Chinese Science Bulletin

Estimation of emissions from field burning of crop straw in China

CAO GuoLiang[1,2], ZHANG XiaoYe[2], WANG YaQiang[2] & Zheng FangCheng[1]

1. School of Environmental and Municipal Engineering, Xi'an University of Architecture & Technology, Xi'an 710055, China
2. Centre for Atmosphere Watch & Services, Chinese Academy of Meteorological Sciences, China Meteorological Administration, Beijing 100081, China

Emissions resulting from crop straw field burning in China, which have caused serious environmental problems in China, are estimated in this paper. From the county-level data of crop production in 2000－2003 from the government statistics, taking into account the ratio of residue and grain, the total amount of crop straw production is estimated to be about 600 Tg per year, 76% of which are rice, wheat and corn straw. With reference to the data of living standards, the percentage of crop straw burnt in fields for counties are obtained and consequently the total amount of burnt straws is approximately 140 Tg/year. With the emission factors from literature and experiments, appropriate emission factors have been obtained. The total amounts of PM, SO_2, NO_x, NH_3, CH_4, BC, OC, VOC, CO, CO_2 emissions from field burning of crop straw in China are estimated. All emissions are presented at county level. Some pollutants, such as BC, VOC, OC, CO and CO_2, are contributing a major portion to the total emissions of China. This paper uses a map with resolution of 0.2°×0.2° to present the PM emissions distribution from crop straw burnt in 2003. The results show a significant regional unevenness of emissions, with larger amounts of pollutions coming from the provinces in eastern and northeast China. The regions with higher emissions per unit area are located as a belt stretching from northeast China to eastern China.

China, crop straw, field burning, emission inventory

China is one of the largest agricultural countries in the world, and before the 1970s, the crop straw was mainly used as a fuel source for household and fodder for domestic animals. Due to the low straw yield per unit, the production of crop straw was consequently limited. Since the 1980s, with the increase of crop yield, the total amount of crop straw has increased rapidly, while the proportion of the straw as a fuel source for household and fodder for domestic animals has apparently decreased. This is due to the fact that farmers want to remove the straws from fields quickly and save the cost of transportation and the storage of the straws, and therefore in most regions as a normal practice the crop straws are burnt in fields after harvest. The field burning of crop straw in wide areas not only results in serious environmental issues[1−3], affects air visibility[4], but also wastes the precious biological resources. The field burning of crop straws has already become the social and environmental problem in China[1,5] and has been concerned by public communities. Chinese government has banned the field burning of crop straws and has even applied satellite technology to monitor the open burning in rural areas, but the effect is far from satisfactory[6].

The emission inventories made for regional aerosols and gaseous pollutants in China have shown the importance of biomass combustion[7−9]. However, although previous emission inventories[7,9−12] included the emissions from crop straw field burning in China, the data they are based on are up-to-date data. Furthermore, due

Received April 2, 2007; accepted May 24, 2007
doi: 10.1007/s11434-008-0145-4
†Corresponding author (email: caogl@cams.cma.gov.cn)
Supported by the National Key Basic Research Project of China (Grant No. 2006CB403700)

to the lack of detailed investigation, especially for rural areas, there was a high degree of uncertainty in the inventories. For example, the population densities of the base years (1980—1990) were used to apportion the emissions among regions for projection years, which apparently need to be updated. In addition, most of the emission factors in use were from foreign countries and involved many assumptions, because there were very few experimental data available for China.

Therefore, a more accurate inventory for aerosols and gaseous pollutants from field burning of crop straw in China using a recent year as base year is needed to provide input to the regional climate-modeling studies. Based on the 2000—2003 official agricultural statistics data, we propose national emission inventories from field burning of crop straw in China with spatial and annual variation.

1 Methodology

Emissions are derived for 31 provinces, excluding Hong Kong, Macao and Taiwan, with each province being subdivided into counties (13—170) which are smallest cells that the statistic data are available. Emission inventories are obtained based on the amount of crop straw burnt and detailed emission factors in literature of or derived by this work. Emissions are estimated for 10 major aerosol and gaseous species: PM (particulate matter), SO_2, NO_x, NH_3, CH_4, BC (black carbon), OC (organic carbon), VOC (volatile organic compounds), CO and CO_2.

