Environmental Pollution 223 (2017) 705–712

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Village energy survey reveals missing rural raw coal in northern China: Significance in science and policy☆

Guorui Zhi [a,*], Yayun Zhang [a,b], Jianzhong Sun [a,c], Miaomiao Cheng [a], Hongyan Dang [a], Shijie Liu [a], Junchao Yang [d], Yuzhe Zhang [a,b], Zhigang Xue [a], Shuyuan Li [b], Fan Meng [a]

[a] State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China
[b] College of Chemical Engineering, China University of Petroleum, Beijing 102249, China
[c] Yantai Institute of Coastal Research, CAS, Yantai, Shandong Province 264003, China
[d] Scientific Research Academy of Guangxi Environmental Protection, Nanning, Guangxi Zhuang Autonomous Region, 530022, China

A R T I C L E I N F O

Article history:
Received 18 August 2016
Received in revised form
3 February 2017
Accepted 3 February 2017
Available online 10 February 2017

Keywords:
Rural energy survey
Solid fuel
Residential coal
Air pollution
China

A B S T R A C T

Burning coal for winter heating has been considered a major contributor to northern China's winter haze, with the district heating boilers holding the balance. However a decade of intensive efforts on district heating boilers brought few improvements to northern China's winter air quality, arousing a speculation that the household heating stoves mainly in rural area rather than the district heating boilers mainly in urban area dominate coal emissions in winter. This implies an extreme underestimation of rural household coal consumption by the China Energy Statistical Yearbooks (CESYs), although direct evidence supporting this speculation is lacking. A village energy survey campaign was launched to gather the firsthand information on household coal consumption in the rural areas of two cities, Baoding (in Hebei province) and Beijing (the capital of China). The survey data show that the rural raw coal consumption in Baoding (5.04×10^3 kt) was approximately 6.5 times the value listed in the official CESY 2013 and exceeded the rural total of whole Hebei Province (4668 kt), revealing a huge amount of raw coal missing from the current statistical system. More importantly, rural emissions of particulate matter (PM) and SO_2 from raw coal, which had never been included in widely distributing environmental statistical reports, were found higher than those from industrial and urban household sectors in the two cities in 2013, which highlights the importance of rural coal burning in creating northern China's heavy haze and helps to explain why a number of modeling predictions on ambient pollutant concentrations based on normal emission inventories were more bias-prone in winter season than in other seasons. We therefore recommend placing greater emphasis on the "missing" rural raw coal to help China in its long-term ambition to achieve clean air in the context of rapid economic development.

1. Introduction

Air pollution in China poses adverse effects on health, long-range pollution transport, and global/regional climate (Chen et al., 2013b; Wang et al., 2014; Wuebbles et al., 2007). With the rapid industrialization and urbanization, air pollutant emissions increased consistently, accompanied by frequent occurrence of heavy pollution events (Herrerias et al., 2013; Hu and Jiang, 2013; Liang et al., 2011; Zhang et al., 2015b). The heavy pollution first climaxed in January 2013 when China experienced an extremely severe and persistent period of haze (Liu et al., 2015; MEP, 2013). Approximately 1.3 million km^2 of Chinese territory and 800 million Chinese people were affected by the heavy haze (Huang et al., 2014). According to the report of the Ministry of Environmental Protection of China (MEP), the daily average $PM_{2.5}$ concentrations in 74 major cities exceeded the limit of Chinese National Ambient Air Quality Standard (75 μg/m3) in almost 70% of calendar days of January, with a daily extreme as high as 772 μg/m3 (CNEMC, 2014). A sharp increase in respiratory distress and an extreme decrease in visibility both appeared, casting a shadow on the public mood, and risking China's clean air commitment to the 2022 Winter Olympic Games in Beijing (Chen et al., 2013a; MEP, 2013; Xinhua News Agency, 2015).

☆ This paper has been recommended for acceptance by Eddy Y. Zeng.

* Corresponding author. 8 Dayangfang, Beiyuan Rd., Chaoyang District, Beijing 100012, China.
E-mail address: zhigr@craes.org.cn (G. Zhi).

http://dx.doi.org/10.1016/j.envpol.2017.02.009
0269-7491/

Although air pollution in China stems from multiple sources, the heating practice in northern China is generally accepted to be the leading driver for the extremely severe and persistent winter haze (Almond and Li, 2009; Liu et al., 2016; Xiao et al., 2015). During the 1950s-1980s, the Chinese government established a free winter heating system for homes and offices. This system covered only areas of northern China with the Huaihe River and Qinling Mountains jointly forming the division between northern and southern China (north-south divide) (Almond and Li, 2009). Even after the commercial heating arrived in China in the mid-1990s, the winter heating remained a unique practice in the northern part of China with coal as the major energy (Makinen, 2014). Burning coal for heating invites additional emissions of air pollutants for winter season and consequently magnifies the background pollution level by 3–7 times (Liu et al., 2010; MEP, 2013; Wang et al., 2015; Xiao et al., 2015).

In the past decade, China has been tightening a range of measures to curb the occurrence of severe haze events. These measures are included in a number of official releases such as the *Law of Prevention and Control of Atmospheric Pollution* (NPC, 2015), the *Atmospheric Pollution Prevention and Control Action Plan* (The Central People's Government of the People Republic of China, 2013), *Guiding Opinions on Promoting the Joint Prevention and Control of Air Pollution to Improve Regional Air Quality* (The Central People's Government of the People Republic of China, 2010), and *12*th *Five-Year Plan of Prevention and Control of Atmospheric Pollution in Key Areas* (MEP, 2012), etc. We notice that all of these policy papers, whenever heating-magnified pollution is concerned, usually lay emphasis on district heating (also referred to as central heating or collective heating) boilers and give minor attention to household heating (heating homes by burning coal in household stoves) stoves. Unfortunately after a decade of intensive effort on district heating boilers, the hoped fundamental improvement in winter air quality is still hard to achieve (China Daily, 2015), which challenges not only the policy of "giving priority to boilers", but also the authoritativeness of the China Energy Statistical Yearbooks (CESYs) because the household (rural and urban) coal consumption given by the CESY 2013 was only 2.5% of the nation total (NBSC, 2013). A speculation then arises that it is the household heating stoves mainly in rural area instead of district heating boilers mainly in urban area that contribute more significantly to the winter heavy pollution. If this speculation was true, the CESYs must have significantly underestimated the household coal consumption.

