Environmental Pollution 238 (2018) 230–237

Contents lists available at ScienceDirect

Environmental Pollution

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

Pollutant emissions from residential combustion and reduction strategies estimated via a village-based emission inventory in Beijing☆

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A R T I C L E I N F O

Article history:
Received 4 January 2018
Received in revised form
10 March 2018
Accepted 12 March 2018
Available online 20 March 2018

Keywords:
Household combustion
Village-based emission inventory
Temporal distribution
Spatial distribution
Coal to gas

A B S T R A C T

Accurate estimation of pollutant emissions from household solid fuel combustion has been a challenging issue in developing regions, especially in the heavily polluted northern China region. Basing on a survey of residential household energy use in all villages in Beijing, this study developed a village-based emission inventory of $PM_{2.5}$, SO_2, NOx, and NMVOCs emitted from household combustion in Beijing, as well as three emission control scenarios. Notably, 3805 kt and 556 kt of coal were used for household heating and cooking in 2015, respectively. The emissions of NO_X, NMVOCs, SO_2, and $PM_{2.5}$forhousehold heating totaled11.5 kt, 29.3 kt, 43.1 kt, and 34.7 kt in 2015, respectively, while those for household cooking totaled 1.55 kt, 4.02 kt, 6.55 kt, and 3.99 kt. Emissions from household heating contributed to~70% of $PM_{2.5}$ and ~60% of SO_2 emissions in winter. Additionally, downtown Beijing is surrounded by polluted suburbs. A coal forbiddance policy (e.g. “coal to gas”) could gradually improve the air quality in urban Beijing.

1. Introduction

Severe haze pollution has long influenced the central and eastern regions of China in winter and seriously affected the lives and health of people (van Donkelaar et al., 2015). In the Beijing-Tianjin-Hebei (BTH) region, the national capital region as well as the cultural and political center of China, one of the highest concentrations of $PM_{2.5}$ in China are observed (Chen et al., 2013). The annual average $PM_{2.5}$ concentration in this region was 85–110 μg/m^3 from 2013 to 2015, which far exceeded the averages in other parts of China (e.g. the Yangtze River Delta region was 55–70 μg/m^3, the Pearl River Delta region was 34–48 μg/m^3) (Zhao et al., 2017; Wang et al., 2017). Beijing, the capital city of China, is suffering from extremely frequent and severe haze events, especially during the heating season (Huang et al., 2016; Lv et al., 2016). The contribution of the $PM_{2.5}$ emission in winter to the annual mean is greater than 35% in Beijing (Chinese Academy of Engineering, 2016).

Residential (mainly household heating and cooking) emission is a major and underappreciated ambient pollution source in northern China (Liu et al., 2016; Liao et al., 2017). Compared to other emission sources, it is difficult to quantify the emission contributions from the residential sector because household coal consumption is underestimated by the China Statistical Yearbook (Cheng et al., 2017; Zhi et al., 2017; Zhao et al., 2015; Zhang et al., 2014). Several studies have focused on household energy use in China and developed emission inventories (Cheng et al., 2017; Li et al., 2017b). Additionally, studies have performed energy use surveys of households in China (Cheng et al., 2017; Zhi et al., 2017; Zhao et al., 2015; Zhang et al., 2014; Li et al., 2017b; Duan et al., 2014; Zhi et al., 2015; CAEPI, 2016; Zhang et al., 2015). Cheng

☆ This paper has been recommended for acceptance by Charles Wong.

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https://doi.org/10.1016/j.envpol.2018.03.036
0269-7491/

et al., 2017 carried outa series of surveys to investigate the residential energy use in BTH region. Zhi et al., 2017 developed a village energy survey to gather the first hand information on household coal consumption in the rural areas of two cities in northern China. However, to the best of our knowledge, most of these studies are questionnaire survey and only contain a part of the samples, none of these studies obtained household energy information from all villages and developed a village-based emission inventory. Therefore, the spatial resolution of previous emission inventories have been insufficient and may not be truly representative.

The Chinese government has released a number of control strategies to reduce air pollutant emissions from household combustion over the past decade (MEP, 2012; The State Council of the People's Republic of The Central People's Government of the People Republic of China, 2013; The General Office of Beijing Municipal People's Government, 2013; NPC, 2015). In 2017, new policies for heating energy replacement in Beijing (Beijing Daily, 2017) and northern China (China Electric Power News, 2017) have been released and showed to be effective in relieving air pollution in winter. However, considering the shortage of natural gas supply, household combustion will still be an important emission source in the next few years. A number of studies have conducted regarding clean solid fuels (Ge et al., 2004; Li et al., 2016a, 2016b) and clean stoves (Li et al., 2016c), as well as control scenarios for Beijing (Li et al., 2017b; Zhang et al., 2017; Cai et al., 2017). However, large differences exist among these studies due to the high uncertainty associated with household emission inventories. To establish effective control policies and mitigate the serious air pollution problem, it is imperative to develop an accurate emission inventory for household combustion.