Figure 1 shows the general methodology used for the estimation of emission. The amount of crop straw burnt in each region is calculated based on the fraction of straw burnt in field, the yield of crop[13,14] and the crop-to-residue ratios[15]. The emissions are products of the amount of each crop straw burnt in field and the corresponding emission factors of each pollutant species.

To match the spatial gridding of the regional climate model of China Meteorological Administration (CMA) aerosol project. We use Geographical Information System (GIS) because it can process spatial data easily such as data interpolation when necessary.

2 Data sources

In China, field burning of crop straw is mainly practised in the following regions: (1) grain-producing regions

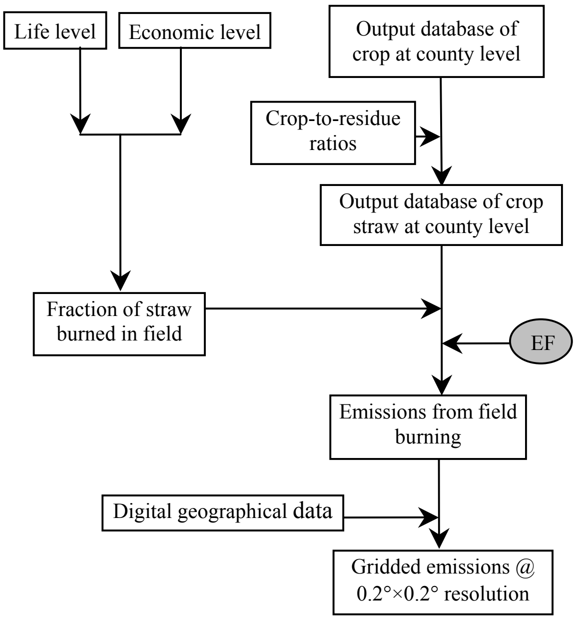

Figure 1 Methodology for constructing a spatially resolved emissions inventory from field burning of crop straw.

with a small population density, such as Jilin and Heilongjing, where the massive surplus crop straw cannot be comprehensively burnt; (2) developed regions like Shanghai, Zhejiang and Jiangsu, where crop straw used as a major fuel source have been gradually replaced by commercial energy; and (3) energy producing regions, including Shanxi and Shaanxi, where the farmers have easy access to cheap energy sources, leaving massive crop straw surplus. Unfortunately, there are no official statistic data on the total amount of crop straw burnt in China.

Statistic data at county level of planting area for each type of crop are accessible from NBSC[14] and MOA[13], including those of rice, wheat, corn, cotton, bean, sugar cane, and others. County level crop production statistics[13] and crop-to-residue ratios[15] are also obtainable. Thus, the regional crop straw production can be calculated.

The amount of field-burning crop straw is determined by climatic zone, rural living level, vegetation coverage and main output of crops for each district. However, there are no statistic data for this and few studies had been done. Limited data show that approximately 27.2% of crop straw was burnt in 1995[16] and 15.2% in 1998[17]. More detailed studies indicate that 33% of the crop straw was burnt in 1998 in Jiangsu Province[2], while the figures were 32.4% for Guangdong Province[18], 50%—60% for Fuzhou city in 2001[19], 39.6% for Shanghai in

