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LETTER

Contributions of open crop straw burning emissions to $PM_{2.5}$ concentrations in China

Libo Zhang[1], **Yongqiang Liu**[2] **and Lu Hao**[1]

[1] International Center for Ecology, Meteorology and Environment, College of Applied Meteorology, Nanjing University of Information Science and Technology, Nanjing, People's Republic of China
[2] Center for Forest Disturbance Science, USDA Forest Service, Athens, GA, USA

E-mail: yliu@fs.fed.us

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Abstract

$PM_{2.5}$ inventories have been developed in major Chinese cities to quantify the contributions from various sources based on annual emissions. This approach, however, could substantially underestimate the contribution from open straw burning during the harvest or other active burning periods. This study examines this issue by estimating monthly and annual straw-burning $PM_{2.5}$ emissions in China and comparing with them with the corresponding emissions from other anthropogenic sources. Annually burned straw $PM_{2.5}$ emissions during 1997 $\sim$ 2013 for 31 China provinces were calculated based on crop and related burning information for 12 months based on satellite detection of agricultural burning. Annual emissions from other anthropogenic sources were collected from the literature and allocated to monthly values using air pollution index measurements. The results indicate that the annual $PM_{2.5}$ emissions from open straw burning in China were 1.036 m tons. The monthly $PM_{2.5}$ emission ratios of straw burning to other anthropogenic sources during June, the harvest period for many regions, were several times larger than the annual ratios at national, regional, and province levels, suggesting that, in contrast to annual emissions that were used in the $PM_{2.5}$ inventories in Chinese cities to assess the contributions from other sources, monthly emissions should be used to assess the contributions from straw burning during the harvest or other active burning periods. The larger contributions from straw burning shown in this study also suggest that substantial reduction of open field straw burning would dramatically improve air quality in many Chinese regions during the harvest or other active burning periods.

1. Introduction

China is among the major agricultural nations in the world. Crop straw resources in China, ranking the first in the world, account for 17.29% of the global production (Bi *et al* 2010). Corn, wheat, and rice straws are the major crop straw resources in China. Farmers need to remove a large amount of crop straws in a short period of time after the harvest in order to plant crops for the next growing season. In comparison with other approaches such as cutting, burning is the most effective and is less expensive to remove straws.

However, straw burning has many adverse environmental and ecological impacts (Shi *et al* 2014). Straw burning wastes valuable biological resources and, more importantly, often causes serious air pollution. Straw burning releases a large amount of pollutants such as $PM_{2.5}$, SO_2, CO, NH_3, VOC, and NO_X (Koppmann *et al* 2005, Li *et al* 2008). Further, straw burning is one of the primary contributors to haze and smog formation during the harvest periods in China (Zha *et al* 2013).

Air pollution is a serious environmental problem in China. Regional haze and smog events have dramatically increased in recent years, due to the rapid development of the economy since the late 1970s. This situation has worsened in recent decades due to dramatic urban expansion and an in increase in automobile use in China (Huang *et al* 2013). For example, there were 124 recorded haze and smog days in Beijing in 2012, 25 of which occurred in January (13 more than the monthly average over previous years), and 18 in June (three times the monthly average over the previous 10 years) (http://beijing.tianqi.com/news/19519.html).

Reversing these declining air quality trends and eventually solving the air pollution problem is one of the fundamental goals of China today. Many research projects have been initiated to assess the intensity of air pollution and to identify the major contributors. China started monitoring PM_{10}, SO_2, and NO_2 as early as 2000 in more than 40 major cities to formulate the air pollution index (API). In 2012, China added $PM_{2.5}$, the most important contributor to smog and haze and one of the major air pollution indicators used by other countries, to the monitoring list together with O_3 and CO to formulate a new air pollution index (i.e., the air quality index (AQI)).

A recent major effort has been the development of $PM_{2.5}$ inventories and the identification of major emission sources based on the $PM_{2.5}$ data together with various analysis tools. This task was accomplished for nine cities in the three most industrialized cities in Beijing-Tianjin-Hebei, the Yangtze River Delta, and the Pearl River Delta in 2014 and 26 more cities will be added to the list in 2015. The inventories are essential for air pollutant control, prediction, and prevention.

The $PM_{2.5}$ particles come from both local and transported sources. In Beijing, for example, they accounted for 64% ~ 72% and 28% ~ 36%, respectively. The local sources were mainly automobiles (31.1%), coal consumption (22.4%), industry (18.1%), construction dust (14.3%), and other sections (14.1%). The percentage of transported sources were not specified, but smoke particles from crop-straw burning were expected to be one of the major components for Beijing (Cheng *et al* 2013, Wang *et al* 2014).

Straw-burning emissions in China have been estimated for 2000 ~ 2003 (Cao *et al* 2008), 2006 (Wang and Zhang 2008), and 2007 (Lu *et al* 2011), based on crop yields and burning properties (Ortiz de Zarate *et al* 2005, Li *et al* 2007, Zhang *et al* 2008, Wang and Zhang 2008, Bi *et al* 2009, Zuo *et al* 2015). According to Guan *et al.* (2014) and Lu *et al* (2011), annual biomass burning contributed about 26% of total particulate matter (PM) emissions, half of which were from open-field straw burning. These results provide useful information to assess how important straw-burning emissions are as a transported source to the $PM_{2.5}$ inventories in China cities.