In fact, a few cases regarding discrepancy between simulation and observation together with several public speeches on rural coal consumption may in some way add to the speculation. Back to a decade ago, Zhu (2004) compared the predictions of 3 air pollution modeling methods, finding that all methods suffered a maximal bias in the heating season. Several years later, Liu et al. (2010) showed that CMAQ V4.7 significantly under-predicted PM_{10} concentration over China's densely populated areas in January. A similar result was reported by Fu et al. (2009) when they modeled the wintertime $PM_{2.5}$ pollution in Beijing; the simulated $PM_{2.5}$ concentration was considerably lower than that measured in the same period (Dan et al., 2004). In 2012, Fu et al. (2012) simulated elemental carbon (EC) and organic carbon (OC) aerosols of China using an inventory based on CESY and compared the model results with surface measurements in order to derive "top-down" emission estimates of EC and OC. It was found that the model underestimated EC and OC concentration at almost all rural sites, particularly in January. The authors also ascribed the difference to anthropogenic emissions due primarily to heating.

Most recent studies continued to show the significant enhancement of pollutants (e.g., $PM_{2.5}$) in northern China's wintertime due mainly to winter heating (Li et al., 2015); such enhancement might be up to 70% in Beijing (Zhang et al., 2016). The GEOS-Chem chemical transport model and its adjoint with improved model horizontal resolution and aqueous-phase chemistry for sulfate production also shows that residential sector is one of the major sector responsible for wintertime surface $PM_{2.5}$ over Beijing (Zhang et al., 2015a). Zhong et al. (2016) conducted simulations using the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) to study the air quality in East Asia; they found that surface PM_{10} concentrations in January, northern part of China, was significantly underpredicted (relative to observation results) based on the inventory of EDGAR (Emissions Database for Global Atmospheric Research), yet things got better if prediction was based on the inventory of REAS (Regional Emission Inventory in ASia) for REAS had much higher PM_{10} emissions than EDGAR. Very interestingly, a latest paper by Cheng et al. (2016) showed that the actual emissions of major pollutants (e.g., PM, PM_{10}, SO_2) are several times higher than those in EDGAR inventory.

When it comes to actual coal consumption in rural areas, although the CESY 2013 states that the residential sector (rural and urban) burned less than 100 million tons of coal nationwide (NBSC, 2013), in an interview in 2014, Wang Zhixuan, the Secretary General of China Electricity Council (CEC), estimated an 800 million tons of annual coal consumption in this sector (Wang, 2014), which was 7 times more than that listed in the CESY 2013 (NBSC, 2013). Lin Jianying, a member of CPPCC Xingtai Municipal Committee, asserted in a 2014 plenary session that the actual consumption of coal by various rural stoves in Beijing-Tianjin-Hebei (BTH) region might be more than 4 times that in the CESY 2013 (Lin, 2013; NBSC, 2013). Although these voices were more of an intuitive estimation based on personal experiences than a systematic investigation and therefore attracted little attention of policy-makers at that time, they pointed to one possibility: the actual consumption of coal in northern China has extremely been underestimated. However the direct and decisive evidence for such a speculation is lacking.

In this context, a rural energy survey campaign was launched by the Chinese Research Academy of Environmental Sciences (CRAES) in the rural areas of two cities in northern China: Baoding, a city with millions of rural households and well-known air pollution in Hebei province, and Beijing, the capital of China. With well-designed questionnaires, information regarding rural energy consumption and related pollutant emissions can be obtained. The results may help scientists to achieve better modeling predictions in heating season and help policy makers to review the efficacy of the established policies and develop more specific measures for attaining long-term clean-air targets.

2. Methods

2.1. Questionnaire survey

A questionnaire was designed for surveying residential energy consumption. The questions concerned the annual consumption of various energy varieties, including raw coal, coal briquette, wood, agricultural stalk, electricity and fuel gas (liquefied gas, LG, for example). In addition to annual consumption, the questionnaire also showed interest in the winter share of each solid fuel (coal, wood, crop stalk, etc.) in a one year total.

Located in northern China, the BTH region is among the worst in air quality in China (MEP, 2013). A rural energy survey campaign here can provide insight into why this region suffers from more-severe air pollution in winter and which measures are more effective to improve the poor air quality. Two cities, namely Baoding and Beijing were selected for rural energy survey in September 2014. Baoding is one of the prefectural cities of Hebei province, where nearly 80% of the population is registered as rural residents.

In contrast, Beijing is the capital of China, where live a low proportion of rural residents compared to Baoding. Note that, in China, a municipal administration governs both urban and rural areas and a city's total population is composed of both urban and rural residents in a general sense. Because almost all urban areas of a city are receiving district heating service, we restricted our questionnaire surveys only to rural areas, where winter heating is generally achieved by individual households themselves through small coal stoves.

Given the widespread differences among villages in economic level (rich or poor), preferred manner of heating (mainly on coal or electricity), and location feature (suburb or rural area), decision on which villages are eligible candidate is significant to the representativeness. In Baoding, the local environmental department assisted us to identify 5 specific villages as survey candidates after a balanced consideration of diverse conditions. While in Beijing, the target villages were not preset by anyone but were momentarily designated depending on which villages were familiar to our interviewers invited; the advantage of this manner lies in the independence of any preconditions.

Questionnaire surveys were completed in two different styles. In Baoding, nine members from CRAES and 3 members from the Baoding Environmental Monitoring Center formed a joint team. The BEMC members instructed the village committees to call villagers together for interviews, and the CRAES members directly interviewed the assembled villagers. The villagers' oral responses to the questions were carefully noted by the CRAES members. When a case of interview was over, the interviewee received a small parcel of washing powder as a reward for participation. In this manner, more than 500 households from five villages were investigated in Baoding. The approach used in Beijing was somewhat different. In each target village, we appointed one or two villager representatives to distribute dozens of questionnaires. The questionnaires were completed by the interviewees themselves and were then returned to CRAES members. In this manner, 243 households in rural Beijing returned their completed questionnaires, of which 163 copies met our criteria. Note that we kept reminding the interviewees to answer our questions based on their billing records if possible, though many villagers could only do based on memory or estimation.

The survey results were used to analyze the rural household energy structure and to calculate the emissions of primary air pollutants (PM, SO_2, NOx, BC, OC, CO, and VOCs).

2.2. Basic information derived from questionnaire survey

Raw information from the questionnaires was input to an Excel spreadsheet for statistical analysis. Basic information obtained directly from the surveys included the percentage of households that used an energy variety (*PER*; usually an energy variety, e.g., wood, is consumed by only a portion of, rather than all of, investigated households), the per-capita annual consumption of an energy variety (*CON*; this is the mean consumption of an energy variety by a person whose household did consume such energy variety), and the standard deviations of *CON*s (*sd*) (Table 1).