Table 1 Emission factors for field burning of crop straw

Crop straw type	Emission factor ($g \cdot kg^{-1}$)									
	PM	SO_2	NO_x	NH_3	CH_4	BC	OC	VOC	CO	CO_2
Rice straw	6.04a), 5.3[12], 3.49[23], 2.28[29]	0.147a), 0.62[23], 0.53[29]	3.52a), 2.84[23], 2.66[29]		0.72[23]	0.52a), 0.86[12], 0.5[29]	1.96a), 0.94[29]		72.4a), 31.39[23], 25.2[29]	1757.6a), 1162.15[23], 1019.9[29]
Wheat straw	9.64a), 12[12], 5.82[23]	0.049a), 0.47[23]	2.59a), 2.33[23]		1.82[23]	0.52a), 1.2[12], 0.8[29]	3.83a), 2.2[29]		65.5a), 66.69[23]	1483.6a), 1194.88[23]
Corn stover	5.26a), 12[12], 6.31[23]	0.026a), 0.2[23]	3.36a), 1.82[23]		1.75[23]	0.78a), 0.96[12], 0.75[29]	2.21a), 1.8[29]		70.2a), 38.78[23]	2200.2a), 1313.61[23]
Cotton stalk	4.53a)	0.002a)	2.68a)		2.7b)	0.82a)	1.83a)		111.8a)	1453.4a)
Unspecified	13[27], 11[24]	0.08b)	2.5[27], 2.7[29]	1.3[27]	2.7[27], 2.7[24], 2.27[29]	0.69[27], 0.47[28]	3.3[27], 2.67[28]	15.7[7], 8.5[11]	92[27], 58[24], 47.6[29]	1515[27], 1246.7[29]

a) Experimental testing; b) no data, value is best guess.

2000[20], respectively. Although Yevich et al.[21] concluded that just 1% of total crop straw was openly burnt in China in 1985, we believe this value is out of date.

Based on the most recent literature, we deduce that the amount of crop straw openly burnt is proportional to farmer's income level, and this hypothesis has been confirmed by an investigation in Henan Province[22]. We estimate that the correlation coefficient between income of farmer and fraction burnt is 0.81. The official per capita average income of farmers for 2000—2003 at county level and the crop-to-residue ratios[15] can help estimate the regional quantities of crop straw being openly burnt.

3 Emission factors

Generally, pollutants emissions from openly burning of crop straw depend on the composition and moisture content of the straw, combustion temperatures, and ambient conditions, including wind speed, ambient temperature[23,24]. Currently, there are few measurements on emission factors for the field burning of crop straw[23,25], especially in China. The emission factors in previous studies varied with a wide range. Therefore, the work for estimating emission factors for burning crop straw in China is in urgent need.

We have designed a combustion tower and installed it in our laboratory to model the condition of open burning in rural areas. The tower is in the form of an inverted funnel which was described in details elsewhere[26]. The tested straw were collected from the representative places from all parts of China, including wheat straw, rice straw, corn stover and cotton stalk, which are of the most common crop straw there. A total of 33 experiments have been conducted: 14 for rice straw, 8 for wheat straw, 9 for corn stover and 2 for cotton stalk. The emission factors of PM, SO_2, NO_x, BC, OC, CO, CO_2 from the experiments are in close agreement with those reported in recent literature[26] with the exception of SO_2. These emission factors derived from our experiments are used in this paper.

Table 1 presents emission factors obtained from literatures and our experiments. We classified crop straw into five types. Since we could not find more information about the emission factors for ammonia and VOC, we used the average values of those reported in literature, except for SO_2. Since high-concentration fertilizers with very low sulphur content are widely used in China, the soil is in a state lack of sulphur[27]. As a result, the content of sulphur in the crop straw is relatively low. So we used the value from our experimental test for this paper.

4 Results and discussion

National crop straw output in China estimated for 2000—2003 are tabulated in Table 2. Annual total output of crop straw in recent years is stable with a value of about 600 Tg, in close agreement with those reported in literature (604.7 Tg[5]; 604 Tg[16]; 655 Tg[17]; 565 Tg[31]). Since rice, wheat, corn crops account for 50% of the total sown area, the straw output of these three crops is 76% of the total straw quantity (Table 2).

The total open burning consumption is estimated at 136.37—143.4 Tg for 2000—2003 (Table 3), about 23% of the total output crop straw in China. The figure is higher than the value of 105 Tg reported by Streets et al.[7] The largest contributions are from Shandong, Jiangsu, Hebei, Heilongjiang and Henan, where the farmers' income and rural population density are higher than elsewhere in China. The smallest contributions are from western China and Inner Mongolia due to their lower rural population density and lower economic level.

