1	Estimating the open biomass burning emissions in Central and
2	Eastern China from 2003 to 2015 based on satellite observation
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18	Abstract. Open biomass burning (OBB) has significant impacts on air pollution, climate change and potential
19	human health. OBB has raised wide attention but with little focus on the annual variation of pollutant emission.
20	Central and Eastern China (CEC) is one of the most polluted regions in China. This study aims to provide a state-of
21	the-art estimation of the pollutant emissions from OBB in CEC from 2003 to 2015, by adopting the satellite
22	observation dataset (the burned area product (MCD64Al) and the active fire product (MCD14 ML)), local biomass
23	data (updated biomass loading data and high-resolution vegetation data) and local emission factors. The successful
24	adoption of double satellite dataset for long term estimation of pollutants from OBB with a high spatial resolution
25	can support the assessing of OBB on regional air-quality, especially for harvest periods or dry seasons. It is also
26	useful to evaluate the effects of annual OBB management policies in different regions. Here, monthly emissions of
27	pollutants were estimated and allocated into a 1×1 km spatial grid for four types of OBB including grassland,
28	shrubland, forest and cropland. From 2003 to 2015, the emissions from forest, shrubland and grassland fire burning
29	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 (SO₂), ammonia (NH₃), carbon monoxide (CO), carbon dioxide (CO₂) 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 , 32 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 33 for all pollutant emissions, by 84%-96%. For the forest, shrubland and grassland fire burning, forest fire burning 34 35 emissions contributed the most and emissions from grassland fire was negligible due to few grass coverage in this region. High pollutant emissions concentrated in the connection area of Shandong, Henan, Jiangsu and Anhui, with 36 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 May, June, September and October, at which ~50% of the total pollutants emission were emitted in these months . 39 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 influencing factors for OBB emissions.

46

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 (PM2.5) 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 and Andreae, 1990; Andreae and Merlet, 2001; Bond et al., 2004; Akagi et al., 2011; Zhang et al., 2016). 56

From 1970s (Crutzen et al., 1979), emission estimation of biomass burning has been a research hot topic from
global (Seiler and Crutzen et al., 1980; Levine, 1995; Liousse et al., 1995; Bond et al., 2004; Randerson et al., 2012;
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 million tons of biomass open burned each year 60 (Zhang et al., 2015). The quantitative estimation of pollutants emission for the whole China (Streets et al., 2003; 61 62 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 63 deterioration. The Central and Eastern China (CEC), including the Central China (Hunan, Henan and Hubei) and 64 65 the Eastern China (part of the North Plain of China (Shandong), the Yangtze River delta (YRD, including Zhejiang, 66 Jiangsu, Anhui and Shanghai) and part of the Pan-Pearl River delta (Fujian and Jiangxi)) (Figure 1), is an area with 67 plenty of vegetation coverage (as listed in Figure S1 of Supplementary File). Yin et al (2017) have indicated that 68 the crop residue fire burning in summer harvest time can lead to the increase of $PM_{2.5}$ concentration in China's 69 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 70 71 highlighted the role of OBB on worsening air quality regionally or at megacities, especially for crop residue 72 burning at harvest periods (Yamaji et al., 2010; Zhu et al., 2010; Yin et al., 2011; Huang et al., 2012b; Su et al., 73 2012; Cheng et al., 2014; Zhou et al., 2016; Zhang et al., 2017).

74 Previous studies mainly focused on crop residue burning emissions with relatively low spatial and temporal 75 resolution (Yamaji et al., 2010; Huang et al., 2012b), which may limit its adoption in air quality modeling to give 76 an accurate result. An accurate estimation of monthly emissions from OBB with a long timescale and high spatial 77 resolution is still limited. It should be noted that, the OBB activities owned spatial-temporal variation properties 78 and have changed greatly during the last two decades in China, especially for forestland fire burning (Huang et al., 79 2011) and crop residue burning, considering the implementation of related policies (Table S1 and Table S2). As a 80 big agricultural country, the Chinese government has placed a high priority on environmental pollution prevention 81 caused by OBB. From 1965 to 2015, 51 management documents for crop straw have been formulated and 34 82 documents were intensively issued after 2008 (Chen et al., 2016). Up to now, few studies have accurately estimated 83 the biomass burning emissions in a long time period (Fu et al., 2013; Cheng et al., 2014). The role of the pollution 84 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

