d]	2.87[d]	1.5[d]	0.43[d]	1.08[m]	0.57[d]	2.01[d]	0.43[d]	0.56[d]
Henan	1[c]	0.96[c]	1.08[h]	2.41[i]	2.87[d]	1.5[d]	0.34[d]	0.89[d]	0.57[d]	1.78[d]	0.43[d]	0.49[d]
Hubei	1.17[e]	1.04[c]	1.17[c]	4.09[j]	3.17[k]	1.5[d]	0.43[d]	1.14[d]	0.57[d]	2.01[d]	0.43[d]	0.71[d]
Hunan	0.94[f]	1.11[g]	1.17[c]	2.91[d]	3[l]	1.5[d]	0.43[d]	1.38[n]	0.57[d]	2.23[d]	0.43[d]	0.85[d]
Jiangsu	1.04[a]	1[a]	1.41[c]	2.61[i]	2.98[a]	1.52[a]	0.34[a]	1.26[a]	0.53[a]	2.01[a]	0.37[a]	0.71[a]
Jiangxi	1[c]	1.04[c]	1.17[c]	2.91[d]	2.87[d]	1.5[d]	0.43[d]	1.14[d]	0.57[d]	2.01[d]	0.43[d]	0.71[d]
Shandong	1[c]	0.96[c]	1.33[c]	2.91[d]	2.87[d]	1.5[d]	0.43[d]	0.85[d]	0.57[d]	2.01[d]	0.43[d]	0.71[d]
Shanghai	1.28[a]	0.93[a]	1.09[a]	3.35[a]	2.98[a]	1.52[a]	0.34[a]	1.26[a]	0.53[a]	2.01[a]	0.37[a]	0.71[a]
Zhejiang	1.07[a]	0.96[a]	1.2[a]	3.35[a]	2.98[a]	1.52[a]	0.34[a]	1.26[a]	0.53[a]	2.01[a]	0.37[a]	0.71[a]

References: [a] Zhu et al. (2017); [b] Chen et al. (2008); [c] Xie et al. (2011a); [d] Xie et al (2011b); [e] Zeng et al (2007); [f] Ao et al. (2007); [g] Lei et al. (2009); [h] Zhao et al. (2008); [i] Xue et al. (2006); [j] Yu et al (2009); [k] Zou et al (2008); [l] Liu et al. (2010); [m] Tang et al. (2009); [n] Li et al. (2008).

Table 4. Detailed crops straw burned ratio data for each province.

Region	Crops straw burning percentage
Anhui	0.10[a]
Fujian	0.188[b]
Henan	0.208[c]
Hubei	0.207[c]
Hunan	0.278[c]
Jiangsu	0.10[a]
Jiangxi	0.18[c]
Shandong	0.178[c]
Shanghai	0.148[d]
Zhejiang	0.319[c]

References: [a] Tian (2011); [b] Huang (2014); [c] Peng et al; (2016). [d] Zhou et al (2017).

Table 5. The emission factors of open biomass burning emissions for various pollutants (g kg^{-1} dry matter)

Vegetation	OC	EC	CO	CH$_4$	NO$_x$	NMVOCs	SO$_2$	NH$_3$	CO$_2$	PM$_{2.5}$
Corn	1.457[*]	0.14*	70.2[a]	4.4[b]	3.36[a]	10[c]	0.45[c]	0.68[g]	1261[f]	5[c]
Rice	1.96[a]	0.52[c]	52.32[c]	3.9[b]	1.42[d]	6.05[f]	0.147[a]	0.53[g]	791[f]	3.03[d]
Wheat	2.7[b]	0.49[a]	61.90[c]	3.4[b]	1.19[d]	7.5[c]	0.147[c]	0.37[b]	1557[f]	7.6[a]
Cotton	3.06[c]	0.57[f]	70.29[c]	4.4[b]	2.98[c]	10[c]	0.23[c]	0.68[b]	1445[h]	11.7[c]
Rapeseed	1.08[d]	0.23[d]	34.3[d]	3.9[b]	1.12[d]	8.64[c]	0.25[c]	0.53[g]	1445[h]	5.76[c]
Soya bean	1.05[d]	0.13[d]	32.3[d]	3.9[b]	1.08[d]	8.64[c]	0.25[c]	0.53[g]	1445[h]	3.32[d]
Sugar cane	2.03[c]	0.41[c]	40.08[f]	3.9[b]	2.03[c]	11.02[f]	0.25[c]	0.53[g]	1445[h]	4.12[f]
Peanut	2.03[c]	0.41[c]	55.13[c]	3.9[b]	2.11[c]	8.64[c]	0.25[c]	0.53[g]	1445[h]	5.76[c]
Potato	2.03[c]	0.41[c]	55.13[c]	3.9[b]	2.11[c]	8.64[c]	0.25[c]	0.53[g]	1445[h]	5.76[c]
Tobacco	2.03[c]	0.41[c]	55.13[c]	3.9[b]	2.11[c]	8.64[c]	0.25[c]	0.53[g]	1445[h]	5.76[c]
Sesame	2.03[c]	0.41[c]	55.13[c]	3.9[b]	2.11[c]	8.64[c]	0.25[c]	0.53[g]	1445[h]	5.76[c]
Sugar beet	2.03[c]	0.41[c]	55.13[c]	3.9[b]	2.11[c]	8.64[c]	0.25[c]	0.53[g]	1445[h]	5.76[c]
Coniferous forest	7.8[e]	0.2[e]	118[e]	6[e]	2.4[e]	28[e]	1[i]	3.5[e]	1514[e]	9.7[e]
Broadleaf forest	9.2[e]	0.6[e]	102[e]	5[e]	1.3[e]	11[e]	1[e]	1.5[e]	1630[e]	13[e]
Mixed forest	9.2[e]	0.6[e]	102[e]	5[e]	1.3[e]	14[e]	1[i]	1.5[e]	1630[e]	9.7[e]
Grassland	2.6[e]	0.4[e]	59[e]	1.5[e]	2.8[e]	9.3[e]	0.5[e]	0.5[e]	1692[e]	5.4[e]
Shrubland	6.6[e]	0.5[e]	68[e]	2.6[e]	3.9[e]	4.8[e]	0.7[e]	1.2[e]	1716[e]	9.3[e]

References: [a] Cao et al. (2008); [b] Li et al. (2007); [c] He et al. (2015); [d] Tang et al. (2014); [e] Akagi et al. (2011); [f] Zhang et al. (2008); [g] EPD (2014); [h] Wang et al. (2008); [i] Andreae and Rosenfeld (2008); [*] This study.