Total amounts of pollutants emission from crop straw field burning are estimated and tabulated in Table 4. The

Table 2 Output of crop straw in China

Straw type	Output of grain (Tg)				Output of crop straw (Tg)			
	2000	2001	2002	2003	2000	2001	2002	2003
Rice straw	18791	17758	17454	16065	11707	11063	10874	10008
Wheat straw	9964	9388	9029	8649	13611	12823	12334	11814
Corn stover	10600	11409	12131	11583	21200	22818	24262	23166
Other crops	1177	1093	1185	1132	1177	1093	1185	1132
Bean stalk	2010	2053	2241	2128	3015	3079	3362	3191
Tubers	3685	3563	3666	3513	1843	1782	1833	1757
Oil-bearing crops	2955	2865	2897	2811	5910	5730	5794	5622
Cotton stalk	442	532	492	486	1326	1597	1475	1458
Fiber crop	53	68	96	85	90	116	164	145
Sugar cane	7635	8655	10293	9642	764	866	1029	96
Total					60643	60967	62311	59257

Table 3 The amount of crop straw openly burnt in field in Chinese provinces, autonomous regions and municipalities (excluding Hong Kong, Macao and Taiwan)

	Output of crop straw (Tg)				Crop straw openly burnt in field (Tg)			
	2000	2001	2002	2003	2000	2001	2002	2003
Beijing	360	362	370	352	163	164	167	159
Tianjin	282	284	290	276	114	115	117	112
Hebei	4735	4760	4865	4626	1146	1152	1177	1120
Shanxi	1478	1485	1518	1444	310	312	319	303
Inner Mongolia Autonomous Region	2218	2230	2279	2167	472	475	485	461
Liaoning	2278	2290	2341	2226	480	483	493	469
Jilin	4013	4035	4124	3922	842	846	865	823
Heilongjiang	4455	4479	4578	4353	999	1004	1026	976
Shanghai	160	161	164	156	78	78	80	76
Jiangsu	3437	3456	3532	3359	1175	1181	1207	1148
Zhejiang	1053	1059	1082	1029	449	451	461	438
Anhui	3010	3026	3093	2942	562	565	577	549
Fujian	651	654	669	636	212	213	218	207
Jiangxi	1263	1270	1298	1235	274	275	282	268
Shandong	6938	6976	7129	6780	1841	1850	1891	1798
Henan	5806	5837	5966	5674	1143	1149	1174	1116
Hubei	2465	2478	2533	2408	576	580	592	563
Hunan	1947	1957	2001	1902	434	436	446	424
Guangdong	1375	1382	1413	1344	501	504	515	490
Guangxi Zhuang Autonomous Region	1452	1459	1492	1418	243	244	249	237
Hainan	152	153	156	149	46	47	48	45
Chongqin	1099	1105	1129	1074	213	214	219	208
Sichuan	3309	3326	3400	3233	659	662	677	644
Guizhou	995	1001	1023	973	149	150	154	146
Yunnan	1395	1403	1434	1363	160	161	164	156
Xizang Autonomous Region	48	48	49	47	4	4	4	4
Shaanxi	1607	1616	1651	1570	238	239	245	233
Gansu	998	1003	1025	975	166	166	170	162
Qinghai	151	152	155	148	15	15	16	15
Ningxia Hui Autonomous Region	321	323	330	314	65	65	67	63
Xinjiang Uygur Autonomous Region	1191	1197	1223	1163	228	229	235	223
Total	60643	60967	62311	59257	13956	1403	1434	13637

Table 4 Summary of emission from field burning of crop straw for 2000－2003

	PM	SO_2	NO_x	NH_3	CH_4	BC	OC	VOC	CO	CO_2
2000	110.7	0.89	37.0	18.1	23.5	10.5	31.5	168.9	802.0	21020
2001	111.3	0.9	37.2	18.2	23.6	10.6	31.7	169.8	806.3	21140
2002	113.8	0.92	38.0	18.6	24.1	10.8	32.4	173.5	824.1	21600
2003	108.2	0.87	36.2	17.7	22.9	10.3	30.8	165.0	783.7	20540

a) Data are in Gg (Tg for CO_2).

annual amount of open burning consumption has little change in recent years, and accordingly the amounts of pollutants emissions do not show much changes.