As shown in Table 1, all the 6 energy varieties were used in the villages, but energy-specific percentages varied. Electricity, raw coal and LG were the most widespread energy varieties: each was used in more than 87% of households (*PER*>87%). However, crop stalk was used in approximately 10% of households in both cities, reflecting a change from traditional low-calorie easy-to-get fuels (e.g., crop stalks) to high-calorie commercial fuels or electricity. Significant difference between the two cities was observed in wood and briquettes. Wood was used in only 13% of rural households in Baoding, whereas in Beijing, was used in up to 71% of rural households. Many of Beijing's suburban counties are located in mountainous areas, where wood is relatively easy to obtain. Less than 10% of households in Baoding used coal briquettes, whereas more than a third did in Beijing. The fact that Beijing's municipal government was subsidizing the users of coal briquettes may account for this difference (The General Office of Beijing Municipal People's Government, 2013).

Among the 6 energy varieties, electricity and LG are among clean energy sources that emit few or no air pollutants. This allows us to focus only on solid fuels (coal chunks, coal briquettes, wood, and crop stalks) for emission estimation.

2.3. Estimation of pollutant emissions from rural solid fuels

The annual total consumption of a given energy variety (*TOL*, in units of tons, t) among all of a city's rural households (Baoding or Beijing) was calculated using the equation

$$TOL = CON*POP*PER \Big/ 10^2, \quad (1)$$

where *POP* is the rural population of the city.

The annual emissions of a pollutant from a fuel (raw coal chunk, coal briquette, wood, or stalk) (*EM*, t) were calculated using the expression

$$EM = CON*POP*PER*EF \Big/ 10^5, \quad (2)$$

where *EF* is the emission factor of a specific pollutant (kg/t). Table 2 lists the *EF*s used in this study. The detailed information on how to derive these *EF*s from literature data is given in Table S1 in the Supporting Information (SI).

2.4. Evaluation of uncertainties in estimated TOLs and EMs using the Monte Carlo approach

According to expression 1 and 2 in subsection 2.3, *TOL* is dependent on the input variables *CON*, *POP*, and *PER*, and *EM* is dependent on the input variables *TOL* (*CON*, *POP*, *PER*) and *EF*;

Table 1
Per-capita annual consumption (*CON*) of individual energy varieties.

Parameter	Raw coal	Coal briquettes	Electricity[a]	LG	Wood	Stalks
Baoding						
CON (t)	0.794	0.764	0.578	0.025	0.273	0.356
sd	0.423	0.384	0.209	0.018	0.270	0.467
PER (%)	97.1	3.5	100.0	93.6	13.1	11.4
Beijing						
CON (t)	0.856	0.232	0.844	0.068	0.569	0.234
sd	0.565	0.177	0.712	0.055	0.401	0.146
PER (%)	87.7	33.7	100.0	96.3	70.6	8.6

[a] Units of electricity consumption are MWh.

Table 2
Emission factors (*EF*s) used in this study. *sd* means standard deviation.

Pollutant	Raw coal		Briquettes		Wood		Stalks	
	Mean	*sd*	*Mean*	*sd*	*Mean*	*sd*	*Mean*	*sd*
PM	9.99	3.72	7.10	3.42	5.23	2.50	7.48	1.84
SO_2	18.5	5.0	13.81	3.65	0.35	0.31	0.54	0.59
NOx	1.83	0.62	1.64	0.43	0.90	0.43	1.11	0.35
CO	105.7	65.6	53.4	16.1	63.2	31.3	84.5	23.4
BC	2.86	1.04	0.35	0.34	1.11	0.34	0.94	0.48
OC	3.74	2.28	2.88	1.48	2.41	1.98	2.79	1.93
VOCs	0.57	0.11	0.57	0.11	4.78	2.73	5.97	2.04

therefore the uncertainty of either *TOL* or *EM* is logically dependent on the propagation of uncertainties of all the relevant inputs. Crystal Ball software was used to incorporate a Monte Carlo stochastic simulation for propagating the probability distributions of the input variables to *TOLs* or *EMs* (Goldman, 2002). The method for evaluation of uncertainties in estimated *TOLs* and *EMs* using the Monte Carlo approach is described in Table S2 in SI.

3. Results and discussion

3.1. Rural energy structure: coal dominated

The total consumption (*TOL*) of each energy variety in each city was calculated separately as described in subsection 2.3. The *TOLs* were converted to energy in units of TJ (1 TJ = 10^{12} J). The calculated *TOLs* and annual energy consumption in the rural areas are presented in Table 3. In Baoding, almost 6.00×10^3 kt of solid fuels was used in the year 2013, of which more than 5.00×10^3 kt was raw coal. In Beijing, solid fuel consumption amounted to almost 5.60×10^3 kt, of which nearly two thirds was raw coal.

Based on Table 3, the rural energy structures of the two cities were constructed (Fig. 1). According to Fig. 1, solid fuels (including raw coal, coal briquette, wood, and crop stalk) dominated the rural household energy structure in both Baoding and Beijing (>80%). Clean energy varieties, including LG and electricity, combined to account for not more than 20% of the total, implying that there is a long way to go before clean energy dominates rural energy structure. Meanwhile raw coal also dominated the total energy structure. In Baoding, raw coal represented more than 70% of the total energy consumption, and in Beijing, more than half. Raw coal and briquette coal in combination contribute 78% and 55% of the total energy consumptions in Baoding and Beijing, respectively.

3.2. Extreme underestimation of raw coal consumption

The investigations in Baoding and Beijing have deeply impressed us that winter heating in northern China's rural households depends chiefly on coal, particularly raw coal, and almost all of rural coal is burned for winter heating purpose (cooking can also be performed simultaneously with heating in winter). We have noticed that northern China's heavy air pollution usually peaks during the heating season (Nov 15 to next year Mar 15) (Xiao et al., 2015; Zhang et al., 2015b), highly coincident with the intensive coal burning season.

The annual coal (raw chunks and briquettes) consumptions obtained in this study for Baoding and Beijing are compared with those in the CESY 2013 (NBSC, 2013) (Fig. 2). A significant difference between the survey results and the official yearbook data is observed. The calculated raw coal and briquette consumptions (5.04×10^3 kt and 175 kt, respectively) in rural Baoding are approximately 6.5 and 2.5 times their respective values listed in the CESY 2013, and the calculated raw coal consumption alone (5.04×10^3 kt) exceeds even the rural total of whole Hebei Province in CESY 2013 (4668 kt). Since Baoding is only one city of Hebei province, with a population approximately one sixth of the provincial total. The consumption of raw coal by a city's rural area exceeding that by whole province's rural area is anyway impossible and absurd. The only explanation for this conflict is an extreme underestimation of rural raw coal by the CESY 2013. Similar results were obtained for Beijing: we calculated raw coal consumption of 3.31×10^3 kt and coal briquette consumption of 348 kt, both of which significantly exceed their respective values listed in CESY 2013. There is a clear need to improve the existing statistical system so that the missing coal in rural areas could be properly covered.