Table 6. Cumulative emissions of major pollutants from open biomass burning in Central and Eastern China during 2003-2015 (Gg)

Province	OC	EC	CH$_4$	NO$_x$	NMVOCs	SO$_2$	NH$_3$	CO	CO$_2$	PM$_{2.5}$
Shandong	783.9	48.56	669.4	479.3	1505	54.55	95.56	10880	226705	1007
Henan	1068	63.19	738.3	512.1	1629	54.23	101.3	11869	260239	1155
Anhui	238.2	20.24	197.7	115	410	12.94	29.75	2939	63623	283.1
Jiangsu	201.6	19.88	178	98.48	341	9.29	23.89	2543	53106	228.5
Hubei	234.2	33.92	337.7	173.1	660.7	19.86	48.5	4555	97788	415.8
Hunan	202	40.34	376.8	179.1	738.4	24.33	64.3	5239	96338	418.8
Jiangxi	132.8	27.88	236.1	109	447.6	14.2	40.55	3305	57692	252.3
Fujian	97.15	15.15	148.1	71.14	347.4	12.81	34.45	2285	40095	190.2
Zhejiang	91.41	16.22	147.9	70.53	290.9	9.62	25.83	2055	39142	167.8
Shanghai	14.34	2.09	17.14	8.56	29.89	0.76	2.29	233.8	4392	17.88
Total	3064	287.5	3047	1816	6399	212.6	466.5	45904	939120	4136

Table 7. Correlation of the variation tendency between $PM_{2.5}$ emission from crops straw burning and rural population, agricultural output, per capita incomes of rural residents in each province from 2003 to 2015.

$PM_{2.5}$ emission (Gg)	Rural population (10 thousand)	Per capita income of rural residents (RMB)	Agricultural output (0.1 billion RMB)
Shanghai	y = -0.001x + 1.64 $R^2 = 0.17$ P > 0.05	y = -5E-06x + 1.4 $R^2 = 0.09$ P > 0.05	y = 7E-05x + 1.36 $R^2 = 0.0005$ P > 0.05
Zhejiang	y = 0.002x + 6.19 $R^2 = 0.06$ P > 0.05	y = -6E-05x + 10.47 $R^2 = 0.19$ P > 0.05	y = -0.001x + 10.72 $R^2 = 0.19$ P > 0.05
Fujian	y = -0.0002x + 8.219 $R^2 = 0.01$ P > 0.05	y = -3E-05x + 8.1884 $R^2 = 0.06$ P > 0.05	y = -0.0002x + 8.2144 $R^2 = 0.06$ P > 0.05
Jiangsu	**y = -0.002x + 23.41 $R^2 = 0.8$ P < 0.01**	**y = 0.0002x + 15.33 $R^2 = 0.66$ P < 0.01**	**y = 0.001x + 15.18 $R^2 = 0.69$ P < 0.01**
Hubei	**y = -0.008x + 56.19 $R^2 = 0.94$ P < 0.01**	**y = 0.0009x + 25.39 $R^2 = 0.86$ P < 0.01**	**y = 0.004x + 24.31 $R^2 = 0.92$ P < 0.01**
Anhui	**y = -0.005x + 37.11 $R^2 = 0.91$ P < 0.01**	**y = 0.0007x + 16.12 $R^2 = 0.79$ P < 0.01**	**y = 0.004x + 14.5 $R^2 = 0.85$ P < 0.01**
Hunan	**y = -0.01x + 62.66 $R^2 = 0.78$ P < 0.01**	**y = 0.0008x + 20.66 $R^2 = 0.8$ P < 0.01**	**y = 0.003x + 20.1 $R^2 = 0.91$ P < 0.01**
Jiangxi	**y = -0.008x + 33.73 $R^2 = 0.92$ P < 0.01**	**y = 0.0006x + 11.19 $R^2 = 0.82$ P < 0.01**	**y = 0.006x + 9.84 $R^2 = 0.87$ P < 0.01**
Henan	**y = -0.01x + 150.14 $R^2 = 0.8$ P < 0.01**	**y = 0.003x + 70.41 $R^2 = 0.59$ P < 0.01**	**y = 0.008x + 62.79 $R^2 = 0.72$ P < 0.01**
Shandong	**y = -0.009x + 122.46 $R^2 = 0.73$ P < 0.01**	**y = 0.0014x + 66.48 $R^2 = 0.66$ P < 0.01**	**y = 0.004x + 62.11 $R^2 = 0.77$ P < 0.01**

Table 8. Comparison of the emissions with previous studies in different years (Gg)

Reference	Year	OC	EC	CH_4	NO_x	NMVOCs	SO_2	NH_3	CO	CO_2	$PM_{2.5}$
Wang et al., 2008	2006	252	25.8	197	189	459	31.8	44.1	3841	81225	1138
This study		215.3	21.13	220.7	131.9	451.1	14.33	31.46	3267	67753	293.09
Huang et al., 2012	2006	54	17.4	136	123	1196	8.1	50.6	2379	36886	146
This study		209.8	20.67	215.8	129.1	436.4	13.56	29.64	3172	66088	283.3
Qiu et al., 2016	2013	222	41.5	243	168	591	30.2	46.9	3273	78633	475
This study		258.2	23.53	252.1	151.2	531.5	17.86	38.67	3817	78050	343.44
Zhou et al., 2017	2012	185	16.9	254	160	543	40.4	34.5	3330	92797	484
This study		248.6	23.11	245.7	148.5	507.8	16.71	35.92	3688	75785	329.46

Table 9. The uncertainty estimation of open biomass burning emissions for various pollutants from 2003 to 2015.