However, straw burning is essentially a seasonal activity and it peaks with crop harvests. The harvest periods are mostly in June—July and around October in southern China and late May—early June, and late September—early October in northern China (Wang and Zhang 2008). This strong seasonal dependence suggests that the $PM_{2.5}$ emission ratios of straw burning to other anthropogenic sources during the harvest periods are much larger than the annual ratios. Thus, the current approach to developing $PM_{2.5}$ inventories in China cities using annual values underestimates the contributions of straw-burning emissions during the harvest periods. For the $PM_{2.5}$ inventory in Beijing, the contributions from the transported sources were more than 50% during severe air pollution periods, 15% ~ 20% more than the annual values. This is a common feature of biomass burning.

The aim of this study was to examine the above issue by estimating and analyzing the monthly $PM_{2.5}$ emissions from open straw burning during 1997 ~ 2013 in China and comparing the emission ratios of straw burning to other anthropogenic sources. The results are expected to provide useful information for improving our understanding of the roles of straw-burning emissions in air pollution formation and for better assessing the contributions of transported sources in the $PM_{2.5}$ inventories in Chinese cities.

2. Methods

The methods used in this study are briefly described as follows. An illustration of the calculation procedure (figure S1) with a detailed description of emission estimation is provided in the supplemental material.

2.1. Emissions

Annual emissions of open straw burning were obtained using (Lu *et al* 2011)

$$M_i = \sum_m P_m \times N_m \times R_r \times F \times EF_i, \qquad (1)$$

where M_i is emission of ith straw-burning pollutant, m crop species, P annual crop yield, N yield-to-straw ratio, R_r portion of open straw burning in region r, F combustion efficiency, and EF_i emission factor of the pollutant.

To estimate emissions from open straw burning, the annual crop yields of 31 China provinces during 1997 ~ 2013 (Chinese Statistical Yearbook), the yield-to-straw rates from Bi *et al* (2009) and Zuo *et al* (2015), the straw-burning proportions from Wang and Zhang (2008), and the average combustion efficiency from Zhang *et al* (2008) were used. The emission factors of the straw burning were provided in many studies (e.g. Cao *et al* 2008, Li *et al* 2007, Zhang *et al* 2015, Zhu *et al* 2005). This study used the results from Ni *et al* (2005) and Li *et al* (2007) with the $PM_{2.5}$ emission factors of 8.5, 9.5, 12.0, and 9.5 g kg^{-1} for rice, wheat, corn, and other crops, respectively. An average value of 9.65 g kg^{-1} was also used without distinguishing crop types. In addition, PM_{10} emissions were calculated using an emission factor of 11.7 g kg^{-1} based on Li *et al* (2007), Lu *et al* (2011), and Zhu *et al*

(2012). The results for 2006 were also used for comparison to examine interannual variability.

Annual $PM_{2.5}$ emissions from other anthropogenic sources (mainly traffic, energy, industry, and construction) were estimated for 2001 (Zhang *et al* 2007), 2007 (Cao *et al* 2011), and multiple years (Xie and Han 2014). The 2006 $PM_{2.5}$ emissions from Zhang *et al* (2009) were used, which were part of an inventory of air pollutant emissions of INTEX-B in 2006 from all major anthropogenic sources except biomass burning, with $PM_{2.5}$ emission of 13.3 m tons and PM_{10} of 18.2 m tons (1 m $ton = 1\ Tg = 10^{12}$ g).

2.2. MODIS monthly agricultural burning emissions

The Moderate Resolution Imaging Spectroradiometer (MODIS) is the most frequently used satellite remote sensing (RS) sensor to detect straw burning in China (Li *et al* 2009). The monthly global fire emission data for agricultural burning from GFED4.0 s (van der Werf *et al* 2010, Giglio *et al* 2013) (http://www.globalfiredata.org) were used to allocate the calculated annual straw-burning emissions to monthly values. The data combine MODIS information on fire activity and vegetation productivity to estimate gridded monthly burned area and fire emissions. The RS detection has a spatial resolution of 0.25 degrees and is available from 1997 and onwards. Note that GFED4.0s includes an algorithm to detect small fires that is helpful to improve the accuracy of the estimation of agricultural straw burning. However, straw burning in China is scattered in residential areas with small burn sizes. In addition, the MODIS detections during the day are available around 10 am and 1 pm local time. The flaming stage of straw burning may be last shorter than the interval between the two detection times. Thus, it is likely that the GFED data could have missed many small burns in China. Our comparison indicated that the detected emissions were much smaller than those obtained using crop yield data (figure S2). Nonetheless, little impact on the detection of straw burning season is expected (He *et al* 2007), Li *et al* 2009). Thus, we estimated straw-burning emissions based on crop data while using the GFED data for monthly allocation.

2.3. Air pollution index

Monthly means of API in 42 key cities were obtained based on daily values (http://www.mep.gov.cn) and averaged over 2001 ~ 2012. They were used to allocate the monthly variations of PM emissions from other anthropogenic sources. The API values are divided into five grades of 0 ~ 50, 51 ~ 100, 101 ~ 200, 201 ~ 300, and 301 ~ 500 with increasing severity of air pollution.