90 burning was highly improved by the satellite observations of fire burned area or active burning fires (Freitas et al., 91 2005; Wooster et al., 2005; Roy et al., 2008; Giglio et al., 2008; Roy et al., 2008; Reid et al., 2009; Sofiev et al., 92 2009; Giglio et al., 2010; Liousse et al., 2010; Huang et al., 2012; Li et al., 2016). The improvement of 93 spatial-temporal distribution evolution was achieved by active fire products (e.g., the AVHRR fire count product 94 (Setzer and Pereira, 1991), MODIS active fire satellite products (Cooke et al., 1996) and VIRS fire count product 95 (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 96 97 Database (GFED) (Randerson et al., 2012)). However, satellite observation also exhibited weakness in estimating 98 fire burning emissions (Duncan et al., 2003; He et al., 2015). One is the burned area product, which provides fire 99 burned areas of the whole month. It is limited by the lower pixel resolutions. The size of many small burn scars is 100 below the detection limit of these products (Eva and Lambin, 1998; Laris, 2005; McCarty et al., 2009; Roy and 101 Boschetti, 2009). Therefore, the contribution of small fires to fire burned area and corresponding fire burning 102 emissions are still poorly understood (Randerson et al., 2012). The other is the active fire product, which can 103 provides information on small fire locations, occurrence time and small fire burned area (Prins and Menzel, 1992; 104 Giglio et al., 2006; Chuvieco et al., 2008; Roberts et al., 2009; Aragao and Shimabukuro, 2010; Bowman et al., 105 2011; Lin et al., 2012; Arino et al., 2012). The uncertainty of fire detection is mainly due to the limitation of 106 satellite overpass periods. To reduce the uncertainty of emission estimation by satellite products, the combination of 107 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., 2009; Chen et al., 2013; Shi et al., 2015). The results here will provide scientific evidence for policy making on
controlling OBB emission and modeling its regional impact on air quality, climate and human health. The methods
are also helpful for other regions for OBB emission estimation.

123 **2. Methods**

124 **2.1 Estimation of burned areas**

OBB emissions in CEC were initially estimated based on the local biomass data (biomass loading data and vegetation speciation data), satellite burned area data (Figure S2) and emission factors. Fire burning emission amount was calculated by the following equation (Wiedinmyer et al., 2011; Shi et al, 2015).

128
$$E_{i, x, t} = \sum_{j=1}^{n} BA_{x, t} \times CE_{x} \times BL_{x} \times EF_{i, j}$$
(1)

where j stands the different aggregated vegetation types; i stands for different pollutant species; $E_{i,x,t}$ is the emission amount of pollutant i in location x and month t; $BA_{x,t}$ is the total burned area (km²) of aggregated vegetation class in location x and month t; CE_x is defined as the combustion efficiency in location x; BL_x is the 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 $1 \text{ km} \times 1 \text{ km}$ grid. The total burned area in each grid cell was estimated by 140 the following equation (Randerson et al., 2012).

141

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

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

BA_{MCD64AL(i,t,j)} was directly detected from MCD64AL product. MCD14ML active fire points in each grid included two parts: active fires points with or near MCD64A1 burned area (FC_{in}) and active fires outside the 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 to the active fire product existed as the fire points and could not directly obtain the burned area data, the burned area of small fire was estimated based on the following method (Randerson et al., 2012).

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

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; 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 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 if BA_{MCD64A1} is equal to 0; γ is an additional unit less scalar which indicates the difference between F_{in} and F_{out} and γ is assumed equal to 1 in this research; r denotes the burning region; s indicates the burning period.

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157 2.2 Biomass fuel loading

For forestland, most previous studies used the forest biomass loading data from Fang et al (1996). The forest biomass loading data in recent years need to be updated. In this study, the forest loading data between 2003 and 2008 was collected from Fang et al (1996). From 2008-2015, the forest loading data was calculated based on the 8th Chinese National Forest Resource Inventory (Xu, 2014). The forest biomass density data (Table 1) was estimated by the following equation:

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$$\mathbf{B}_{i,r} = \mathbf{T}_{i,r} / \mathbf{A}_{i,r} \tag{4}$$

where i stands for different forest species (broadleaf forest, coniferous forest and mixed forest); r means each 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 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 as168 follows (Fang et al., 1996):

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

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

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.