Year	OC	EC	CO	CH_4	NO_x	NMVOC	SO_2	NH_3	CO_2	$PM_{2.5}$
2003	(-31%, 31%)	(-46%, 46%)	(-20%, 20%)	(-20%, 20%)	(-23%, 23%)	(-52%, 53%	(-52%, 51%)	(-33%, 33%)	(-3%, 3%)	(-44%, 44%)
2004	(-29%, 29%)	(-47%, 48%)	(-21%, 21%)	(-22%, 22%)	(-24%, 24%)	(-45%, 45%)	(-56%, 58%)	(-34%, 34%)	(-3%, 3%)	(-47%, 47%)
2005	(-31%, 31%)	(-42%, 44%)	(-16%, 16%)	(-16%, 17%)	(-19%, 19%)	(-41%, 40%)	(-44%, 44%)	(-32%, 33%)	(2%, 3%)	(-35%, 34%)
2006	(-32%, 33%)	(-44%, 44%)	(-13%, 13%)	(-14%, 14%)	(-16%, 17%)	(-43%, 43%)	(-34%, 35%)	(-34%, 34%)	(-3%, 3%)	(-25%, 25%)
2007	(-30%, 30%)	(-46%, 46%)	(-18%, 19%)	(-19%, 19%)	(-22%, 22%)	(-50%, 51%)	(-50%, 50%)	(-33%, 34%)	(-3%, 3%)	(-42%, 42%)