3. Results

3.1. Annual $PM_{2.5}$ emissions

The annual straw yield averaged during 1997 ~ 2013 and calculated using the crop yield data in China was 626.41 m tons, or province average of about 20 m tons. Straw yields varied dramatically across regions and provinces (figure 1(a)). Straw yields were relatively small in South and Northwest China and large in other regions (see the horizontal coordinate of figure 1 for each of the seven China geographic regions and 31 provinces included in each region; the geographic locations of the provinces are shown in figure 2). Ten provinces had yields much more than the province average, including Henan (60 m tons) of Central China, Shandong (52 m tons) of North China, and Heilongjiang (45 m tons) of Northeast China. The regional distributions of burned straw in open fields (figure 1(a)) were similar, but the values became large for South China and small for Southwest and Northeast China. The largest burned amounts at province level occurred in Jiangsu and Anhui (more than 10 m tons) of East China, followed by Hunan and Henan (about 9 m tons) of Central China, and Shandong (8 m tons) of North China. Heilongjiang of Northeast China only burned less than 5 m tons per year despite the large straw yield. Apparently the more economically developed regions such as East China had larger burning rates than the less developed regions such as Northeast China.

The annual $PM_{2.5}$ emission from open straw burning in China was 1.036 m tons, calculated using one single emission factor for all kinds of crops, which was very close to the value of 1.044 m tons calculated using three different emission factors for cereal crops and one emission factor for other crops. The emission value is comparable to the estimate by Cao *et al* (2008), but about half of the estimate by Wang and Zhang (2008), who used much larger yield-to-straw rate, proportion of burning, burning efficiency, and emission factors. Consistent with the amounts of burned straw shown in figure 1(a), larger PM emissions from straw burning occurred in East, Central, and North China (figures 1(b)) and 2(a)). The $PM_{2.5}$ emissions from Jiangsu and Anhui in East China reached 107.04 and 99.64 k tons, respectively (1 k $ton = 1\ Gg = 10^9$ g). In comparison, the annual PM_{10} emission was 1.256 m tons nationally, and 129.77 and 120.80 k tons, respectively, for Jiangsu and Anhui. This spatial distribution is consistent with other studies (e.g., Lu *et al* 2011).

The $PM_{2.5}$ emissions from other anthropogenic sources occurred mainly in North and East China, as well as in Sichuan of Southwest China and Guangdong of South China (figure 1(b)). These regions have high population density and more advanced industry and economy than other regions. In contrast, $PM_{2.5}$ emissions in the less industrialized areas of Xizang, Qinghai, Ningxia of Southwest and Northwest China, and the tourist-oriented Hainan of South China were very

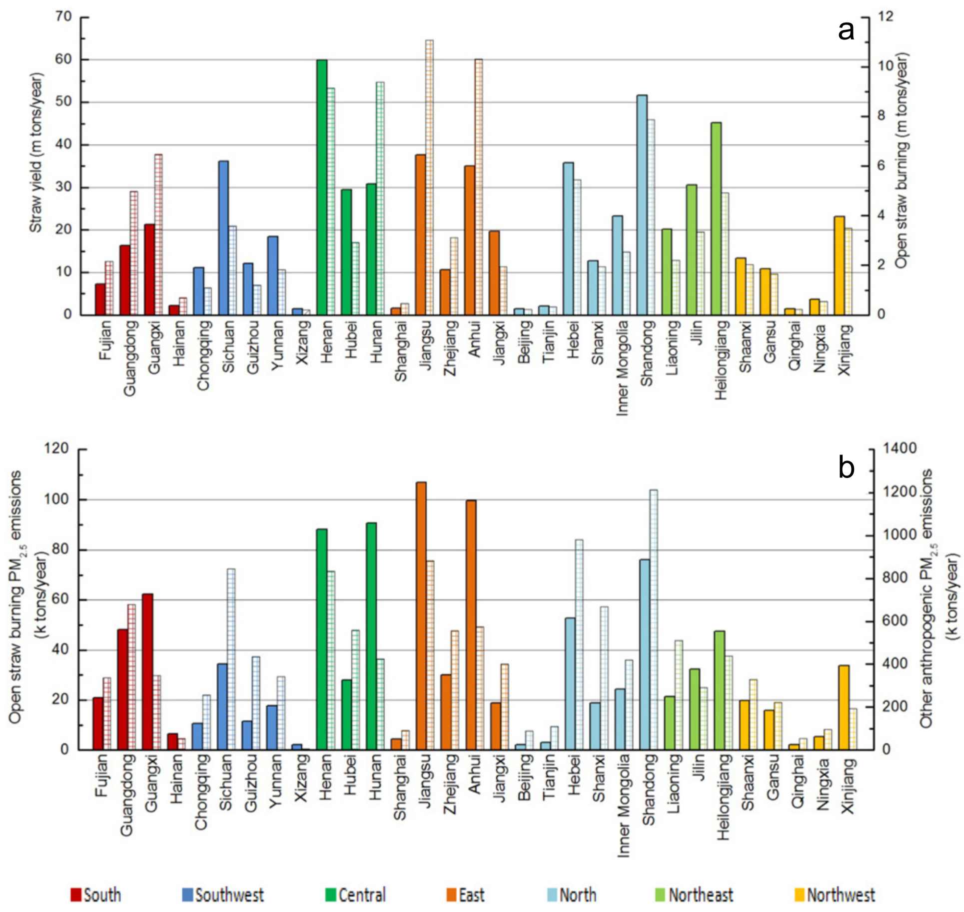

Figure 1. Annual properties of crop straw at province level. (a) Straw yields (solid bars) and open burned straw (shadow lines) during 1997-2013. (b) $PM_{2.5}$ emissions from straw burning (solid bars) during 1997-2013, and $PM_{2.5}$ emissions from other anthropogenic sources (shadow lines) for 2006.