Regional emissions from field burning of crop straw in China for 2000 are estimated and tabulated in Table 5. Emissions are derived for 31 provinces, excluding Hong Kong, Macao and Taiwan. According to SEPA (http://www.zhb.gov.cn/plan/zkgb/2000/) in 2000, the total anthropogenic emission of PM and SO_2 was 10.5 and 21.6 Tg, respectively (excluding biomass burning). From our estimation, PM emissions from crop straw field burning (1,107.1 Gg) contribute a great portion (11.5%) to the total anthropogenic emission of PM in China, while SO_2 emissions contribute a small portion (0.04%) to its total emissions. Tsinghua University[32] estimated CO_2 and CH_4 emission from China were 3111.5 Tg and 59.6 Tg in 2000, while the EDGAR inventory reported 3749.2 Tg for CO_2 and 45.67 Tg CH_4 in 1995[33]. However, Streets et al.[34] argued that since China started reform on its coal and energy industries and revised the technologies in energy-intensive industries, CO_2 and CH_4 emissions should decline to 2690 Tg and 33.3 Tg in 2000, respectively. With the help of latest literature of emissions in China[7] for 2000, we estimated the emissions from field burning contribute to the total national emission as follows: BC (11.17%), VOC (10.78%), OC (10.37%), CO (7.71%), CO_2 (6.13%), NO_x (3.63%), NH_3 (1.49%), CH_4 (0.68%), SO_2 (0.05%). Therefore, the emissions of BC, VOC, OC, CO and CO_2 from crop straw field burning contribute a significant part to the total emissions.

The total PM emission from crop straw field burning in 2003 is allocated among grid cells of size 0.2°×0.2° (~20×20 km) (see Figure 2), and the same processes are conducted for other. The results show that the distributions vary significantly across the country, with higher

Table 5 Inventories of pollutions from field burning of crop straw in Chinese provinces, autonomous regions and municipalities (excluding Hong Kong, Macao and Taiwan) in 2000