2008	(-26%, 26%)	(-52%, 53%)	(-25%, 25%)	(-28%, 28%)	(-29%, 29%)	(-69%, 69%)	(-62%, 61%)	(-38%, 39%)	(-3%, 3%)	(-55 %, 56%)
2009	(-28%, 28%)	(-48%, 48%)	(-21%, 21%)	(-21%, 22%)	(-24%, 24%)	(-59%, 59%)	(-54%, 54%)	(-34%, 35%)	(-3%, 3%)	(-47%, 47%)
2010	(-31%, 31%)	(-44%, 44%)	(-16%, 17%)	(-17%, 17%)	(-19%, 19%)	(-45%, 46%)	(-42%, 42%)	(-33%, 34%)	(-3%, 3%)	(-34%, 34%)
2011	(-29%, 29%)	(-46%, 46%)	(-18%, 18%)	(-19%, 19%)	(-21%, 21%)	(-52%, 53%)	(-47%, 47%)	(-34%, 35%)	(-3%, 3%)	(-40%, 40%)
2012	(-32%, 33%)	(-44%, 44%)	(-14%, 14%)	(-14%, 14%)	(-17%, 17%)	(-35%, 35%)	(-35%, 35%)	(-34%, 35%)	(-3%, 3%)	(-27%, 26%)