Since this study intends to emphasize the special role of rural raw coal in northern China's winter pollution, it is necessary to assess the above mentioned data of annual consumption (*TOL*) of rural raw coal. The assessment method is included in subsection 2.4 of this paper and Table S2 in SI. According to Fig. S1 (based on *sd* in Table 1 and Table S2; *sd* means the standard deviation of surveyed individuals), the 10–90% probability of *TOL* covers 1.50×10^3–8.8×10^3 kt for Baoding and 509–6.29×10^3 kt for Beijing, respectively. That is, the households in 90 percentile consume raw coal more than 12 times those in 10 percentile, reflecting the severe difference in coal consumption among households. However, we are actually more interested in the *TOL* that is based on the mean of surveyed individuals than based on surveyed individuals themselves, the standard deviation sd_m ($sd_m = sd/n^{0.5}$; sd_m is new for revision R2 and means the standard deviation of mean of surveyed individuals) is used to derive another distribution for *TOL*, as shown in Fig. S2. According to Fig. S2, the uncertainty for *TOL* is about 525 kt from the mean value of 5.04×10^3 kt for Baoding and about 692 kt from the mean value of 3.34×10^3 kt for Beijing.

Following Baoding's example that the actual rural raw coal consumption is 6.5 times that in CESY2013 and the uncertainty (with 5% significant level) is about 10.4% of *TOL*, the actual rural raw coal consumption for whole Hebei province are estimated to be 3.07×10^4 kt (rather than 4668 kt in CESY 2013) with an uncertainty of 3.20×10^3 kt. Note that, according to China's Population Census, the rural population of Hebei province is 6.1 times that of Baoding.

Assuming the rural raw coal consumption in the 15 provincial level administrative regions with winter heating practice (Heilongjiang, Jilin, Liaoning, Inner Mongolia, Xinjiang, Gansu, Shaanxi, Shanxi, Ningxia, Shangdong, Henan, Hebei, Tianjin, Beijing and Qinghai) having been underestimated by 6.5 times as in Heibei province, the actual *TOL* in the whole heating areas would be (222 ± 23) million tons. The climbing income, growing living demand, and falling raw coal price are supposed to account for such flying raw coal consumption, which was unfortunately overlooked by CESYs, reflecting a need to reform the statistical methodology in terms of residential coal consumption. By the way, we have no proof of the underestimation of rural raw coal consumption in non-winter heating areas and therefore the total rural raw coal consumption across China ought to be the sum of the value reported

Table 3
The total consumption (*TOL*) and converted calorific value of each energy variety in 2013.

City		Raw coal	Briquettes	LG	Electricity	Wood	Stalks	Total
Baoding	*TOL*[a] (kt)	5.04×10^3	175	151	3.78×10^3	234	265	5.71×10^3[c]
	Energy[b] (TJ)	1.11×10^5	2.91×10^3	7.53×10^3	1.43×10^4	4.38×10^3	5.01×10^3	1.45×10^5
Beijing	*TOL*[a] (kt)	3.34×10^3	348	289	3.75×10^3	1.78×10^3	89.0	5.56×10^3[c]
	Energy[b] (TJ)	6.99×10^4	5.54×10^3	1.37×10^4	1.35×10^4	3.22×10^4	1.61×10^3	1.36×10^5

[a] Units are kt except for electricity, 10^3 kWh.
[b] Conversion factors from *TOL* (kt) to energy (TJ) are found in the literature (Zhi et al., 2015).
[c] Only for solid fuels.

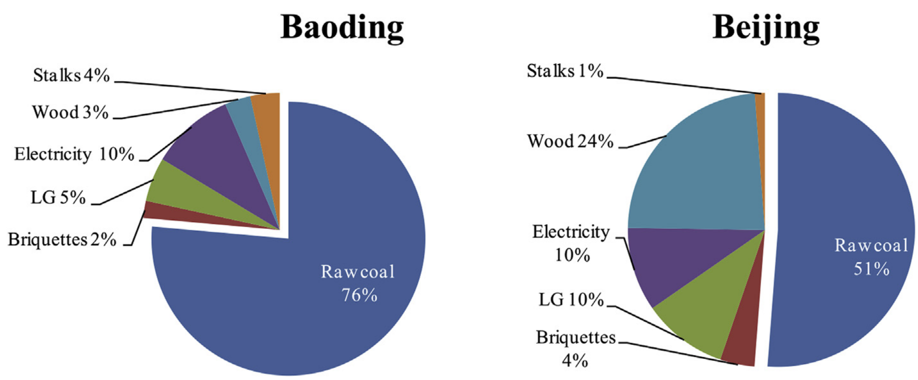

Fig. 1. Rural energy structures of Baoding and Beijing.

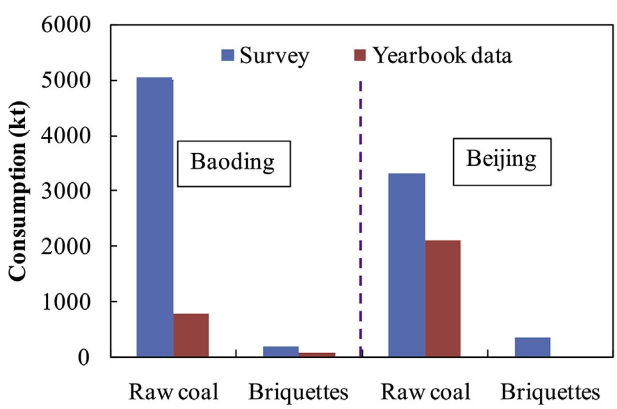

Fig. 2. Comparison of coal consumption based on the surveys with that based on the energy yearbook data (NBSC, 2013).

here for winter heating areas (much higher than CESY) and the value in CESY for non-winter heating areas. Considering that the winter heating areas consume about 2/3 of the total rural raw coal (NBSC, 2013), the CESY-based national total may have been underestimated by 4.7 times. That is, the actual consumption of raw coal in China's rural areas should not be only 55.7 million tons in CESY2013 but about 260 million tons after consideration of the underestimation.