low. In addition, emissions were low in the four municipalities of Beijing, Tianjin, Shanghai, and Chongqing. The largest $PM_{2.5}$ emission of about 1200 k tons occurred in Shandong of North China (figure 2(b)), followed by about 800 ∼ 1000 k tons in Hebei, Jiangsu, Henan, and Sichuan. Different from $PM_{2.5}$ emissions from straw burning, all regions except Northwest China had one or more provinces with considerably large emissions from anthropogenic sources. Note that the proportion rate for Hunan is 32.9% (district 6), which is nearly two times larger than the rate of 10.7% for Hubei (district 1) (table S2). Thus, despite having very similar straw yields, the amount of burned straw is about two times larger in Hunan than in Hubei. Also note that the emissions in Beijing, Shanghai, and Tianjin are relatively small. There are two reasons: (1) The emissions for each area is the total amount rather than the amount per unit. All three cities are extensively urbanized with little farming land.

3.2. Monthly $PM_{2.5}$ emissions

The maximum monthly variations of $PM_{2.5}$ emissions from open straw burning of 110, 76, and 45 k tons occurred in June in East, North, and Central China (figure 3(a)). At the province level in these regions, large $PM_{2.5}$ emissions in June were 58.51 k tons (Jiangsu), 48.10 k tons (Anhui), 41.79 k tons (Shandong), 40.98 k tons (Henan), and 21.29 k tons (Hebei). In other regions, the maximum emissions occurred in spring and/or fall months, with much smaller values of about 25 k tons. The large emissions in June and during the fall months were a result of the summer and fall harvest seasons, respectively. Some areas did not burn straw immediately after the fall harvest, but waited until the next spring planting season. This caused large emissions in some spring months.

The monthly API looked different than the monthly straw-burning emissions. Only one pattern was found for all regions (figure S3), with the worst air pollution (the highest API) found in winter, the best in summer, and a second peak in spring. Heating using coal is one of the major air pollution sources in China, mostly in the winter. In addition, the atmosphere is more stable and rainfall is the lowest in winter but the opposite is true in summer. Dust storms are a major environmental hazard, mainly in northern China during spring. These natural and human activities explain the seasonal API pattern. The main seasonal cycle is consistent with Zhang *et al* (2009) who estimated the

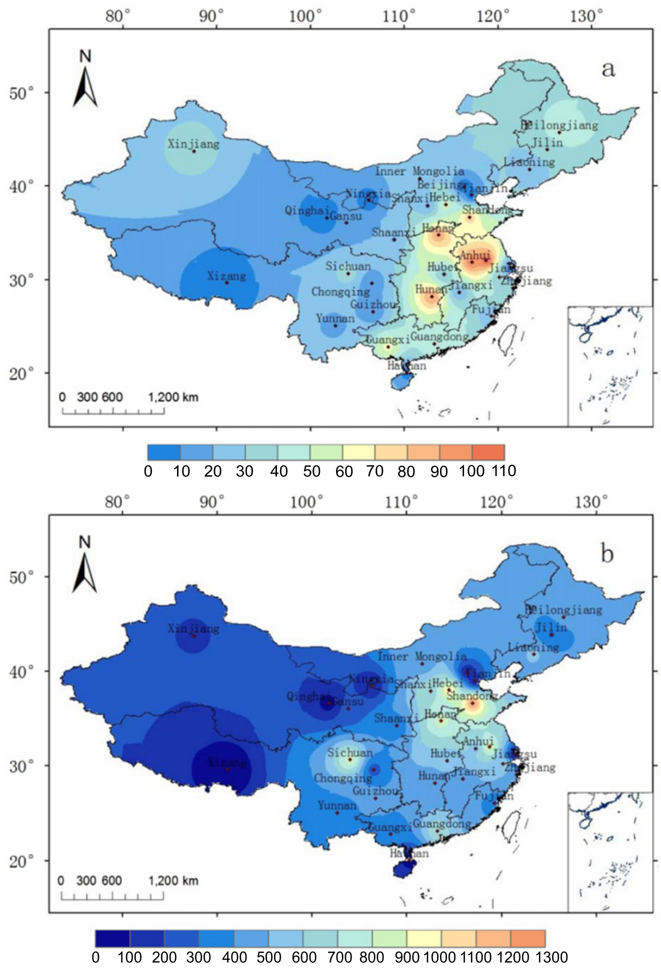

Figure 2. Spatial distributions of annual $PM_{2.5}$ emissions (*k* tons) from straw burning during 1997-2013 (a) and other anthropogenic sources for 2006 (b).

monthly variations based on the monthly distributions of energy consumption of residents according to temperature and other energy and industrial emissions according to power generation, cement production, and gross domestic product.

Consistent with the seasonal API variations, larger emissions from other anthropogenic sources in China occurred in the winter months of January and December with $PM_{2.5}$ of about 1.303 and 1.325 m tons, respectively. In the spring months of March and April, $PM_{2.5}$ emissions were about 1.207 and 1.181 m tons, respectively. At the regional level, the largest monthly variations occurred in North China, followed by East China, and relatively small variations were seen in Northwest, South, and Northeast China (figure 3(b)).