2013	(-30%, 30%)	(-44%, 44%)	(-16%, 16%)	(-17%, 17%)	(-20%, 20%)	(-51%, 51%)	(-42%, 43%)	(-33%, 34%)	(-3%, 3%)	(-36%, 36%)
2014	(-32%, 32%)	(-45%, 46%)	(-15%, 15%)	(-16%, 16%)	(-19%, 18%)	(-43%, 43%)	(-42%, 42%)	(-35%, 35%)	(-3%, 3%)	(-33%, 33%)
2015	(-31%, 31%)	(-44%, 44%)	(-14%, 146%)	(-14%, 13%)	(-17%, 17%)	(-41%, 41%)	(-34%, 34%)	(-34%, 35%)	(-3%, 3%)	(-26%, 26%)
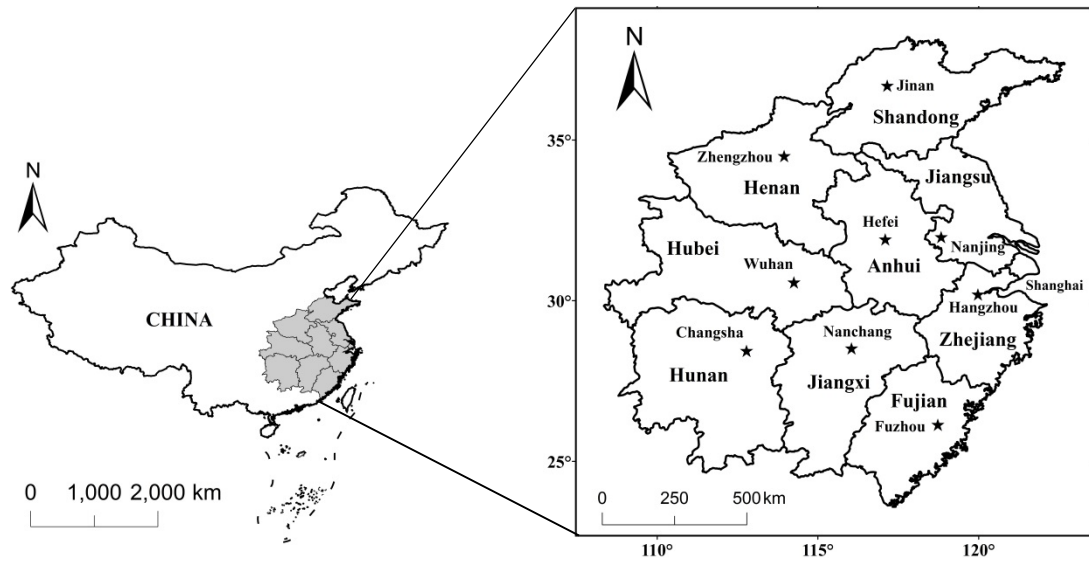
Figure 1. Location of Central and Eastern China and the key megacitie
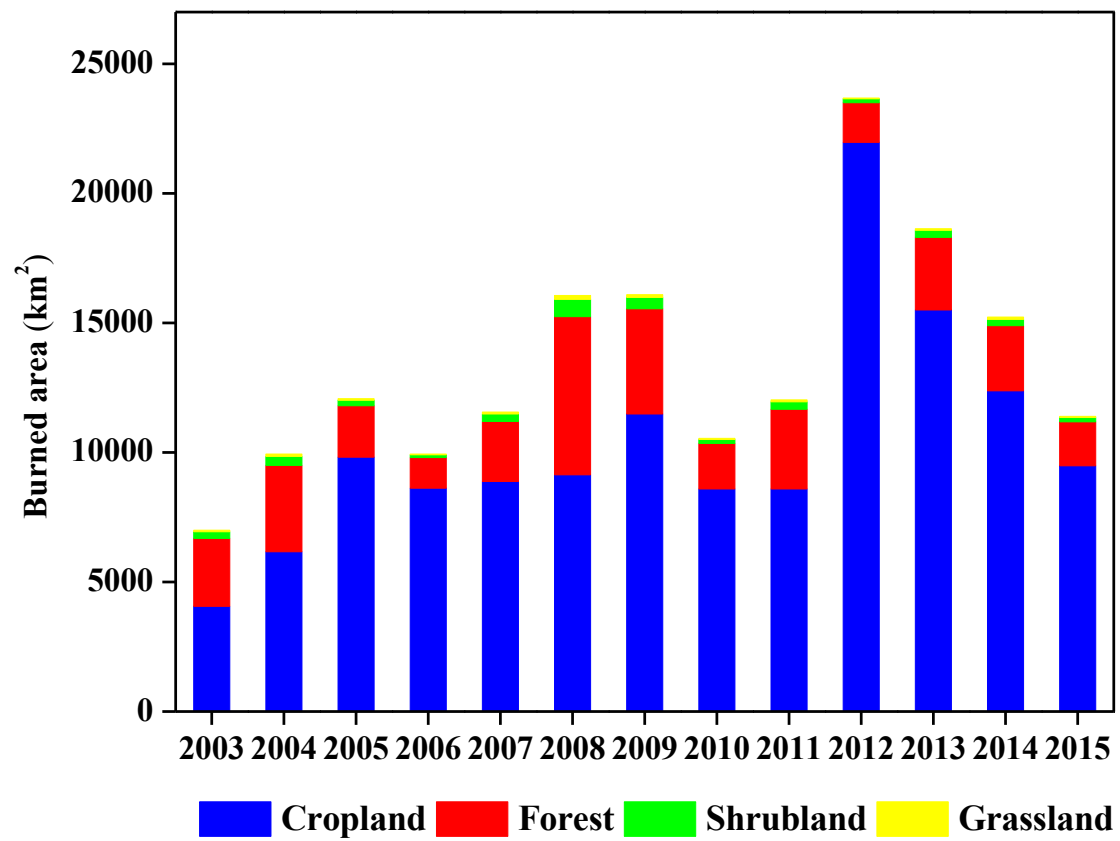
Figure 2. The integrated open biomass burned area in Central and Eastern China from 2003 to 2015.
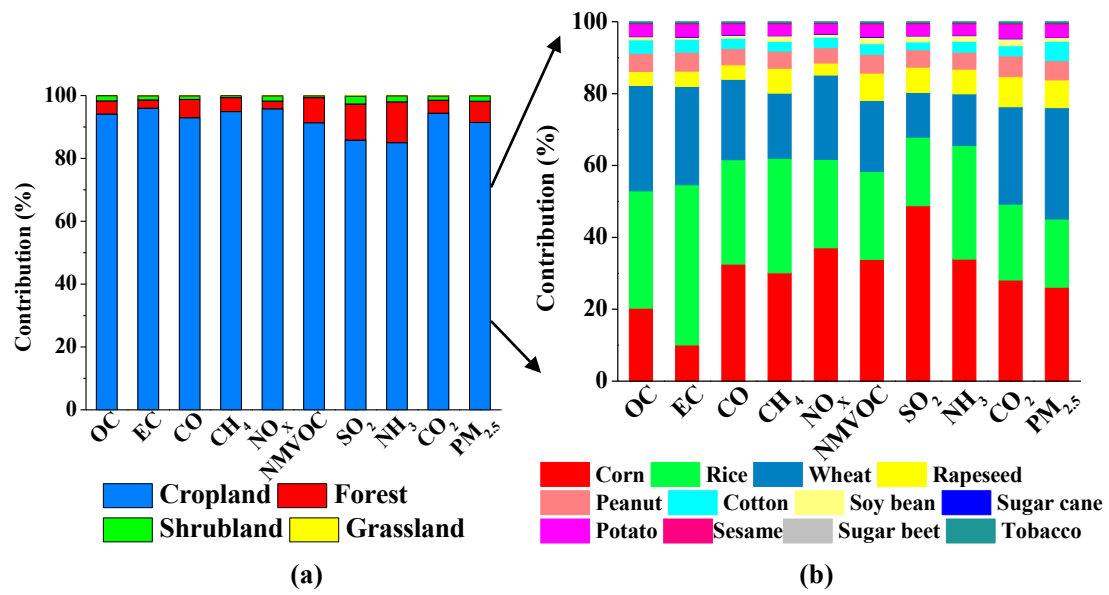