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, 2004-2016). 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

In previous studies (Wang et al., 2008; Tian et al., 2011), the combustion efficiency (CE) of OBB was mainly 185 set as a constant, which may bias the emission estimation. To improve the accuracy, for cropland, the CE was set as 186 0.68 for soya bean and 0.93 for other types (Koopmans and Koppejan, 1997; Wang and Zhang, 2008; Zhang et al., 187 188 2011). For forest, shrubland and grassland, the CE of fires at each grid cell was assumed as a function of forest cover of corresponding grid cell (Ito et al, 2004; Wiedinmyer et al, 2006). If areas with tree coverage exceeding 189 190 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:

(6)

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

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

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

209 **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.

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

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

217 Where j means different biomass species; i denotes different provinces; $E_{t,j}$ is the emission of different biomass 218 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 219 in province i; $E_{i,j}$ is the total emission amounts from OBB in province i.

220 **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.

225 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.

229 3. Results and Discussion

230 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, CH₄, NO_x, NMVOCs, SO₂, NH₃, CO, CO₂ 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 variation of OBB emissions, the $PM_{2.5}$ variation was detailedly discussed as an example. From 2013 to 2015, the highest emission amounts of $PM_{2.5}$ were found in Henan and Shandong, accounting for 27.93% and 24.35% of the total emission amounts, respectively. The lowest emission appeared in Zhejiang and Shanghai, which only contributed for 4.05% and 0.43%. For other provinces, Hunan, Hubei, Fujian, Anhui, Jiangxi and Jiangsu accounted from 5.52% to 10.13% of the whole emission.

The contributions of different biomass burning types for various pollutants were shown in Figure 2a. Cropland burning contributed the most emission for all the pollutants, by84%-96%. The forest fire exhibited higher emission of NH₃, SO₂, NMVOCs and PM_{2.5}, accounting for 12%, 11%, 7% and 5% of corresponding total emission, respectively. As shown in Figure 2b, for cropland, wheat, corn and rice straw burning were the top three emission source types for all the pollutants. Corn straw burning contributed the most to SO₂(48%), NO_x(37%), NMVOCs (33%), CO (32%) and CO₂ (28%) emission. Highest contributions of EC (45%), OC (33%) and CH₄ (32%) from rice straw burning was found, while wheat straw burning contributed the most (31%) to PM_{2.5} emission.

In Figure 3, except for Fujian, cropland burning emission was the largest contributor to $PM_{2.5}$ emission, with 247 248 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%).

From Figure 4, emissions from wheat and corn straw burning mainly concentrated in Shandong and Henan (totally accounting for 82% and 78% of the whole emissions, respectively) and the rice straw burning exhibited 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.

271 3.2 Temporal variation and spatial distribution for OBB emissions in CEC

272 3.2.1 Yearly variation

273 Multi-year emissions of OBB from 2003 to 2015 in CEC were shown in Figure 5. The multi-year variation of
274 OBB emissions for various pollutants was similar (Figure 6).

The increase of crops residue burning dominated the significant growth of OBB emission. Pollutants emitted 275 276 from OBB all increased obviously from 2003 to 2008. Then with the adoption of strict control policies (Table S1 in 277 Supplement), the growth of crops residue burning emission gradually slow down. The forest, shrubland and 278 grassland fire burning were related to weather conditions and human activities. Their emissions were difficult to 279 predict and control and existed random yearly variation. Therefore, we discussed the multi-year variation during 280 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 322 281 282 Gg. After 2010, there existed higher (2011, 2013 and 2015) and lower values (2010, 2012 and 2014) alternately. 283 The values in 2011, 2013 and 2015 all did not exceed the peak values in 2008.

284 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 PM2.5 from forest, shrubland and grassland fire burning 285 were found in 2008, as 49 Gg, 8.9 Gg and 0.7 Gg, respectively. In 2008, intensive policies for utilization of straw 286 energy (Table S1) and strengthening the forestry fires prevention (Table S2) were published, which effectively 287 288 limited the emissions from forest and shrubland fire burning as Figure 6a 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 289 from 2010 to 2015, with higher emission in 2011, 2013 and 2015 and lower emission in 2012 and 2014 (Jin et al., 290 291 2017a). The multi-year tendency for forest, shrubland and grassland fire burning were mainly affected by the 292 variations in climate, management measures and other human forcing. It can also conclude that the yearly 293 fluctuation of pollutants from OBB was mainly impacted by the emission of forest, shrubland and grassland fire 294 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 residue burning significantly increased from 2003 (228 Gg) to 2008 (294 Gg), due to the increase of crops 301 302 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 2008 to 2015, strict policies were developed to improve the straw energy utilization and reduce the air pollution 305 306 raised by its burning. However, it has to say, the policies may not be well implemented, with the annual averaged increasing amounts of 7.3 Gg for PM_{2.5}. From Figure 6b, the large contributions to PM_{2.5} (22%-28% and 29%-33%) 307 308 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 7 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.