	PM	SO_2	NO_x	NH_3	CH_4	BC	OC	VOC	CO	CO_2
Beijing	1.35	0.01	0.42	0.21	0.29	0.13	0.38	1.97	9.53	260
Tianjin	0.93	0.01	0.3	0.15	0.2	0.09	0.27	1.38	6.68	180
Hebei	9.83	0.05	2.93	1.49	2.11	0.93	2.78	13.86	68.85	1800
Shanxi	2.68	0.01	0.79	0.4	0.58	0.25	0.74	3.75	18.57	490
Inner Mongolia Autonomous Region	4.15	0.02	1.21	0.61	0.89	0.37	1.12	5.71	27.73	750
Liaoning	3.7	0.02	1.26	0.62	0.81	0.38	0.97	5.81	26.03	810
Jilin	6.62	0.03	2.2	1.09	1.46	0.68	1.7	10.19	45.86	1450
Heilongjiang	8.24	0.04	2.61	1.3	1.79	0.78	2.15	12.09	55.83	1650
Shanghai	0.54	0.01	0.22	0.1	0.11	0.05	0.16	0.94	4.11	110
Jiangsu	8.84	0.09	3.16	1.53	1.85	0.86	2.71	14.21	69.07	1640
Zhejiang	2.7	0.06	1.29	0.58	0.52	0.29	0.83	5.43	22.45	600
Anhui	4.5	0.04	1.5	0.73	0.94	0.41	1.34	6.8	33.24	790
Fujian	1.4	0.03	0.61	0.28	0.27	0.13	0.41	2.57	10.64	280
Jiangxi	1.65	0.03	0.8	0.36	0.32	0.17	0.5	3.32	13.72	370
Shandong	16.21	0.08	4.69	2.39	3.47	1.47	4.6	22.27	112.14	2840
Henan	10.01	0.05	2.91	1.49	2.17	0.91	2.94	13.83	72.41	1700
Hubei	4.16	0.05	1.59	0.75	0.88	0.4	1.25	6.98	33.07	800
Hunan	2.52	0.05	1.26	0.56	0.5	0.28	0.77	5.25	21.52	580
Guangdong	3.31	0.06	1.44	0.65	0.64	0.31	0.96	6.07	25.04	680
Guangxi Zhuang Autonomous Region	1.75	0.03	0.68	0.32	0.35	0.16	0.49	2.94	12.58	340
Hainan	0.34	0.01	0.13	0.06	0.07	0.03	0.1	0.56	2.43	60
Chongqin	1.63	0.02	0.58	0.28	0.34	0.15	0.46	2.58	11.68	320
Sichuan	5.08	0.05	1.77	0.86	1.05	0.48	1.48	7.97	37.01	960
Guizhou	1.18	0.01	0.4	0.19	0.25	0.11	0.32	1.81	8.24	230
Yunnan	1.29	0.01	0.43	0.21	0.27	0.12	0.36	1.94	8.94	240
Xizang Autonomous Region	0.04	0	0.01	0.01	0.01	0	0.01	0.05	0.28	10
Shaanxi	2.04	0.01	0.61	0.31	0.43	0.19	0.57	2.88	14.13	370
Gansu	1.49	0.01	0.42	0.22	0.32	0.13	0.43	2	10.27	250
Qinghai	0.16	0	0.04	0.02	0.03	0.01	0.05	0.18	1	20
Ningxia Hui Autonomous Region	0.53	0	0.17	0.08	0.11	0.05	0.15	0.78	3.72	100
Xinjiang Uygur Autonomous Region	1.86	0.01	0.59	0.3	0.44	0.18	0.55	2.76	15.24	350
Total	110.71	0.89	37	18.14	23.47	10.53	31.54	168.87	802.01	21020

a) Data are in Gg (Tg for CO_2).

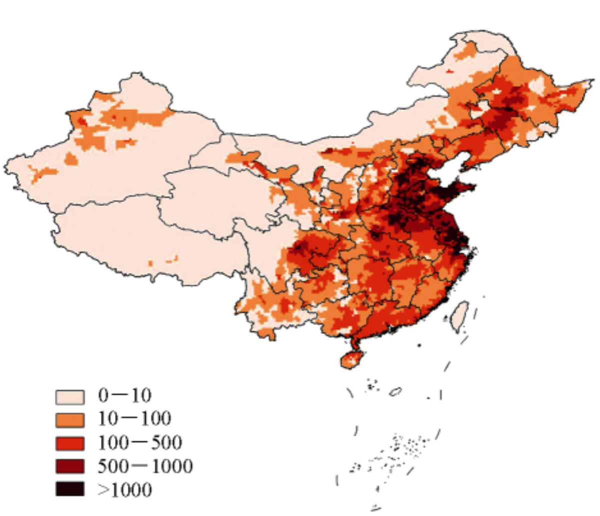

Figure 2 Gridded PM emissions from field burning of crop straw for the year 2003 in China (0.2°×0.2°, unit: kg km^{-2}).

emission of PM (>100 kg km^{-2}) from open burning being from the provinces in eastern China and northeast China, such as Hebei, Shandong and Jiangsu, and lower emissions from western China and Inner Mongolia (<10 kg km^{-2}) where rural population density and economic level are lower. The regions with higher emission densities form a belt area across the agricultural heartland of China, from northeast China to eastern China.

5 Uncertainty in emission estimations

Several factors may affect the accuracy of the estimation of emissions, including emission factors, statistical information and economy level of each rural region. Therefore, the estimated emissions rely heavily on inferences of economy levels from limited statistical information and extrapolations of emission factors from limited literature. We estimated the error allowance by combining the coefficients of variation (CV, or the standard deviation divided by the mean) of the contributing factors. The relative 95% confidence intervals for emissions are calculated at 1.96 times CV. Furthermore, the error allowance of emission quantity can be estimated in a way similar to that described by Streets et al.[7]. If there is no way to judge the accuracy of statistical quality, expert judgment should be used.