Figure 3. The mean contributions of different types of biomass to biomass burning pollutant emission (a) and the mean contributions of different types of crops to cropland accumulative pollutant emission (b) from 2003 to 2015.
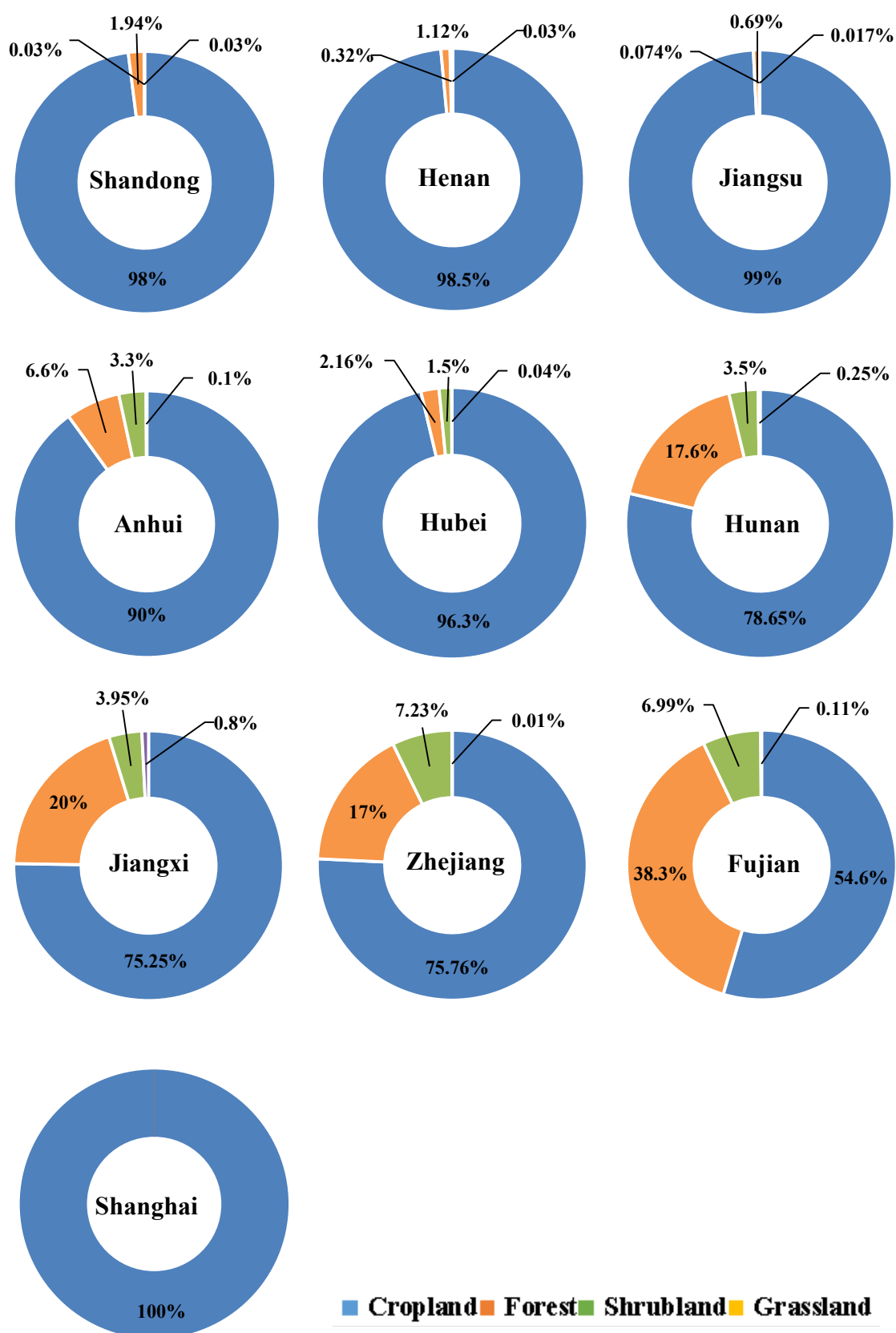
Figure 4. The averaged contributions of different biomass burning types to PM$_{2.5}$ emission in each province.
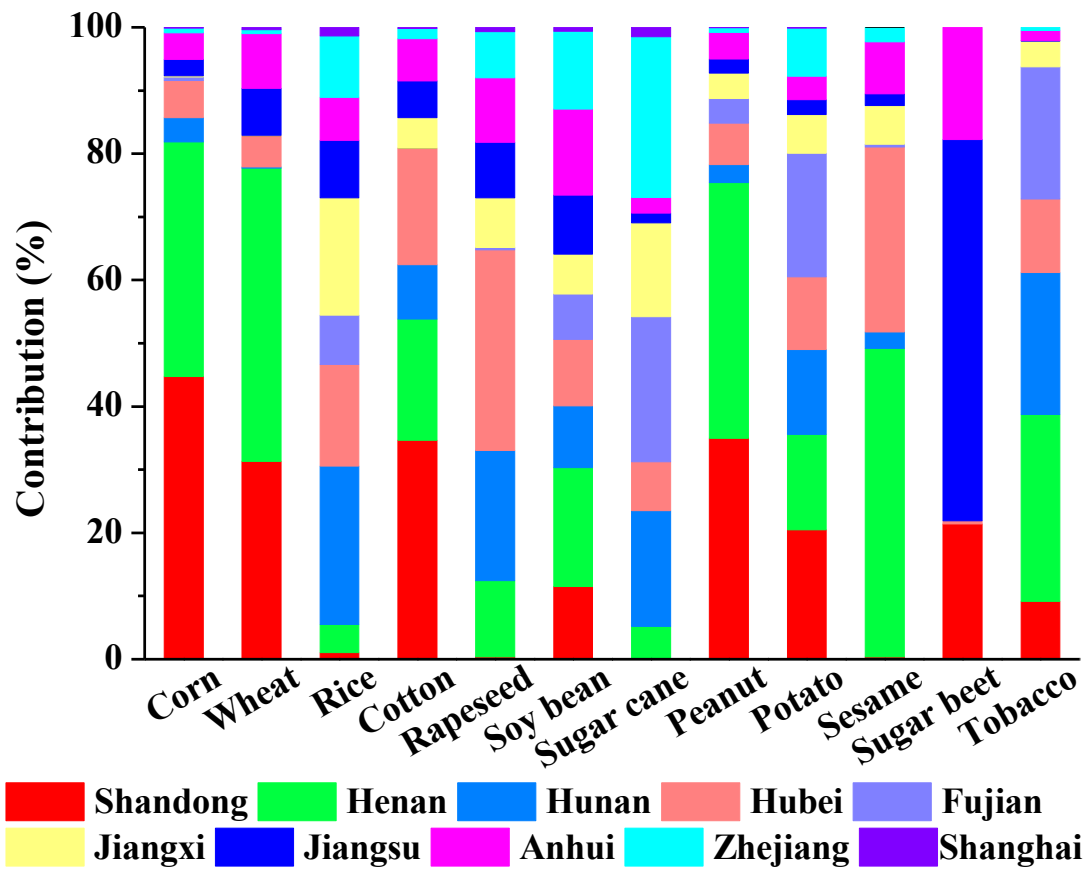
Figure 5. The averaged contributions of various crops straw burning to cropland PM$_{2.5}$ emission in different provinces.
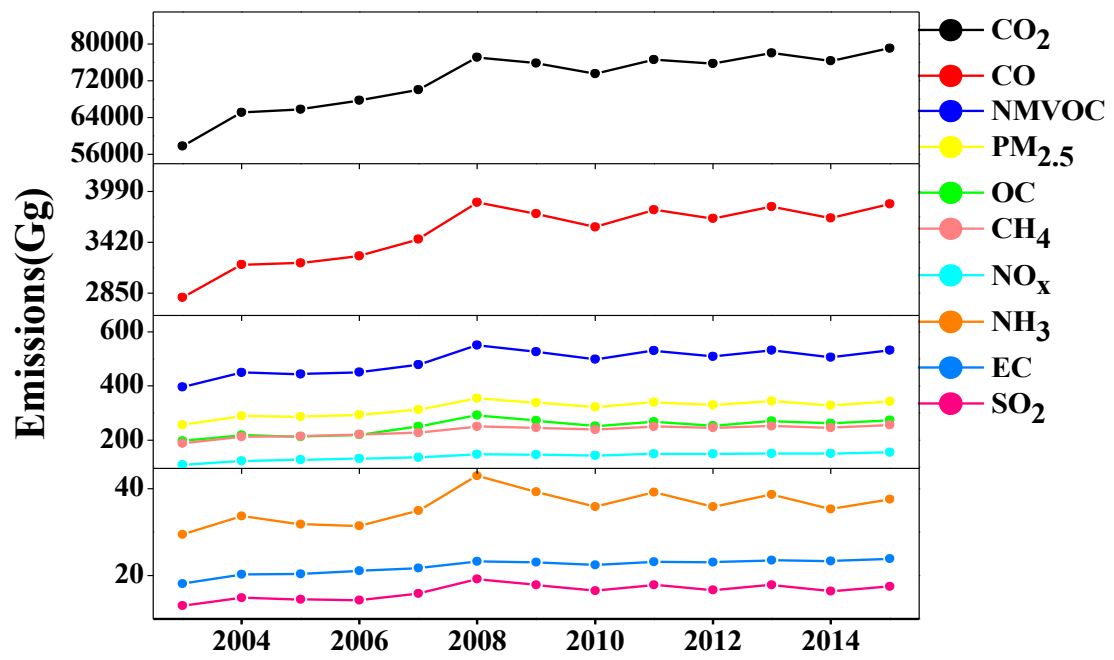
Figure 6. Yearly emissions of open biomass burning from 2003 to 2015.
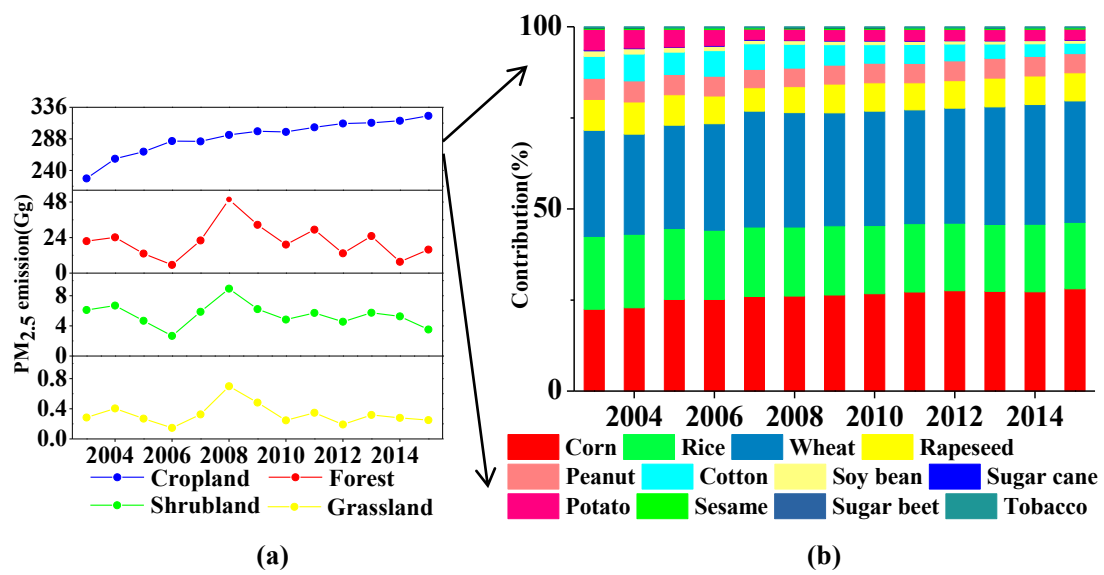