In Figure 8, the PM_{2.5} emission from crop residue burning exhibited higher amounts for Henan and Shandong province in 2015, as 100 Gg and 82 Gg, respectively, which are 200%-1200% times of those for other provinces. As the main source regions for air pollution of Yangtze River Delta (YRD) and Beijing-Tijin-Hebei (BTH) region (Fu et al., 2013; Zhou et al., 2015), the enforced and effective control of crop residue burning in the two provinces 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 8a. PM_{2.5} emission held higher amounts in May and June (90.4 Gg-179.3 Gg), followed by December to March of next year (32.2 Gg-127.3 328 Gg) and September-October (8.2 Gg-89.2 Gg), and was lowest during July-August (14.3 Gg-65.9 Gg). As the 329 330 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 burning of winter wheat, especially in Henan, Shandong, Jiangsu and Anhui (Figure 8b). Large amounts of wheat 335 straw were burned after the harvest to increase the soil fertility and prepare for following corn cultivation (Levine 336 337 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 9 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 for winter wheat harvesting (sown in October and harvested from May to June) and corn harvesting (sown in 351 352 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,

Fujian and Hunan (R^2 higher than 0.9, P<0.01), the largest monthly emissions were observed with forest and shrubland fire burning during the time between December and March, which is the dry season in these provinces (Li et al., 2014; Li et al., 2015). While in other months, the emissions were limited. For Shanghai and Zhejiang (R^2 = 0.7, P<0.01), lowest levels of PM_{2.5} emission were found, with peak values occurring in summer and autumn harvest periods. Obvious two peaks were found for April-May and July-August periods, which may reflect the rice harvesting at these times. To sum up, the regional differences of monthly PM_{2.5} emissions from OBB were mainly 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 burned area and a high-resolution vegetation map (1:1 000000) in CEC. The multi-year averaged spatial 364 distributions of PM2.5 emission were shown in Figure 10. It can be found that the OBB was widespread and 365 scattered. The average emissions intensity of $PM_{2.5}$ ranged from 0 to 15 tons per pixel in most provinces. The 366 367 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 provinces. The pixels of high emission intensity more than 70 tons from crop straw burning were also found in 371 372 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.

Though the emission intensities varied in the past ten years, the areas with high emission amounts remain similar. They were mainly located in the main agricultural areas in eastern Henan, southern Shandong, northern Anhui, northern Jiangsu, eastern Hubei and northern Hunan. This result is in accordance with formers (Huang, et al., 2012b). The junction regions of the four provinces (Henan, Shandong, Anhui and Jiangsu) should be paid more attention, where the pollutants emission from OBB jointed together. This was similar to a recent research (Jin et al., 2017b). This region belongs to HuangHuai Plain, with large area of cropland and low economic development levels. 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.

Figure 11 highlights the spatial distribution of $PM_{2.5}$ emitted from OBB in different seasons of 2015. Emissions were more concentrated in summer, followed by winter. In summer, the emission was concentrated in the connection regions of Henan, Shandong, Anhui and Jiangsu, which is mainly raised by the crop residue burning as discussed before. In winter, Jiangxi, Hunan and Fujian showed the higher emission intensities from forest and shrubland burning.

396 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.