3.3. Emissions from raw coal: a major contributor to air pollution

The calculated pollutant emissions from the rural solid fuels in the two cities are listed in Table S3 of the SI. Their uncertainties based on the Monte Carlo simulations are also presented in Table S3 (in percentages) after taking into account the uncertainties of related input variables described in subsections 2.3 and 2.4. According to Table S3, rural solid fuels released 54.3 (−40%, +42%), 100.5 (−23%, +28%), 9.8 (±39%), 703.4 (−37%, +51%), 14.4 (−41%, +39%), 21.3 (−60%, +64%), and 5.78 (−30%, +35%) kt of PM, SO_2, NOx, CO, BC, OC, and VOCs, respectively, in Baoding and 46.4 (−46%, +57%), 69.7 (−35%, +42%), 8.3 (−43%, +51%), 54.9 (−50%, +52%), 11.2 (−43%, +52%), 18.6 (−62%, +76%), and 11.6 (−55%, +72%) kt of PM, SO_2, NOx, CO, BC, OC, and VOCs, respectively, in Beijing.

More noteworthy, raw coal played a decisive role in the emissions of evaluated pollutants of solid fuels in this study. As shown in Fig. 3, more than 90% of PM, SO_2, NOx, CO, OC and BC emissions were attributable to raw coal in Baoding and 68–92% of PM, SO_2, NOx, CO, OC and BC emissions were attributable to raw coal in Beijing, demonstrating the leading role of raw coal in the emissions from solid fuels in the two cities.

The burning of raw coal in rural areas also plays an important role in the overall pollutant emissions from various sources in the two cities. Fig. 4 compares the emissions from rural raw coal based on our investigation and those from the industrial and urban residential sectors based on the *2013 Annual Statistic Report on Environment in China* (MEP, 2014). Rural raw coal in Baoding released PM (49.9 kt, −40%, +41%) and SO_2 (97.9 kt, −23%, +27%) in greater amounts than either the industrial sector (39 kt and 79 kt) or urban household sector (9.6 kt and 16.3 kt). Similarly, in Beijing, rural raw coal released PM (32.9 kt) and SO_2 (64.3 kt) in greater amounts than either the industrial sector (27 kt and 56 kt) or urban household sector (28 kt and 35). Furthermore, compared with large point-sources (e.g., power plants), greater health hazards may result from household raw coal burning due to the relatively low emission heights and high emission factors (Lei et al., 2011; Wang, 2008; Zhang et al., 2008; Zhi et al., 2011). Given the dominant role of raw coal in the rural energy structure (as shown in Fig. 1) and the major contribution of raw coal to the primary pollutant emissions (as shown in Fig. 3) together with the strong seasonality of raw coal burning (almost completely burned in winter), an intensified effort in tackling the rural raw coal problem promises a fundamental change in mitigating northern China's heavy haze in winter.

3.4. Significance in science and policy

So far, persuasive academic papers on rural raw coal consumption based on direct and systematic energy survey are rare. Zhao et al. (2015), by combination of field sampling and high resolution remote sensing, estimated that raw coal consumption in Beijing's cottage areas (mainly rural areas) was 2169 kt, about two thirds of our data. In contrast, Zhang et al. (2014)'s questionnaire survey (in the manner similar to ours in Beijing) demonstrated that raw coal consumption in Beijing was 4700 kt, about 1.5 times of our data. Zhang et al. (2014) also found that Hebei province consumed 26,946 kt of raw coal, nearly 6 times that in CESY 2013, which corroborates our conclusion that official statistics have extremely underestimated the real raw coal consumption.

3.4.1. Science

The huge consumption of raw coal and resulting higher-than-expected air pollutant emissions in Baoding and Beijing's rural areas challenge the clean air pursuit in northern China. Subsequent to decades of economic growth, the demand for more adequate and comfortable heating in cold season is rising, bringing about continuing increase in coal consumption in northern China. Considering that many emission inventories of China rely

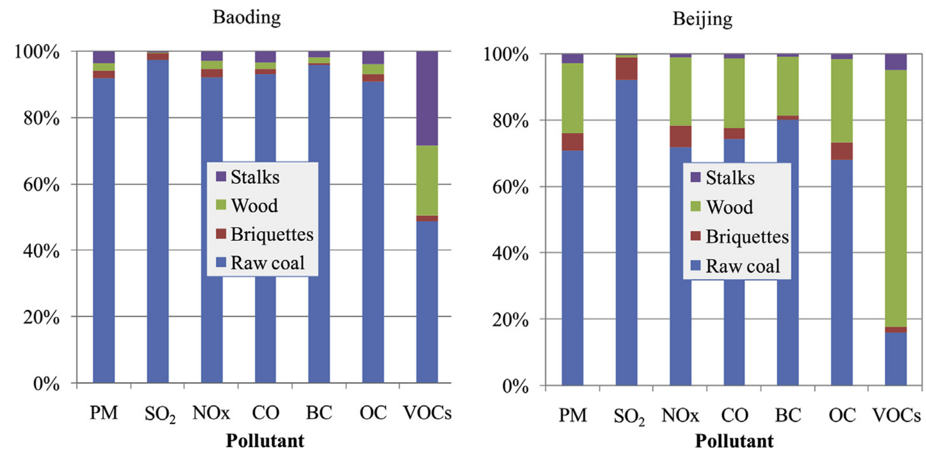

Fig. 3. Contributions of individual solid fuels to pollutant emissions.

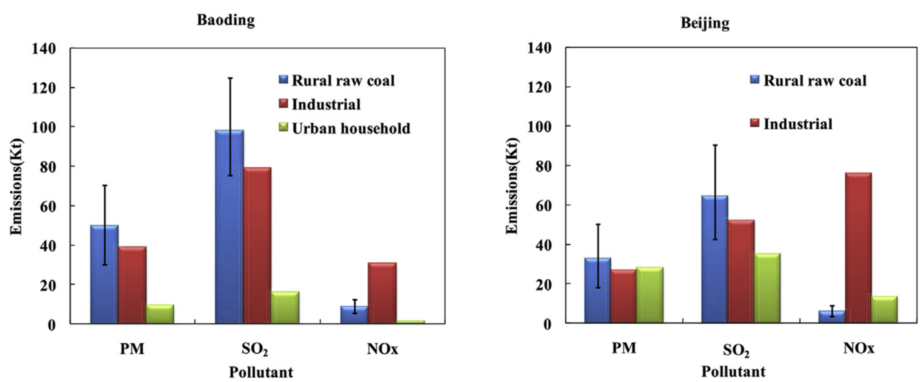

Fig. 4. Comparison of emissions from rural household raw coal based on this study with those from other sectors (industrial sector and urban household sector) based on the *2013 Annual Statistic Report on Environment in China* (MEP, 2014).

completely or partly on official energy yearbooks (Lei et al., 2011; Shi et al., 2014; Zhao et al., 2011), in which the information regarding rural coal burning does not fully take into account the emissions from the extra coal consumption, the accuracy of the inventories is somewhat questionable, which may introduce a large uncertainty to model simulation studies. It seems reasonable to believe that replacing the pollutant emissions used in aforementioned modelings with those based on direct village surveys likely contributes to the improvement in the modeling-based pollution predictions of heating season. Researchers on modeling are proposed to test this supposition with updated coal consumption.