In this study, we conduct a village-based survey of household energy use that included all 3612 villages in Beijing. Based on the survey data from 2015, a village-based emission inventory of air pollutants (NO_X, non-methane volatile organic compounds NMVOCs, SO_2, and $PM_{2.5}$) is developed, while the temporal and spatial distributions are presented. Furthermore, we quantitatively estimate emission reductions for several control scenarios of household combustion and provide suggestions for future environmental policy.

2. Materials and methods

2.1. Study domain

Beijing is located from 115.7 °E to 117.4 °E and 39.4 °N to 41.6 °N. The city includes 16 districts/counties (see Fig. 1) and covers 16,410.54 km^2, approximately 0.17% of China (BMBS, 2016); however, it represented 1.58% of the national population (21.71 million residents) and 3.33% of the national GDP in 2015 (NBS, 2016a,b). The energy consumption in the residential sector for heating and cooking in Beijing accounts for 3.29% of the total residential consumption in China (BMBS, 2016; NBS, 2016a,b). As shown in Supporting Information (SI) Figure S1, residential coal consumption has been relatively stable in China and Beijing for some time (NBS, 2016a,b, 2017). Since the total coal consumption in Beijing has been dramatically reduced in recent years, residential sources are becoming increasingly important in Beijing. Residential coal is mainly used in rural households, so the location of villages are shown in Fig. 1 to clearly show the distribution of residential coal in Beijing. The red circle in Fig. 1 represent the Sixth ring road, and residential coal combustion is not allowed inside this circle.

2.2. Sampling method

The survey of this study was conducted in all of Beijing, including 181 towns and 13 counties. 3612 villages (all the villages in Beijing) have been investigated. The villages are sub-components of towns, and the towns are sub-components of counties. These villages comprise 1.551 million households and 4.256 million residents in total. Since household coal combustion has been prohibited in the downtown of Beijing (Xicheng and Dongcheng Districts in Fig. 1), the village households outside the downtown represent the residential source in Beijing. The distribution of village centersis shown in Fig. 1.

Fig. 1. Study domain and the locations of 3612 villages in Beijing. There are no villages in the Xicheng and Dongcheng Districts, which are located in downtown Beijing, as well as Shijingshan District, which is a famous scenic mountain spot. The red circle is a schematic of the Sixth Ring Road. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

A questionnaire was designed for surveying heating and cooking energy consumption. The questions concerned the population, income per capita, per capita living area, heating type (coal stove, biomass stove, district heating, natural gas, electric, heat pump, solar, or others), cooking type (coal and biomass stoves, natural gas, liquefied petroleum gas (LPG), electric, bio-gas, or others), number of heating days, and energy consumption index for heating or cooking in each village. The village headmen from 3612 villages were asked to complete the questionnaire after the investigation of energy use in their villages. Detailed information on household energy use for all villages in Beijing was collected in 2015. Therefore, the representativeness of this study has been greatly improved compared to that of previous studies. In addition, the locations of the 3612 villages were obtained from Google maps (see Fig. 1) (GPSspg map, 2017). The spatial resolutions of this study has also been significantly improved compared to previous studies.

2.3. Village-based emission inventory

A unit-based method is applied to develop a high-resolution emission inventory of household heating and cooking in Beijing. The emission inventory structure was described in detail in our previous publications (Wang et al., 2014; Zhao et al., 2013a, 2013b, 2013c). The emissions from heating and cooking are calculated based on activity data (energy consumption), technology-based emission factors, and effectiveness of control technologies (there are no end-of-pipe control technologies for heating and cooking), as shown in the following equations:

$$E = \sum_{i,j} C_{i,j} \times EF_{i,j} \quad (1)$$

$$\text{Heating: } C_{i,j} = A_{i,j} \times 3600 \times 24 \times Z_i \times q_i \div \eta_n \quad (2)$$

$$\text{Cooking: } C_{i,j} = P_{i,j} \times Q_i \div \eta_m \quad (3)$$

where E is emissions, C is the coal consumption in each village, EF is the emission factor for each type of fuel used for heating or cooking, A is the household area, Z is the number of heating days, q is the energy consumption index for building heating, Q is the energy consumption index for cooking, P is the population, and η is the thermal efficiency. Additionally, i, j, n, and m are parameters that represent the village, type of fuel, heating type (coal stove, biomass stove, district heating, natural gas, electric, heat pump, solar, or others), and cooking type (coal and biomass stoves, natural gas, LPG, electric, bio-gas, or others), respectively. A Monte Carlo uncertainty analysis method was used to evaluate the uncertainty associated with the emission inventory, and the methodology was described in our previous studies (Wang et al., 2014; Wei et al., 2011).