Given that government statistic data are believed to be highly reliable, CV can be assigned to a low value of ±10%. The CV of the emission factors are ±34.8% for PM, ±21.3% for NO_x, ±30.3% for BC, ±31.5% for OC, ±37.3% for CO and ±25.9% for CO_2. We assumed the CV is ±100% in the estimations for SO_2, NH_3, CH_4 and VOC. Therefore, the following ranges of 95% confidence intervals for emissions from open field burning are ±68.3% for PM, ±197.0% for SO_2, ±41.7% for NO_x, ±197.0% for NH_3, ±197.0% for CH_4, ±59.4% for BC, ±61.6% for OC, ±197.0% for VOC, ±73.1% for CO and ±50.8% for CO_2. These values for emission uncertainties are close to the estimates made by Streets et al.[7].

6 Conclusions

This paper presents the detailed inventories of pollutants emission from field burning of crop straw in China. It uses available information on straw open burning activity rates and emission factors. Basic data are obtained from government statistics, and emission factors are either compiled from experimental tests or from public literature. The national and regional emissions from field burning of crop straw in China are presented. Gridded emissions with 0.2°×0.2° resolution are also shown (taking PM as an example). The output of crop straw was estimated at 600 Tg in China in recent years, about 23% (140 Tg) out of which has been openly burnt in fields. Some pollutants, such as BC, VOC, OC, CO and CO_2, make significant contributions to the total emission of China. The distribution of emissions from field burning across China indicates significant regional unevenness, with emission densities being higher in eastern China and Northeast China and lower in western China and Inner Mongolia.

We appreciate the help from members of CAWAS and Dr. Qu Wenjun with Ocean University of China with experimental work.

1 Hang W Q, Chen J J. Effect on environmental quality of and control of setting straw on fire on field. The Administration and Technique of Environmental Monitoring (in Chinese), 2000, 12(2): 36−37
2 Wu L, Chen J, Zhu X D, et al. Straw-burning in rural areas of China: caused and controlling strategy. China Population Resour Environ (in Chinese), 2001, 11: 110−112
3 Duan F K, Liu X D, Yu T. Identification and estimate of biomass burning contribution to the urban aerosol organic carbon concentrations in Beijing. Atmos Environ, 2004, 38(9): 1275−1282
4 Chan Y C, Simpson R W, Mctainsh G H, et al. Source apportionment of visibility degradation problems in Brisbane (Australia) using the multiple linear regression technique. Atmos Environ, 1999, 33: 3237−3250
5 Liu Y. Managing and integrated using of crop biomass. Liaoning Agr