3.3. $PM_{2.5}$ emission ratios

The annual $PM_{2.5}$ emission ratio of open crop straw burning averaged over 1997 ~ 2013 to other anthropogenic sources for the year of 2006 was 7.8% at the national level (table 1). The monthly $PM_{2.5}$ emission ratios were 26% in June, 11% in May, 9.7% in October, and 8% in March and April. The June ratio was about 3.4 times the annual ratio.

At the regional level, the annual ratios were about 10% for Central, East, and South China, and as low as about 5% for Southwest and North China. The June ratios were about 56% in East China and 30% in North and Central China. The October ratios were about 29% in Northwest China and 22% in Northeast China (figure 4 and table 1). The monthly ratios were about 3 ~ 5 times the annual ratios.

At the province level, the annual emission ratios were the largest at nearly 35% in Xizang of Southwest China, over 20% in Hunan of Central China, over 15% in Guangxi of South China, Anhui of East China, and Xinjiang of Northwest China, and below 10% in 21 out of the 31 provinces (figure S4; also see figure S5 (a) for the geographic distribution). The June ratios (figures S4 and S5(b); table 1) were about 107% in Anhui and 81% in Jiangsu of East China, 63% in Henan of Central China, 47% in Shaanxi of Northwest China, and 45% in Shandong of North China, which were about 6 ~ 7 times the corresponding annual ratios. The other months with relatively large ratios were about 33% in Guangxi of South China and 41%

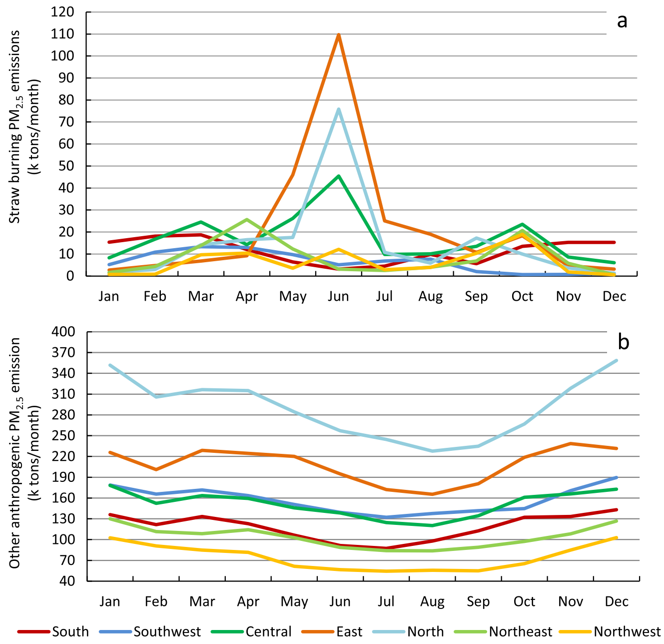

Figure 3. Monthly distributions of $PM_{2.5}$ emissions for Chinese regions from open straw burning during 1997-2013 (a) and other anthropogenic sources for 2006 (b).

Table 1. Comparisons between monthly $PM_{2.5}$ emission ratios (%) of straw burning during 1997-2013 to other anthropogenic sources for 2006 during harvest or other active burning period (measured by the largest monthly value) and annual ratios (%) at national, regional, and province levels.

Level	Area	Monthly ratio	Annual ratio	Monthly ratio/ annual ratio
Nation		26.3	7.8	3.4
Region	South	14.9	9.7	1.5
	Southwest	7.9	4.0	2.0
	Central	32.8	11.4	2.9
	East	56.3	10.4	5.4
	North	29.5	5.1	5.8
	Northeast	22.4	8.1	2.8
	Northwest	29.1	8.5	3.4
Province	Guangxi	32.6	17.9	1.8
	Xizang	87.6	34.5	2.5
	Hunan	41.0	21.4	1.9
	Henan	63.0	10.6	5.9
	Jiangsu	81.0	12.1	6.7
	Anhui	107.2	17.4	6.1
	Shandong	45.2	6.3	7.2
	Jilin	41.3	11.0	3.8
	Shaanxi	47.0	6.0	7.8
	Xinjiang	96.8	17.4	5.6

in Hunan of Central China in March (figure S5(c)), 97% in Xinjiang of Northwest China in October (figure S5(d)), 88% in Xizang of Southwest China in February, and 41% in Jilin of Northeast China in April.

According to the analysis described in the supplementary material, the provinces with extremely large monthly ratios were Jiangsu and Anhui of East China, Shandong of North China, and Hunan and Henan of Central China; the provinces with large monthly ratios were Guangxi of South China, Hebei of North China, Jilin and Heilongjiang of Northeast China, and Shaanxi and Xinjiang of Northwest China (table S3).

Straw-burning emissions had some interannual variability (figure S6). To examine the possible impact of the variability on the emission ratios, the $PM_{2.5}$ emission ratios using open crop straw burning for the year 2006 only instead of the average over 1997 ∼ 2013 were calculated. The results are the same as those described above, with slightly larger magnitude (figure S7 and table S4).

4. Discussion

The findings from this study, the $PM_{2.5}$ emission ratios of straw burning compared to other anthropogenic sources, may be valuable for the development of the $PM_{2.5}$ inventories in China cities. First, it provides new evidence for the important contribution of straw-burning emissions to air pollution in China, suggesting that the $PM_{2.5}$ inventories should include straw burning as an emission source. Previous studies have provided this evidence based on burning information of single or several years, while this study analyzed the long-term burning information of 17 years and thus is more meaningful from a statistical point of view.