Social customs also pose impact on OBB emissions. Biomass burning emissions in April can be enhanced by human burning activities in the tomb-sweeping day. The tomb-sweeping day (often in April 4 or April 5) is a time to memorize the death. People sweep graves and burn sacrifices by ignited straw, which can easily cause grass, shrub and forest fires (Qiu et al., 2016). The fire points at the tomb-sweeping day in CEC occupied by 22%-38% of the whole fire points in April in some years (Figure S5). The Chinese government has also introduced policies to prevent forest, shrubland and grassland fires on tomb-sweeping day (Table S2). The wildfires caused by biomass burning from late January to early February are partially related to the firework burning in the Spring Festival (Zuo, 2004). The firework burning activities for celebration and official sacrifices to ancestors in the Spring Festival
easily lead to grass, shrub and forest fires. All these activities can affect the emission levels and air quality in a
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 (R² higher than 0.58, P<0.01) for 423 the whole CEC (Figure 12a). 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 high emissions from cropland fire burning. No significant correlations were found for PM2.5 emission from crop 425 straw burning with the income of rural residents (Figure 15), which indicates that the rural economic level in 426 427 different regions in CEC have no relationship with the $PM_{2.5}$ emission. Then we calculated the correlations between 428 the change tendency of PM2.5 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 R² higher than 0.59, P<0.01) and negative correlation were found for $PM_{2.5}$ emission with rural population (most R² higher than 0.73, P<0.01) 431 432 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 R² lower 437 than 0.19, P>0.05), which holds less crop residue production and high utilization efficiency of crop straws.

Positive correlations were also found between forestry output and $PM_{2.5}$ emission from forestland, shrubland and grassland fire burning ($R^2 = 0.14$, P < 0.01) in the whole CEC (Figure 12b), which indicated that human forestry activities played positive role on open fire burning (Yan et al., 2006). According to our survey, human forest activities such as felling trees or picking up branches from trees can easily cause more forest and shrubland burning. However, compared with the crops straw burning, no correlation was found between $PM_{2.5}$ emission and other statistics data (the rural population and the per capita net income of rural residents) (Figure 13b and Table S4). It 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).

447 **3.4** Comparison with others

448 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 449 differences of OC, EC, CH₄, NO_x, NMVOCs, NH₃, CO₂ and CO emissions ranged from -41% to 12%. For SO₂ 450 451 (121%) and PM_{2.5} (288%) emission, the differences were relative high. All these differences were mainly caused by 452 the selection of EFs. The EFs employed in Wang et al.(2008) were constant values for different biomass species. In 453 addition, the crop residue to production ratio data and the burned ratio for various crop types were all specific to 454 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 455 Wang et al. (2008) and Huang et al. (2012), the estimate in our study is believed to be more accuracy. An obvious 456 underestimation of $PM_{2.5}$ emission from crop straw burning were found in Jin et al. (2017), in which not all the 457 458 crop species were considered.

459 The estimation based on satellite observation was prevalent recently. Compared to Zhou et al. (2017) who 460 estimated the pollutant emission amounts from MODIS burned area product, the results in this study were much 461 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 CO₂, 462 NMVOCs, SO₂ and NO_x in our study is due to the adoption of more accurate and suitable EFs values as those in a 463 464 previous study (Tang et al, 2014). Our emission estimation of the pollutants is more similar to the results of Qiu et 465 al. (2016), who also used multiple satellite products (MCD14 ML and MCD64Al) to estimate the OBB emissions 466 of China in 2013, with the differences of the two studies ranging from -42% to 22%. For CH₄, NO_x, NMVOCs, NH₃ and CO₂, the differences were less than 10%. The reason for the differences is due to the use of updated local 467 468 biomass data and EFs in this study. Therefore, the combination of multiple satellite products with local EFs data 469 and updated local biomass data (updated forest loading data, the crop residue to production ratio data and the 470 burned ratio for various crop types) are likely to have improved the estimation of pollutant emission from OBB 471 effectively.

472 **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 (Zhao et al., 2011). The uncertainty of biomass loading data and combustion efficiency was estimated to be 481 482 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 these parameters, 20,000 Monte Carlo simulations were performed to evaluate the estimation uncertainty 484 quantitatively for pollutant emissions with 95% coincidence level. Table 9 showed the emission uncertainty for 485 486 different pollutants from 2003-2015. On average, the uncertainty of the estimated OC, EC, CH₄, NO_x, NMVOCs, CO, SO₂, NH₃, CO₂ and PM_{2.5} were (-30%, 30%), (-48%, 48%), (-20%, 20%), (-20%, 20%), (-45%, 45%), (-18%, 487 488 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, updated forest loading data, the adoption of local crop residue to production ratio data and the crop residue burned 491 492 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 reflect the actual combustion conditions (Chen et al., 2013) Therefore, due to the adoption of multiple satellite 495 496 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

In this study, a combination of the burned area product (MCD64Al) with the active fire product (MCD14 ML), as well as local high resolution vegetation speciation data, updated local biomass data, local emission factors and survey results were used to estimate the pollutant emissions from open burning in Central and Eastern China (CEC)