Sci (in Chinese), 2003, 1: 18－23
6 Yuan Z H, Wu C Z, Ma L L, et al. Biomass Utilization and Technology Development in China. 2. Internationals Symposium Zukunftsenergien für den Süden. April 2003, Gelsenkirchen (www.solartransfer.de)
7 Streets D G, Bond T C, Carmichael G R, et al. An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. J Geophys Res, 2003, 108(D21), 8809, doi: 10.1029/2002JD003093
8 Guo H, Wang T, Simpson I J, et al. Source contributions to ambient VOCs and CO at a rural site in eastern China. Atmos Environ, 2004, 38(27): 4551－4560
9 Bond T C, Streets D G, Yarber K F, et al. A technology-based global inventory of black and organic carbon emissions from combustion. J Geophys Res, 2004, 109: 14203
10 Streets D G, Gupta S, Waldho S T, et al. Black carbon emissions in China. Atmos Environ, 2001, 35: 4281－4296
11 Klimonta Z, Streets D G, Gupta S, et al. Anthropogenic emissions of non-methane volatile organic compounds in China. Atmos Environ, 2002, 36(8): 1309－1322
12 Liousse C, Penner J E, Chuang C, et al. A global three -dimensional model study of carbonaceous aerosols. J Geophys Res, 1996, 101: 19411－19422
13 Ministry of Agriculture of China, 2001, 2002, 2003, 2004. China Agriculture Yearbook 2001/2002/2003/2004 (in Chinese), Beijing: China Agriculture Press
14 National Bureau of Statistics of China. China Statistical Yearbook 2001/2002/2003/2004 (in Chinese). Beijing: China Statistics Press
15 Chinese Association for Rural Energy Industries. Strategic Considerations for Development and Utilization of Biological Energy in China (in Chinese). Beijing. 2000. 1－61
16 Hu D Z. The utilizing status and prospects of the crop straw resources in China. Resour Develop Market (in Chinese), 2000, 16(1): 19－20
17 Weng W, Yang J T, Zhao Q L, et al. Current situation and developing direction of straw utilization technology in China. China Resources Comprehensive Utilization (in Chinese), 2004, 7: 19－21
18 Lin R Q, Song D L. Utilizing status and problems of crop straw on Guangdong province. Soil Environ Sci (in Chinese), 2002, 11(1): 110
19 Yu Z. The developing trend of resources treatment of crop stalk in Fuzhou city. Fujian Environ (in Chinese), 2003, 20(5): 31－32
20 Yao Z, Wang S H, Jiang X H. The current situation and approach of return straw to field in suburb of Shanghai. Agro-Environ Develop, 2001, 3: 40－41
21 Yevich R, Logan J A. An assessment of biofuel use and burning of agricultural waste in the developing world. Global Biogeochem Cycles, 2003, 17(4): 1095, doi: 10.1029/2002GB001952
22 Chen X F. Economics analysis on pollution from straw burning and managing in rural China. China Rural Economy (in Chinese), 2001, 2: 47－52
23 Jenkins B M, Turn S Q, Williams R B, et al. Atmospheric pollutant emission factors from open burning of agricultural and forest biomass by wind tunnel simulations, Vol 1. California State Air Resources Board U.S. Environmental Protection Agency, (NTIS PB97-133037), 1996
24 U.S. EPA ed. Compilation of Air Pollutant Emission Factors: open burning, 5th ed. (with updates through 2001), http://www.epa.gov/ttn/chief/ap42/index.html
25 Turn S Q, Jenkins B M, Chow J C, et al. Element characterization of particulate matter emitted from biomass burning: wind tunnel derived source profiles for herbaceous and wood fuels. J Geophys Res, 1997, 102(D3): 3683－3699
26 Cao G L, Zhang X Y, Zheng F C, et al. Emission factor estimates of crop residues burning in rural China. Environ Manage, 2006, in revision
27 Cui Y S, Wang Q R. Sulfrr behavior in soil and atmosphere environment and its effect on plants. Chin J Eco-Agr (in Chinese), 2002, 10(3): 80－82
28 Andreae M O, Merlet P. Emissions of trace gases and aerosols from biomass burning. Glob Biogeo Cycles, 2001, 15(4): 955－966
29 Reddy M S, Venkataraman C. Inventory of aerosol and sulphur dioxide emissions from India: Part II-biomass combustion. Atmos Environ, 2002, 36: 699－712
30 Intergovernmental Panel on Climate Change. Greenhouse Gas Inventory Reference Manual. Revised 1996 IPCC guidelines for national greenhouse gas inventories. IPCC/OECD/IES, UK Meteorological Office, Bracknell, UK, 1997
31 Zhang W D, Zhou B, He C Y, et al. Organic waste resources and their biogas potentiality in rural areas of China. Nat Resour, 1997, 1: 67－71
32 Tsinghua University ed. China Climate Change Country Study, Beijing: Tsinghua University Press, 1999
33 Olivier J G J, Bouwman A F, vander Maas C W M, et al. Description of EDGAR Version 2.0, Rep. 771060 002, Natl. Inst. of Public Health and the Environ, Bilthoven, Netherlands, 1996
34 Streets D G, Jiang K, Hu X, et al. Recent reductions in China's greenhouse gas emissions. Science, 2001, 294: 1835－1836