Moreover, the uncertainty in household raw coal consumption incurs vague understanding of China's contribution to climate warming. BC is regarded as the strongest light-absorbing aerosol and thus an important climate warming contributor, possibly second only to CO_2 (IPCC, 2013; Jacobson, 2001; Ramanathan and Carmichael, 2008). Quite a few assessment reports published by UNEP and other institutions recommend controlling BC and other short-lived climate pollutants (SLCPs) for health-climate co-benefits (e.g., UNEP, 2009, 2011; UNEP and WMO, 2011a; World Bank, 2013). China is usually thought to be the largest BC emitting country in the world (Bond, 2010; Bond et al., 2004) and the residential sector is believed to be the major contributor (Qin and Xie, 2011). However, many inventories for China estimate their black carbon emissions from residential sector directly or indirectly based on the standard CESYs (e.g. ref. Lu et al., 2011; Qin and Xie, 2011; Zhang et al., 2013), allowing BC emissions to be necessarily underestimated. This underestimation causes an underappreciated contribution of China's light-absorbing carbon to regional or global warming and may eventually make the world miss a good opportunity of cutting China's BC emissions from rural winter heating activities for climate-health co-benefits (Jacobson, 2001; Streets and Aunan, 2005; Streets et al., 2013; UNEP and WMO, 2011b).

As for long range transport of pollutants, it is easy to understand that China's contribution would be noticeably underestimated if the revealed missing rural coal was not taken into consideration (Wuebbles et al., 2007).

3.4.2. Policy

China has been taking increasingly stringent measures against pollution from large scale sources such as industry, power generation, and transportation. The missing rural raw coal consumption revealed by this study is very likely to be the last but most stubborn barrier for China to achieve its clean air target due to the widespread use of small stoves, high emission factors, high pollution efficiency and difficulty of monitoring and regulation. In this sense, it is important and imperative for the government to allocate more attention and resources to rural energy, rural coal, or more precisely, rural raw coal when planning measures and policies to control air pollution.

Firstly, it is time to give priority to solving rural coal problem as a part of the national energy restructuring program. Clean energy such as electricity, fuel gas, solar energy, and wind energy should be brought into widespread use to substitute for solid fuels in rural areas. Cleaner coal (e.g., anthracite) or coal products (e.g., clean coal briquette) may temporarily serve the transitional period before clean energy can feed the rural households with sufficient resources and infrastructure facilities. Secondly, to suffice rural households with electricity, it is necessary to reappraise the current limitations on coal-fired power plants. Given the highly effective pollution-control devices installed in China's coal-fired power plants (Huang et al., 2015; MEP, 2011), it seems more advisable to support the development of power plants and supply more electricity to rural households. For this purpose, the preset ceiling on the amount of coal consumption for power sector in China needs to be reconsidered. Thirdly, whenever possible, collective heating in rural BTH region should be promoted to facilitate the application of advanced pollution-control technologies such as dust precipitation, desulphurization and denitrification. Then, significant reductions in emissions could be anticipated due to improved combustion efficiency of and pollution-control devices for the large boilers (Bond et al., 2004; Streets et al., 2001). Finally, we recognize that all of above mentioned clean air efforts are generally more expensive than burning raw coal, and hence cannot be independent of government participation in the manners of, for example, subsidizing former rural coal users. This is actually crucial to China's winter air improvement.

By the way, an international sports event, the 2022 Olympic Winter Games, will be held in Beijing. As one of the host cities, Beijing has made a commitment to clean air to the world (Xinhua News Agency, 2015). The emissions from rural coal found in this study, which have been significantly underestimated, may compromise China's commitment to clean air for the 2022 Games if stagnant air conditions occur by chance (Xinhua News Agency, 2015). In this respect, what is imperative is to accelerate the recommended measures for clean energy substitution or other low-pollution options in northern China. This would also undoubtedly help China in its long-term ambition to achieve clean air in the context of rapid economic development.

3.5. Conclusion

We performed a village energy survey in two northern Chinese cities and concluded that solid fuels (coal, biomass) play a leading role in the rural household energy structure (>80%), with coal alone representing 78% and 55% of the total rural energy consumption in Baoding and Beijing, respectively. We also identified the rural raw coal that was missing from the current energy statistics. In Baoding, the actual consumption was more than six times the amount listed in the official *Yearbook 2013*. The newly identified burning of rural raw coal for winter heating resulted in a newly identified contribution to air pollution. The emissions of PM and SO_2 from rural raw coal exceeded those from the industrial and urban household sectors listed in official reports, which reveals the importance of rural coal in producing northern China's heavy winter haze. We recommend placing greater emphasis on the formerly missing rural coal, which would also assist China in achieving its long-term goal of clean air and its commitment to the 2022 Olympic Winter Games in Beijing.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (41373131, 41173121). Thanks are given to those in Baoding Environment Monitoring Center and CRAES who participated in the survey campaign. We also are grateful to Mr. Oscar Laurent from Belgium who helped us polish the English language.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envpol.2017.02.009.

References

Almond, D., Li, H., 2009. Winter heating or clean Air? unintended impacts of China's Huai River policy. Am. Econ. Rev. 99, 184–190.

Bond, T., 2010. Clearing the Smoke: black Carbon Pollution. Testimony for the House Committee on Energy Independence and Global Warming United States House of Representatives.

Bond, T.C., Streets, D.G., Yarber, K.F., Nelson, S.M., Woo, J., Klimont, Z., 2004. A technology-based global inventory of black and organic carbon emissions from combustion. J. Geophys. Res. 109, D14203. http://dx.doi.org/10.1029/2003JD003697.

Chen, R., Zhao, Z., Kan, H., 2013a. Heavy smog and hospital visits in Beijing, China. Am. J. Respir. Crit. Care Med. 188, 1170–1171.