Secondly, this study further indicates that the contributions of straw-burning emissions during harvest or other active burning periods are much larger than the contributions from previous assessments, which were based on annual emissions of straw burning and other anthropogenic sources. This suggests that the

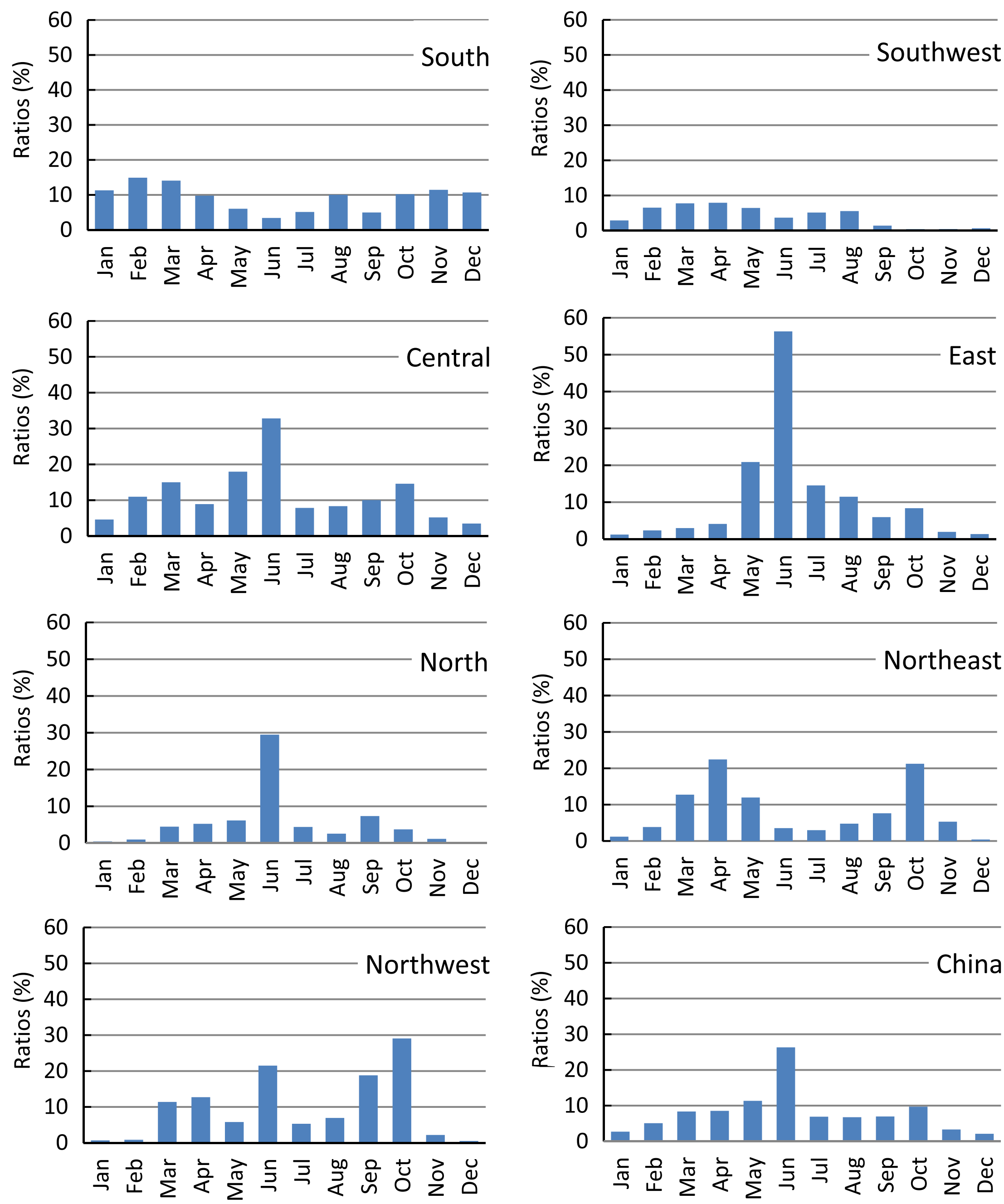

Figure 4. Monthly $PM_{2.5}$ emission ratios of straw burning during 1997-2013 to other anthropogenic sources for 2006 for all regions and China (%).

$PM_{2.5}$ inventories should use monthly rather than annual straw-burning emissions while assessing its contribution as a transported source. The importance of more detailed wildland fire information than the annual data from the US EPA national emission inventories for improving air quality simulations is indicated (e.g., Battye and Battye 2002). This study provides evidence for this by showing the large difference between monthly and annual contributions of straw-burning $PM_{2.5}$ emissions to other anthropogenic emissions in China.

Thirdly, this study identifies the specific time of a year (June, October, March, etc) for a region or province when the monthly contribution from straw-burning emissions was the largest. Thus, the $PM_{2.5}$ inventories for a specific city could focus on the corresponding time of year to determine the straw-burning contribution. Dynamic models such as CMAQ (Byun and Schere 2006) and HYSPLIT (Draxler and Hess 1998, Zhu *et al* 2010) are needed to simulate transport of smoke particles from the rural burning sites to urban area where the impact of smoke on the air quality conditions are assessed (Liu *et al* 2009, Su *et al* 2012). Simulations of such models requires a large amount of computational resources, while much less is needed for simulations if a specific harvest or other active burning period is used instead of an entire year.