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 505 concentrated in agricultural provinces, such as Henan and Shandong. For forest and shrubland, the fire burning was 506 mainly concentrated in Fujian, Jiangxi and Hunan provinces, with abundant forest resources. Wheat, corn and rice 507 straw were the major three types of crop straws for pollutant emission. Wheat and corn straw burning dominated in 508 Shangdong and Henan and the rice straw burning dominated in Hunan, Jiangxi and Hubei provinces. For various 509 pollutant emissions, corn straw burning was the largest contributor to SO₂, NO_x, CO, NMVOCs, CO₂, NH₃. OC, 510 EC and CH₄ 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 511 512 emissions were mainly found in the major agricultural areas in eastern Henan, southern Shandong, northern Anhui, 513 northern Jiangsu, eastern Hubei and northern Hunan, due to their abundant agricultural cultivated areas and low 514 straw utilization efficiency.

From 2003 to 2015, the multi-year tendency of opening biomass residue burning emission for various 515 pollutants was similar. Emissions from crop straw burning continued to increase, due to the gradual increase of crop 516 517 residue production. While emissions from forest, shrubland and grassland fire burning exhibited yearly fluctuations, 518 which was mainly influenced by the environmental conditions, management measures and other human driving 519 factors. Monthly distributions revealed that the pollutant emissions were at the highest levels in May and June, with 520 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 521 522 to be regulated continuously by local governments and emissions from forest and shrubland burning accounted for 523 the vast majority of total emissions in December to March should also be paid attention. The emission of crop 524 residue burning was associated with the rural population, agricultural output and economic levels while the 525 environmental conditions play an important role in the emissions from forestland, shrubland and grassland fire 526 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 $(1 \times 1 \text{ km})$ 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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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

Table 1. Forest, shrubland and grassland biomass fuel loading (kt km⁻²) in each province.

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

Tree species	а	b	Tree species	a	b
Larix	0.967 ^a	5.7598ª	Cinnamomum camphora	1.0357ª	8.0591ª
Pinus koraiensis	0.5185 ^a	18.22 ^a	Phoebe	1.0357 ^a	8.0591ª
Pinus sylvestris var. mongolica	1.11 ^a		Elm	0.7564^{f}	8.3013 ^f
Pinus densiflora	1.0945 ^b	2.004 ^b	Robinia	0.7564ª	8.3103ª
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	18.7435ª	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	1.0357ª	8.0591ª
Pinus kesiya var. langbiamensis	0.510 ^b	1.045 ^b	Populus	0.4754ª	30.603 ^a
Pinus densata	0.5168 ^b	33.237 ^b	Salix	0.4754°	30.6034°
Foreign pine	0.5168	33.2378	Paulownia	0.8956 ^d	0.0048 ^d
Pinus elliottii	0.51 ^e	1.05 ^e	Eucalyptus	0.7893ª	6.9306ª
Pinus taeda	0.5168 ^f	33.2378 ^f	Rich acacia	0.4754 ^a	30.60 ^a
Mount huangshan pine	0.5168^{f}	$33.2378^{\rm f}$	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	41.3318ª	Broad-leaved mixed	0.8392 ^b	9.4157 ^b
Metasequoia	0.4158ª	41.3318 ^a	Coniferous and broad-leaved mixed	0.7143 ^b	16.9154 ^b
Taxodium ascendens	0.399ª	22.541ª	Betula	0.9644 ^a	0.8485 ^a
Abies	0.4642 ^a	47.499	White birch	0.9644 ^a	0.8485ª
Picea	0.4642 ^a	47.499ª	Betula costata	0.9644ª	0.8485ª
Tsuga	0.4158ª	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	0.6129ª	26.1451ª	Juglans mandshurica	0.798°	0.42 ^c
Yew	0.4642 ^b	47.499 ^b	Amur corktree	0.798°	0.42 ^c
Other fir	0.399ª	22.541ª	Ouercus	1.3288ª	-3.8999ª

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

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).

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	0.37ª	0.71ª
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	31	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	0.53ª	2.01 ^a	0.37ª	0.71ª
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	0.37ª	0.71ª
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	0.53ª	2.01ª	0.37 ^a	0.71ª

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

References: ^aZhu et al. (2017); ^bChen et al. (2008); ^cXie et al. (2011a); ^dXie et al (2011b); ^eZeng et al (2007); ^fAo et al. (2007); ^gLei et al. (2009); ^hZhao et al. (2008); ⁱXue et al. (2006); ^jYu et al (2009); ^kZou et al (2008); ¹Liu et al. (2010); ^mTang et al. (2009); ⁿLi et al. (2008).