Figure 7. The multi-year PM$_{2.5}$ emission of different opening biomass burning sources (a) and various crop types (b) from 2003 to 2015.
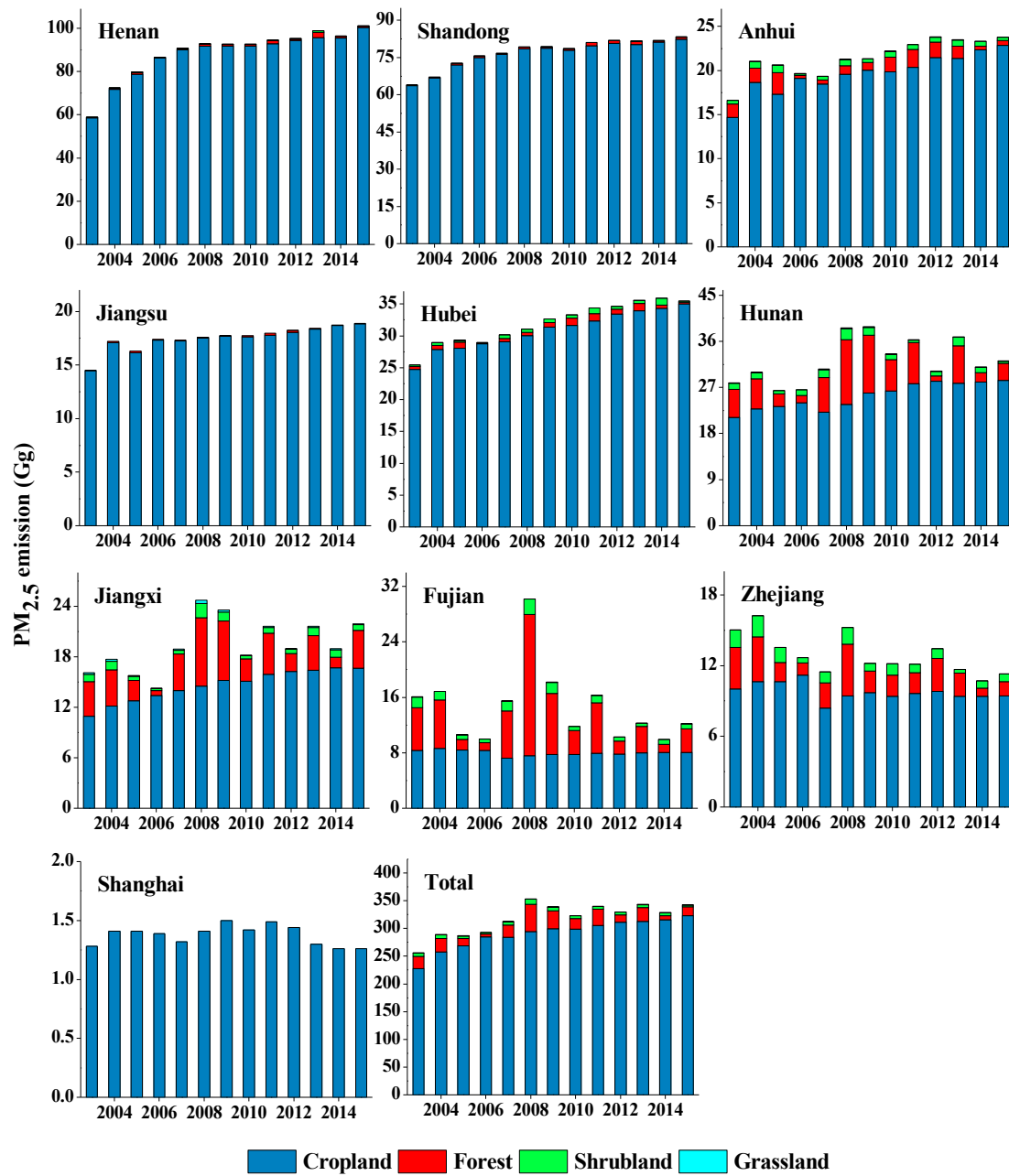
Figure 8. The multi-year PM$_{2.5}$ emission of the four types of biomass burning in different provinces from 2003 to 2015.
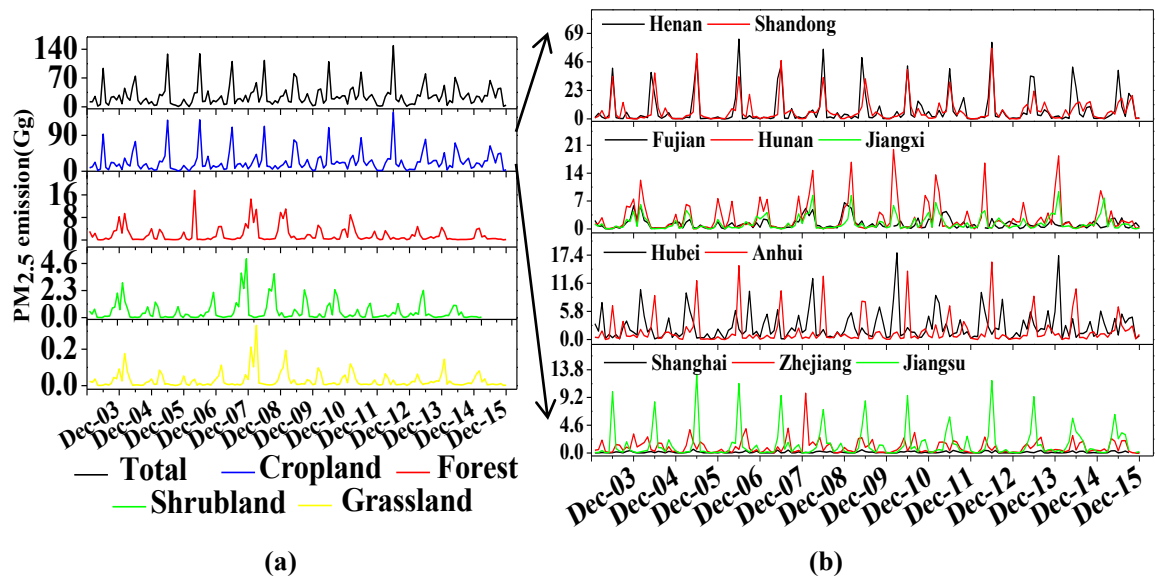
Figure 9. The monthly PM$_{2.5}$ emission of different open biomass burning from 2003 to 2015 for the whole Central and Eastern China (a) and each province (b).
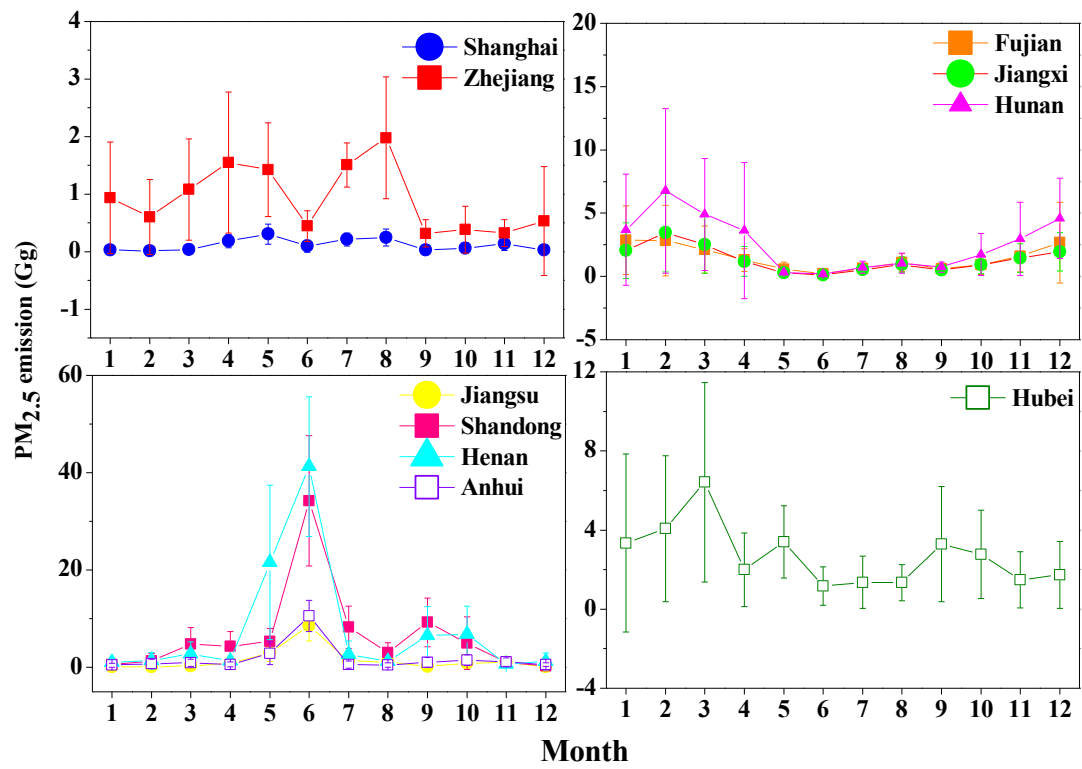
Figure 10. The monthly PM$_{2.5}$ emission from open biomass burning in each province.
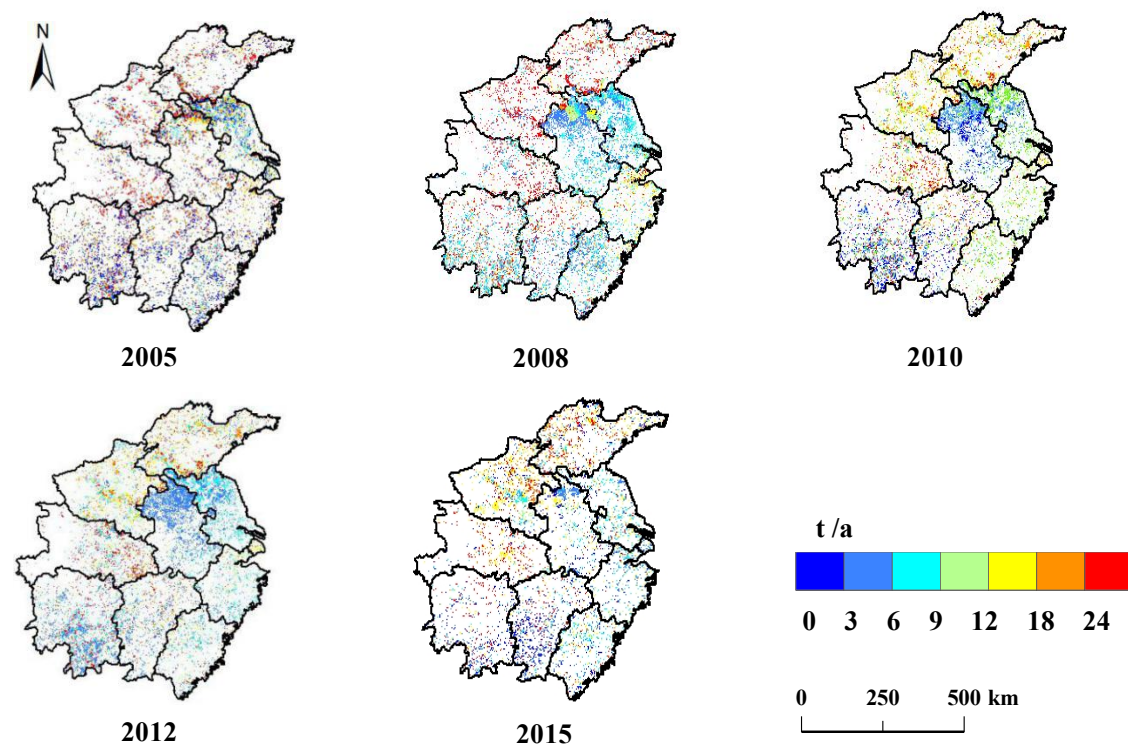