Chen, Z., Wang, J.-N., Ma, G.-X., Zhang, Y.-S., 2013b. China tackles the health effects of air pollution. Lancet 382, 1959–1960.

Cheng, M., Zhi, G., Tang, W., Liu, S., Dang, H., Guo, Z., Du, J., Du, X., Zhang, W., Zhang, Y., Meng, F., 2016. Air pollutant emission from the underestimated households' coal consumption source in China. Sci. Total Environ. 580C, 641–650, 610.1016/j.scitotenv.2016.1012.1143.

CNEMC, 2014. Air Quality Report in 74 Chinese Cities in March and the First Quarter 2013. China National Environmental Monitoring Centre of MEP.

China Daily, 2015. Beijing Issues First Red Alert for Heavy Air Pollution. http://www.chinadaily.com.cn/beijing/2015-12/07/content_22656835.htm.

Dan, M., Zhuang, G., Li, X., Tao, H., Zhuang, Y., 2004. The characteristics of carbonaceous species and their sources in PM2.5 in Beijing. Atmos. Environ. 38, 3443–3452.

Fu, J.S., Streets, D.G., Jang, C.J., Jiming, H., Kebin, H., Litao, W., Qiang, Z., 2009. Modeling regional/urban ozone and particulate matter in Beijing, China. J. Air & Waste Manag. Assoc. 59, 37–44.

Fu, T.-M., Cao, J.J., Zhang, X.Y., Lee, S.C., Zhang, Q., Han, Y.M., Qu, W.J., Han, Z., Zhang, R., Wang, Y.X., Chen, D., Henze, D.K., 2012. Carbonaceous aerosols in China: top-down constraints on primary sources and estimation of secondary contribution. Atmos. Chem. Phys. 12, 2725–2746.

Goldman, L.I., 2002. Crystal ball software tutorial: crystal ball professional introductory tutorial. In: Proceedings of the 34th Conference on Winter Simulation: Exploring New Frontiers, pp. 1539–1545.

Herrerias, M.J., Joyeux, R., Girardin, E., 2013. Short- and long-run causality between energy consumption and Economic growth: evidence across regions in China. Appl. Energy 112, 1483–1492.

Hu, D., Jiang, J., 2013. A Study of smog issues and $PM_{2.5}$ pollutant control strategies in China. J. Environ. Prot. 4, 746–752.

Huang, R.-J., Zhang, Y., Bozzetti, C., Ho, K.-F., Cao, J.-J., Han, Y., Daellenbach, K.R., Slowik, J.G., Platt, S.M., Canonaco, F., Zotter, P., RobertWolf, Pieber, S.M., Bruns, E.A., Crippa, M., Ciarelli, G., Piazzalunga, A., Schwikowski, M., Abbaszade, G., Schnelle-Kreis, J., Zimmermann, R., An, Z., Szidat, S., Baltensperger, U., Haddad, I.E., Prévôt, A.H., 2014. High secondary aerosol contribution to particulate pollution during haze events in China. Nature 514, 218–222.

Huang, Y., Yang, S., Chen, C., Chen, Y., 2015. Discussion on smoke clean emissions technology in coal-fired power plant. Energy Energy Conservation 20, 126–129.

IPCC, 2013. Climate change 2013: the physical science basis. Contribution of Working Group I to the IPCC Fifth Assessment Report (AR5). Cambridge Univ Press, New York.

Jacobson, M.Z., 2001. Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols. Nature 409, 695–697.

Lei, Y., Zhang, Q., He, K., Streets, D., 2011. Primary anthropogenic aerosol emission trends for China, 1990–2005. Atmos. Chem. Phys. 11, 931–954.

Li, X., Zhang, Q., Zhang, Y., Zheng, B., Wang, K., Chen, Y., Wallington, T.J., Han, W., Shen, W., Zhang, X., He, K., 2015. Source contributions of urban PM2.5 in the Beijing-Tianjin-Hebei region: changes between 2006 and 2013 and relative impacts of emissions and meteorology. Atmos. Environ. 123, 229–239.

Liang, Z., Ma, X., Lin, H., Tang, Y., 2011. The energy consumption and environmental impacts of SCR technology in China. Appl. Energy 88, 1120–1129.

Lin, J., 2013. Pollution status of rural household coal burning and countermeasures. In: Xingtai Commitee of Chinese People's Consultative Conference (Xingtai, Hebei province).

Liu, X.H., Zhang, Y., Cheng, S.H., Xing, J., Zhang, Q., Streets, D.G., Jang, C., Wang, W.X., Hao, J.M., 2010. Understanding of regional air pollution over China using CMAQ, part I performance evaluation and seasonal variation. Atmos. Environ. 44, 2415–2426.

Liu, G., Yang, Z., Chen, B., Zhang, Y., Su, M., Ulgiati, S., 2015. Prevention and control policy analysis for energy-related regional pollution management in China. Appl. Energy 166, 292–300.

Liu, J., Mauzerall, D.L., Chen, Q., Zhang, Q., Song, Y., Peng, W., Klimont, Z., Qiu, X., Zhang, S., Hu, M., 2016. Air pollutant emissions from Chinese households: a major and underappreciated ambient pollution source. Proc. Natl. Acad. Sci. 113, 7757–7761.