Decion	Crops straw	
Region	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	

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

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

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	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
forest										
Broadleaf	9.2 ^e	0.6 ^e	102 ^e	5 ^e	1.3 ^e	11 ^e	1^{e}	1.5 ^e	1630 ^e	13 ^e
forest										
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

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

References: ^aCao et al. (2008); ^bLi et al. (2007); ^cHe et al. (2015); ^dTang et al. (2014); ^eAkagi et al. (2011); ^fZhang et al. (2008); ^gEPD (2014); ^hWang et al. (2008); ⁱAndreae and Rosenfeld (2008); ^{*}This study.

Province	OC	EC	CH ₄	NO _x	NMVOCs	SO_2	NH ₃	СО	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 6. Cumulative emissions of major pollutants from open biomass burning in Central and Eastern China during 2003-2015 (Gg)

PM _{2.5} emission	Rural population	Per capita income of rural residents	Agricultural output
(Gg)	(10 thousand)	(RMB)	(0.1 billion RMB)
C1 1 .	y = -0.001x + 1.64	y = -5E-06x + 1.4	y = 7E-05x + 1.36
Shanghai	$R^2 = 0.17 \ P > 0.05$	$R^2 = 0.09 P > 0.05$	$R^2 = 0.0005 \ P > 0.05$
71	y = 0.002x + 6.19	y = -6E - 05x + 10.47	y = -0.001x + 10.72
Znejiang	$R^2 = 0.06 \ P > 0.05$	$R^2 = 0.19 P > 0.05$	$R^2 = 0.19 P > 0.05$
	y = -0.0002x + 8.219	y = -3E-05x + 8.1884	y = -0.0002x + 8.2144
Fujian	$R^2 = 0.01 \ P > 0.05$	$R^2 = 0.06 P > 0.05$	$R^2 {=} 0.06 \; P {>} 0.05$
т.	y = -0.002x + 23.41	y = 0.0002x + 15.33	y = 0.001x + 15.18
Jiangsu	$R^2 = 0.8 P < 0.01$	$R^2 = 0.66 P < 0.01$	$R^2 = 0.69 P < 0.01$
	y = -0.008x + 56.19	y = 0.0009x + 25.39	y = 0.004x + 24.31
Hubei	$R^2 = 0.94 P < 0.01$	$R^2 = 0.86 P < 0.01$	$R^2 = 0.92 P < 0.01$
	y = -0.005x + 37.11	y = 0.0007x + 16.12	y = 0.004x + 14.5
Anhui	$R^2 = 0.91 P < 0.01$	$R^2 = 0.79 P < 0.01$	$R^2 = 0.85 P < 0.01$
	y = -0.01x + 62.66	y = 0.0008x + 20.66	y = 0.003x + 20.1
Hunan	$R^2 = 0.78 P < 0.01$	$R^2 = 0.8 P < 0.01$	$R^2 = 0.91 P < 0.01$
. .	y = -0.008x + 33.73	y = 0.0006x + 11.19	y = 0.006x + 9.84
Jiangxi	$R^2 = 0.92 P < 0.01$	$R^2 = 0.82 P < 0.01$	$R^2 = 0.87 P < 0.01$
	y = -0.01x + 150.14	y = 0.003x + 70.41	y = 0.008x + 62.79
Henan	$R^2 = 0.8 P < 0.01$	$R^2 = 0.59 P < 0.01$	$R^2 = 0.72 P < 0.01$
Chara hara	y = -0.009x + 122.46	y = 0.0014x + 66.48	y = 0.004x + 62.11
Shandong	$R^2 = 0.73$ P < 0.01	$R^2 = 0.66 P < 0.01$	$R^2 = 0.77 P < 0.01$

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.