Figure 11. Annual spatial distribution (1 km×1 km) of PM$_{2.5}$ emission from opening biomass burning in Central and Eastern China.
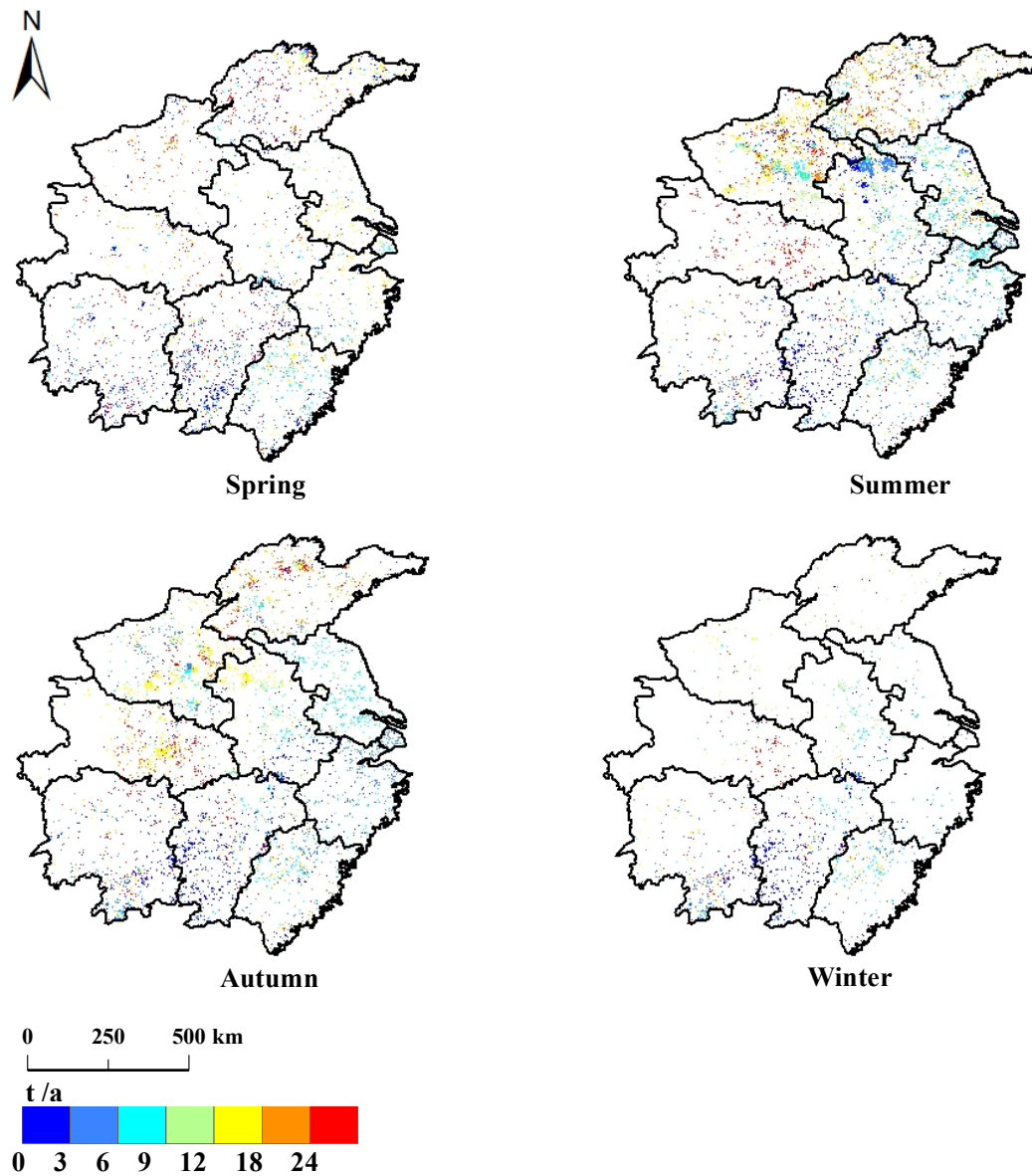
Figure 12. Seasonal emission distribution (1 km×1 km) of PM$_{2.5}$ in 2015 from opening biomass burning in Central and Eastern China.
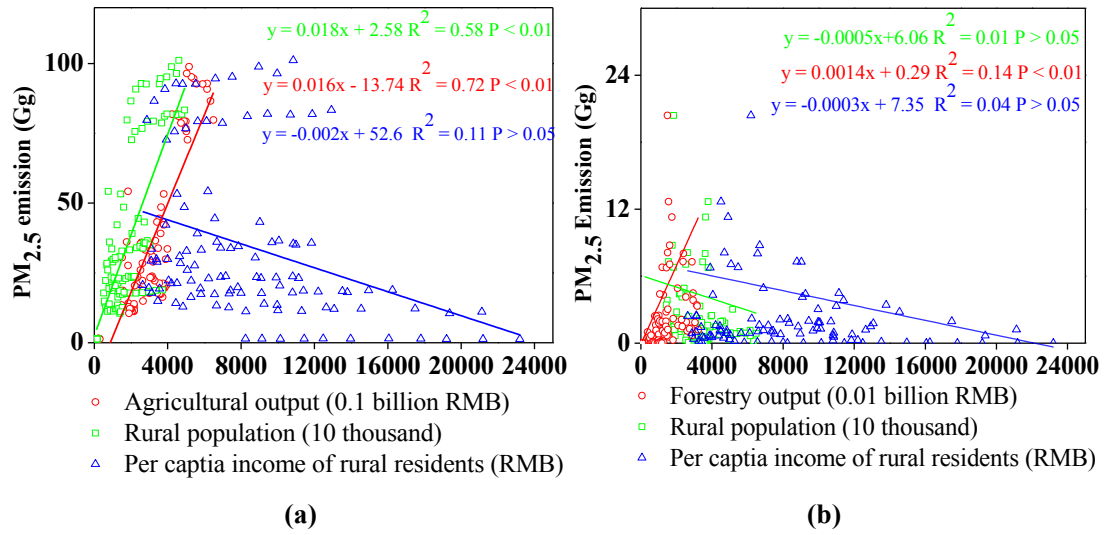
Figure 13. Correlation between PM$_{2.5}$ emission from crop residue burning and agricultural output , rural population, per captia incomes of rural residents (a) and correlation between PM$_{2.5}$ emission from forestry fire burning and forestry output, rural population, per captia incomes of rural residents (b) in different provinces from 2003 to 2015.