The June peak in the major straw-burning regions of China is consistent with the finding from a global MODIS detection over 2001 ~ 2003 for this region (Korontzi *et al* 2006). The peak times, however, are different in other regions, as shown in that study. The peaks occur during April to May and August for the global average. North America has a similar two-peak pattern during March to June and September to November. One peak pattern is dominant in other continents during February and March in South and Southeast Asia, April and May in Central and Northeast Asia and Central America, July and August in Europe, and November and December in North Africa. In the southern hemisphere, the peak occurs during March and April in Australia and New Zealand, July to September in South Africa, and August to October in South America. The amount of $PM_{2.5}$ emissions from agricultural burning in the continental United States detected using MODIS from 2003 ~ 2007 (McCarty 2011) is much smaller than in China, probably because of the extensive use of powerful mechanical chopping. The largest emissions occur mainly in several regions of the Southeast, the Great Plains, and the Pacific Northwest.

There are alternatives to burning for removing crop straw residues in China. Straw can be chopped and directly decomposed in soil or composted outside fields as nutrients and organic materials. However, farmers in China usually use simple tools that can't chop straw fine enough to be well decomposed and absorbed by soil before the next crop season. Using power generation has been explored but has largely failed due to the low efficiency and high costs of straw cutting and transportation. Crop straws were once used as domestic fuel for some farmers. However, this is no longer a practice for the majority of famers due to extensive usage of electric power and natural gas in rural areas in recent years. The Chinese government has banned crop straw burning in most regions in an effort to reduce air pollution but has compensated farmers for the economic burdens of using alternatives to burning. However, this policy is unlikely to be a long-term solution.

5. Conclusions

It can be concluded from the findings of this study that the contributions of straw-burning $PM_{2.5}$ emissions during harvest or other active burning periods to air pollutions in China are substantially larger than previous assessments based on annual emissions of straw burning and other anthropogenic sources in the major burning provinces. China recently identified main urban air pollutant sources from transportation, energy, industrial, and construction dust based on annual emissions. For sources such as crop straw burning, monthly emissions should be used to estimate their contributions to air pollutants. Otherwise, the contributions will be significantly underestimated for certain periods of a year.

The larger contribution of straw burning to air pollution in China for harvest or other active burning periods suggests that a substantial reduction or complete abandonment of open-field straw burning would dramatically improve air quality in many China regions during these periods.

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References

Battye W and Battye R 2002 *Development of Emissions Inventory Methods for Wildland Fire, Final Report. EPA Contract No.* Work Assignment No. 5-03 EC/R Incorporated, Durham, NC (http://epa.gov/ttnchie1/ap42/ch13/related/firerept.pdf)

Bi Y Y, Gao C Y, Wang Y J and Li B Y 2009 Estimation of straw resources in China *Trans. Chin. Soc. Agric. Eng.* **25** 211–7

Bi Y Y, Wang Y J and Gao C Y 2010 Straw resource quantity and its regional distribution in China *Agri. Mech. Res.* **32** 1–7

Byun D W and Schere K L 2006 Review of the governing equations, computational algorithms, and other components of the Models-3 Community Multiscale Air Quality (CMAQ) modeling system *Appl. Mech. Rev.* **59** 51–77

Cao G L, Zhang X Y, Gong S L and Zheng F C 2008 Investigation on emission factors of particulate matter and gaseous pollutants from crop residue burning *J. Envir. Sci.* **20** 50–5

Cao G L, Zhang X Y, Gong S L, An X Q and Wang Y Q 2011 Emission inventories of primary particles and pollutant gases for China *Chin. Sci. Bull.* **56** 781–8

Cao G L, Zhang X Y, Wang Y Q and Zheng F C 2008 Estimation of emissions from field burning of crop straw in China *Chin. Sci. Bull.* **53** 784–90

Cheng Y, Engling G, He K B, Duan F K, Ma Y L, Du Z Y, Liu J M, Zheng M and Weber R J 2013 Biomass burning contribution to Beijing aerosol *Atmos. Chem. Phys.* **13** 7765–81

Draxler R R and Hess G D 1998 An overview of the HYSPLIT_4 modeling system of trajectories, dispersion, and deposition *Australian Meteorol. Mag.* **47** 295–308

Giglio L J, Randerson T and van der Werf G R 2013 Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4) *J. Geo. Res.: Biogeosciences* **118** 317–28

Guan D, Su X, Zhang Q, Peters G P, Liu Z, Lei Y and He K 2014 The socioeconomic drivers of China's primary $PM_{2.5}$ emissions *Environ. Res. Lett.* **024010** 2014c

He L M, Wang W J, Wang Q, Wei B, Li Q, Wang C Z and Liu X M 2007 Evaluation of the agricultural residues burning reduction in China using MODIS fire product *Environ. Monit. China* **23** 42–50

Huang J P, Zhou C H, Lee X H, Bao Y X, Zhao X Y, Fung J, Andreas R, Liu X and Zheng Y Q 2013 The effects of rapid urbanization on the levels in tropospheric nitrogen dioxide and ozone over East China *Atmos. Environ.* **77** 558–67

Koppmann R, Von C K and Reid J S 2005 A review of biomass burning emissions, Part 1: gaseous emissions of carbon monoxide, methane, volatile organic compounds and nitrogen containing compounds *Atmos. Chem. Phys.* **5** 10455–516