Reference	Year	OC	EC	CH ₄	NO _x	NMVOCs	SO_2	NH ₃	СО	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 8. Comparison of the emissions with previous studies in different years (Gg)

Year	OC	EC	СО	CH ₄	NO _x	NMVOC	SO_2	NH ₃	CO_2	PM _{2.5}
2002	(-31%,	(-46%,	(-20%,	(-20%,	(-23%,	(-52%,	(-52%,	(-33%,	(-3%,	(-44%,
2003	31%)	46%)	20%)	20%)	23%)	53%	51%)	33%)	3%)	44%)
2004	(-29%,	(-47%,	(-21%,	(-22%,	(-24%,	(-45%,	(-56%,	(-34%,	(-3%,	(-47%,
2004	29%)	48%)	21%)	22%)	24%)	45%)	58%)	34%)	3%)	47%)
2005	(-31%,	(-42%,	(-16%,	(-16%,	(-19%,	(-41%,	(-44%,	(-32%,	(2%,	(-35%,
2003	31%)	44%)	16%)	17%)	19%)	40%)	44%)	33%)	3%)	34%)
2006	(-32%,	(-44%,	(-13%,	(-14%,	(-16%,	(-43%,	(-34%,	(-34%,	(-3%,	(-25%,
2006	33%)	44%)	13%)	14%)	17%)	43%)	35%)	34%)	3%)	25%)
2007	(-30%,	(-46%,	(-18%,	(-19%,	(-22%,	(-50%,	(-50%,	(-33%,	(-3%,	(-42%,
2007	30%)	46%)	19%)	19%)	22%)	51%)	50%)	34%)	3%)	42%)
2008	(-26%,	(-52%,	(-25%,	(-28%,	(-29%,	(-69%,	(-62%,	(-38%,	(-3%,	(-55 %,
2008	26%)	53%)	25%)	28%)	29%)	69%)	61%)	39%)	3%)	56%)
2000	(-28%,	(-48%,	(-21%,	(-21%,	(-24%,	(-59%,	(-54%,	(-34%,	(-3%,	(-47%,
2009	28%)	48%)	21%)	22%)	24%)	59%)	54%)	35%)	3%)	47%)
2010	(-31%,	(-44%,	(-16%,	(-17%,	(-19%,	(-45%,	(-42%,	(-33%,	(-3%,	(-34%,
2010	31%)	44%)	17%)	17%)	19%)	46%)	42%)	34%)	3%)	34%)
2011	(-29%,	(-46%,	(-18%,	(-19%,	(-21%,	(-52%,	(-47%,	(-34%,	(-3%,	(-40%,
2011	29%)	46%)	18%)	19%)	21%)	53%)	47%)	35%)	3%)	40%)
2012	(-32%,	(-44%,	(-14%,	(-14%,	(-17%,	(-35%,	(-35%,	(-34%,	(-3%,	(-27%,
2012	33%)	44%)	14%)	14%)	17%)	35%)	35%)	35%)	3%)	26%)
2013	(-30%,	(-44%,	(-16%,	(-17%,	(-20%,	(-51%,	(-42%,	(-33%,	(-3%,	(-36%,
2013	30%)	44%)	16%)	17%)	20%)	51%)	43%)	34%)	3%)	36%)
2014	(-32%,	(-45%,	(-15%,	(-16%,	(-19%,	(-43%,	(-42%,	(-35%,	(-3%,	(-33%,
2014	32%)	46%)	15%)	16%)	18%)	43%)	42%)	35%)	3%)	33%)
2015	(-31%,	(-44%,	(-14%,	(-14%,	(-17%,	(-41%,	(-34%,	(-34%,	(-3%,	(-26%,
2013	31%)	44%)	146%)	13%)	17%)	41%)	34%)	35%)	3%)	26%)

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



Figure 1. Location of Central and Eastern China and the key megacitie



Figure 2. 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 3. The averaged contributions of different biomass burning types to $PM_{2.5}$ emission in each province.



Figure 4. The averaged contributions of various crops straw burning to cropland $PM_{2.5}$ emission in different provinces.



Figure 5. Yearly emissions of open biomass burning from 2003 to 2015.



Figure 6. The multi-year $PM_{2.5}$ emission of different opening biomass burning sources (a) and various crop types (b) from 2003 to 2015.



Figure 7. The multi-year $PM_{2.5}$ emission of the four types of biomass burning in different provinces from 2003 to 2015.



Figure 8. 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 9. The monthly PM_{2.5} emission from open biomass burning in each province.



Figure 10. Annual spatial distribution (1 km \times 1 km) of PM_{2.5} emission from opening biomass burning in Central and Eastern China.



Figure 11. Seasonal emission distribution (1 km \times 1 km) of PM_{2.5} in 2015 from opening biomass burning in Central and Eastern China.



Figure 12. 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.