Lu, Z., Zhang, Q., Streets, D.G., 2011. Sulfur dioxide and primary carbonaceous

aerosol emissions in China and India, 1996–2010. Atmos. Chem. Phys. 11, 9839–9864.
Makinen, J., 2014. For Central Heat, China Has a North-south Divide at Qin-huai Line. http://www.latimes.com/world/asia/la-fg-china-heat-20141115-story.html.
MEP, 2011. Emission Standard of Air Pollutants for Thermal Power Plants (GB 13223-2011). China Standards Press, Beijing.
MEP, 2012. 12th Five-year Plan of Prevention and Control of Atmospheric Pollution in Key Areas, Beijing.
MEP, 2013. Report on the State of the Environment in China. Ministry of Environmental Protection of China, Beijing, p. 2013.
MEP, 2014. Annual Statistic Report on Environment in China. China Environmental Press, Beijing, p. 2013.
NBSC, 2013. China Energy Statistical Yearbook 2013. China Statistics Press, Beijing.
NPC, 2015. Law of Prevention and Control of Atmospheric Pollution. National People's Congress of China, Beijing.
Qin, Y., Xie, S.D., 2011. Estimation of county-level black carbon emissions and its spatial distribution in China in 2000. Atmos. Environ. 45, 6995–7004.
Ramanathan, V., Carmichael, G., 2008. Global and regional climate changes due to black carbon. Nat. Geosci. 1, 221–227.
Shi, Y., Xia, Y.-f., Lu, B.-h., Liu, N., Zhang, L., Li, S.-j., Li, W., 2014. Emission inventory and trends of NOx for China, 2000–2020. J. Zhejiang University-SCIENCE A Appl. Phys. Eng. 15, 454–464.
Streets, D.G., Aunan, K., 2005. The importance of China's household sector for black carbon emissions. Geophys. Researcal Lett. 32, L12708. http://dx.doi.org/10.1029/2005GL022960.
Streets, D.G., Gupta, S., Waldhoff, S.T., Wang, M.Q., Bond, T.C., Bo, Y., 2001. Black carbon emissions in China. Atmos. Environ. 35, 4281–4296.
Streets, D.G., Shindell, D.T., Lu, Z., Faluvegi, G., 2013. Radiative forcing due to major aerosol emitting sectors in China and India. Geophys. Res. Lett. 40, 4409–4414.
The Central People's Government of the People Republic of China, 2010. Guiding Opinions on Promoting the Joint Prevention and Control of Air Pollution to Improve Regional Air Quality, Beijing.
The Central People's Government of the People Republic of China, 2013. Atmospheric Pollution Prevention and Control Action Plan.
The General Office of Beijing Municipal People's Government, 2013. 2013 Beijing Implementation Plan for Clean Air Action in Rural Areas via Reduction and Upgradation of Household Coal, Beijing.
UNEP, 2009. Non-CO_2 emissions: options for a way forward. Black carbon e-Bulletin 1, 1–4.
UNEP, 2011. Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-lived Climate Forcers. United Nations Environment Programme (UNEP), Nairobi, Kenya.
UNEP, WMO, 2011a. Integrated Assessment of Black Carbon and Tropospheric Ozone.
UNEP, WMO, 2011b. Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decision Makers.
Wang, Z., 2008. Problems on the emission reduction of SO_2 in the thermal power plants. Electr. Power 41, 44–47.
Wang, Z., 2014. It's Household Coal Instead of Power Coal that Is the True Problem. http://www.cec.org.cn/zdldongtai/benbudongtai/2014-04-15/120232.html.
Wang, Y., Zhang, R., Saravanan, R., 2014. Asian pollution climatically modulates mid-latitude cyclones following hierarchical modelling and observational analysis. Nat. Commun. 5 http://dx.doi.org/10.1038/ncomms4098.
Wang, S., Li, G., Gong, Z., Du, L., Zhou, Q., Meng, X., Xie, S., Zhou, L., 2015. Spatial distribution, seasonal variation and regionalization of PM2.5 concentrations in China. Sci. China 58, 1435–1443.
World Bank, 2013. Integration of Short-lived Climate Pollutants in World Bank Activities: a Report Prepared at the Request of the G8, Washington.
Wuebbles, D.J., Hang, L., Lin, J., 2007. Intercontinental transport of aerosols and photochemical oxidants from Asia and its consequences. Environ. Pollut. 150, 65–84.
Xiao, Q., Ma, Z., Li, S., Liu, Y., 2015. The impact of winter heating on air pollution in China. Plos One 10. http://dx.doi.org/10.1371/journal.pone.0117311.
Xinhua News Agency, 2015. Beijing Promises Better Air Quality and Enough Snow for 2022 Winter Olympic Games. http://news.xinhuanet.com/english/2015-07/28/c_134456417.htm.
Zhang, Y., Schauer, J.J., Zhang, Y., Zeng, L., Wei, Y., Liu, Y., Shao, M., 2008. Characteristics of particulate carbon emissions from real-world Chinese coal combustion. Environ. Sci. Technol. 42, 5068–5073.
Zhang, N., Qin, Y., Xie, S., 2013. Spatial distribution of black carbon emissions in China. Chin. Sci. Bull. 58, 3830–3839.
Zhang, Y., Jiang, J., Ye, J., Fu, M., Zhang, F., 2014. Analysis of rural life energy consumption in Beijing-Tianjin-Hebei and suggestion on coal reduction and replace. Energy China 56, 39–43.
Zhang, L., Liu, L., Zhao, Y., Gong, S., Zhang, X., Henze, D.K., Capps, S.L., F, T.-M., Zhang, Q., Wang, Y., 2015a. Source attribution of particulate matter pollution over North China with the adjoint method. Environ. Res. Lett. 10 http://dx.doi.org/10.1088/1748-9326/10/8/084011.
Zhang, Y., Chen, X., Xie, G., Zhang, J., Zhang, C., Shi, Y., Wang, S., 2015b. Pollution status and spatial distribution of $PM_{2.5}$ in China. Resour. Sci. 37, 1339–1346.
Zhang, Y., Sun, Y., Du, W., Wang, Q., Chen, C., Han, T., Lin, J., Zhao, J., Xu, W., Gao, J., Li, J., Fu, P., Wang, Z., Han, Y., 2016. Response of aerosol composition to different emission scenarios in Beijing, China. Sci. Total Enviroment. http://dx.doi.org/10.1016/j.scitotenv.2016.07.073.
Zhao, Y., Nielsen, C.P., Lei, Y., McElroy, M.B., Hao, J., 2011. Quantifying the uncertainties of a bottom-up emission inventory of anthropogenic atmospheric pollutants in China. Atmos. Chem. Phys. 11, 2295–2308.
Zhao, W., Xu, Q., Li, L., Jiang, L., Zhang, D., Chen, T., 2015. Estimation of air pollutant emissions from coal burning in the semi-rural areas of Beijing plain. Res. Environ. Sci. 28, 869–876.
Zhi, G., Zhang, X., Cheng, H., Jin, J., Zhang, F., Wang, T., Zhang, X., 2011. Practical paths towards lowering black carbon emissions. Adv. Clim. Chang Res. 2, 12–22.
Zhi, G., Yang, J., Zhang, T., Guan, J., Du, J., Xue, Z., Meng, F., 2015. Rural household coal use survey, emission estimation and policy implications. Res. Environ. Sci. 28, 1179–1185.
Zhong, M., Saikawa, E., Liu, Y., Naik, V., Horowitz, L.W., Takigawa, M., Zhao, Y., Lin, N.-h., Stone, E.A., 2016. Air quality modeling with WRF-Chem v3.5 in East Asia: sensitivity to emissions and evaluation of simulated air quality. Geosci. Model Dev. 9, 1201–1218.
Zhu, Y., 2004. Comparison of prediction effects of some urban air pollution methods. Meteorology 30, 30–33.