Korontzi S, McCarty J, Loboda T, Kumar S and Justice C 2006 Global distribution of agricultural fires in croplands rom 3 years of Moderate Resolution Imaging Spectroradiometer (MODIS) data *Glob. Biogeochem. Cycles* **20** GB2021

Li L J, Wang Y, Zhang Q, Li J X, Yang X G and Jin J 2008 Wheat straw burning and its associated impacts on Beijing air quality *Sci. China Series D—Earth Sci.* **51** 403–14

Li Q, Zhang L J, Wu C Q, Sun Z P and Liu X M 2009 Satellite-remote-sensing-based monitoring of straw burning and analysis of its impact on air quality *J. Ecol. Rur. Environ.* **25** 32–7

Li X H, Wang S P, Duan L, Hao J M, Li C, Chen Y S and Yang L 2007 Particulate and trace gas emissions from open burning of wheat straw and corn stover in China *Environ. Sci. Technol.* **41** 6052–8

Liu Y Q, Goodrick S and Achtemeier G 2009 Smoke incursions into urban areas: simulation of a Georgia prescribed burn *Int. J. Wildland Fire* **18** 336–48

Lu B, Kong S F, Han B, Wang X Y and Bai Z P 2011 Inventory of atmospheric pollutants discharged from biomass burning in China continent in 2007 *China Environ. l Sci.* **3** 186–94

Lu Z, Zhang Q and Streets D G 2011 Sulfur dioxide and primary carbonaceous aerosol emissions in China and India, 1996-2010 *Atmos. Chem. Phys.* **11** 9839–64

McCarty J L 2011 Remote sensing-based estimates of annual and seasonal emissions from crop residue burning in the contiguous United States *J. Air Waste Manage. Assoc.* **61** 22–34

Ni H Y *et al* 2005 Emission characteristics of carbonaceous particles and trace gases from open burning of crop residues in China *Atmos. Environ.* **123** 399–406

Ortiz de Zarate I, Ezcurra A, Lacaux J P, Van Dinh P and Diaz de Argandona J 2005 Pollution by cereal waste burning in Spain *Atmos. Res.* **73** 161–70

Shi T T, Liu Y Q, Zhang L B, Hao L and Gao Z Q 2014 Burning in agricultural landscapes: an emerging natural and human issue in China *Landscape Ecol.* **29** 1785–98

Su J F, Zhu B, Kang H Q, Wang H L and Wang T J 2012 Applications of pollutants released form crop residues at open burning in Yangtze River Delta region in air quality model *Env. Sci.* **33** 1418–24

van der Werf G R, Randerson J T, Giglio L, Collatz G J, Mu M, Kasibhatla P S, Morton D C, DeFries R S, Jin Y and van Leeuwen T T 2010 Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997-2009) *Atmos. Chem. Phys.* **10** 11707–35

Wang S X and Zhang C Y 2008 Spatial and temporal distribution of air pollutant emissions from open burning of crop residues in China *Sciencepaper Online* **3** 329–33

Wang W, Maenhaut W, Yang W, Liu X, Bai Z, Zhang T, Claeys M, Cachier H, Dong S and Wang Y 2014 One-year aerosol characterization study for $PM_{2.5}$ and PM_{10} in Beijing *Atmos. Pollut. Res.* **5** 554–62

Xie Z X and Han Z W 2014 Investigation of interannual variations in anthropogenic emission in China based on several emission inventories *J. Univ. Chin. Acad. Sci.* **31** 289–96

Zha S P, Zhang S Q, Cheng T T, Chen J M, Huang G H, Li X and Wang Q F 2013 Agricultural fires and their potential impacts on regional air quality over China *Aerosol Air Qual. Res.* **13** 992–1001

Zhang Q, Streets D G, He K and Klimont Z 2007 Major components of China's anthropogenic primary particulate emissions *Environ. Res. Lett.* **2** 045027

Zhang T, Wooster M J, Green D C and Main B 2015 New field-based agricultural biomass burning trace gas, $PM_{2.5}$, and black carbon emission ratios and factors measured *in situ* at crop residue fires in Eastern China *Atmos. Environ.* **121** 22–34

Zhang Q, Streets D G and Carmichael G R 2009 Asian emissions in 2006 for the NASA INTEX-B mission *Atmos. Chem. Phys.* **5** 5131–53

Zhang H F, Ye X N, Cheng T T, Chen J M, Yang X, Wang L and Zhang R Y 2008 A laboratory study of agricultural crop residue combustion in China: emission factors and emission inventory *Atmos. Environ.* **42** 8432–41

Zhu B, Su J F, Han Z W, Yin C and Wang T J 2010 Analysis of a serious air pollution event resulting from crop residue burning over Nanjing and surrounding regions. China *Environ. Sci.* **30** 585–92

Zhu B, Zhu X L, Zhang Y X, Zeng L M and Zhang Y H 2005 Emission factor of $PM_{2.5}$ from crop straw burning *Res. Environ. Sci.* **18** 29–33

Zhu J L, Wang T J, Deng J J, Jiang A J and Liu D Q 2012 An emission inventory of air pollutants from crop residue burning in Yangtze River Delta Region and its application in simulation of a heavy haze weather process *Acta Scientiae Circumstantiae* **32** 3045–55

Zuo X, Bi Y Y, Wang H Y, Gao C Y, Wang L and Wang Y J 2015 Estimation and suitability evaluation of cotton stalk resources in China *China Population Sources Environ.* **25** 159–66