The values of A, Z, q, Q, and P were collected from the survey data for each village (Table S1), and the values of η for different stoves were obtained from a literature survey (Li et al., 2016a,b,c; Qi et al., 2017). The energy consumption by town is shown in Table S1. EF values are based on a previously established emission factor database (Wang et al., 2014) (Table S2). It is important to note that energy consumption and emission factors are two important aspects of the household emission inventory. This study focused on village-based survey data on fuel consumption, and EFs are obtained from a literature survey. Table S3 shows the EFs in other studies for different coals and biomass. The EF of SO_2 from coal and biomass combustion in this study are relatively lower than that in other studies, owing to low sulfur content in coal and biomass in Beijing.

3. Results and discussion

3.1. Energy use patterns for heating and cooking

3.1.1. Heating

In this study, 1.3831 million households require heating in winter, accounting for 89% of all village households in Beijing. There are 11% of households do not heating in winter, these houses mainly belong to workers who reside in urban Beijing for work purposes and do not return to their rural houses daily, so heating is not required. The fuels used in household heating are shown in Figure S2. In Beijing, 59.9%, 17.8%, 8.1%, and 13.9% of heating households relied on coal, district heating, biomass, and new/clean energy (such as solar or heating pump), respectively. Additionally, 3805 kt of coal was consumed for household heating in Beijing in 2015.

3.1.2. Cooking

In rural areas, cooking occurs in 1454 thousand households, accounting for 95% of rural households in Beijing. Figure S3 shows the fuels used in household cooking in each county. Solid fuels (mainly coal and biomass) are not the predominant fuels used for cooking.556 kt of coal is used for household cooking. Beijing households are more likely to use cleaner fuels, such as LPG and natural gas, which are used in 63.5% and 22.3% of households, respectively.

3.1.3. Factors that affect energy use patterns

As shown in Figure S2 and Figure S3, the energy use patterns varied dramatically in different counties. These differences are likely associated with the village terrain (energy supply) and income level. In Beijing plain areas (e.g., counties such as Haidian and Fengtai, as shown in Figure S4), the percentages of district heating and natural gas heating are obviously higher than those in other areas. In mountainous villages (such as Huairou county), the proportions of gas and district heating are much lower since it is difficult to lay pipeline for natural gas. On the other hand, agriculture and forestry are more developed in mountain areas and biomass is frequently used.

Fig. 2 shows the heating and cooking energy use patterns as a function of income. We divide the annual income per capita into four categories: 0–10 k RMB (22%), 10–15 k RMB (36%), 15–20 k RMB (27%), and >20 k RMB (15%). The results show that in high-income areas, the proportions of coal and biomass used for heating or cooking is small, and the proportions of district heating and natural gas heating area are large.

3.2. Village-based emission inventory

In Beijing, the emissions of NO_X, NMVOCs, SO_2, and $PM_{2.5}$ from household heating were 11.5 kt, 29.3 kt, 43.1 kt, and 34.7 kt in 2015, respectively, as shown in Fig. 3(a) and Figure S5(a). Moreover, the emissions of NO_X, NMVOCs, SO_2, and $PM_{2.5}$ from household cooking were 1.55 kt, 4.02 kt, 6.55 kt, and 3.99 kt in 2015, respectively, as shown in Fig. 3(b) and Figure S5(b).

Figure S6 shows a comparison with other studies of residential household combustion emissions in Beijing (Cheng et al., 2017; Zhi et al., 2017; Zhao et al., 2015; Zhang et al., 2014; MEIC, 2012; Xue et al., 2016; Li et al., 2017a). Although the base year of these studies differs (from 2010 to 2015), the amount of household coal consumption has remained relatively consistent over the past decade (Figure S1); therefore, it is reasonable to compare the coal consumption and pollutant emissions among different studies in recent years. As shown in Figure S6(a), the coal consumed by household heating and cooking in this study totaled 3824 kt and 576 kt, respectively, and the total household consumption of coal is much higher than the value given in the Statistical Yearbook of 273 kt. Many studies have shown that the actual amount of household coal combustion in Beijing is significantly higher than the value given in the Statistical Yearbook (Cheng et al., 2017; Zhi et al., 2017; Zhao et al., 2015; Zhang et al., 2014). Figure S6(b) shows a comparison of $PM_{2.5}$ emissions. The $PM_{2.5}$ emissions reported in most studies are comparable to those in this study because the coal consumption totals and emission factors of these studies are within the same range. However, our result is 4–8 times higher than the emission estimates of Zhao et al. (2015) and Xue et al., 2016. The discrepancies result from different study domains, energy consumption data, and computational methods. The study domain of Zhao et al. (2015) was not all of Beijing, and only semi-rural areas of the Beijing Plain were taken into consideration. Xue et al., 2016 used the energy consumption data from Beijing Statistical Yearbook, and the $PM_{2.5}$ emission factors for coal combustion were relatively low (1.04–4.9 kg/t); therefore, $PM_{2.5}$ emission estimates were lower than those of other studies. The total household coal consumption and $PM_{2.5}$ emissions of this study are comparable with that of Cheng et al. (2017), Zhi et al., 2017, and Liu et al., 2016. However, the spatial resolutions for energy use and emission inventories are much higher in this study.

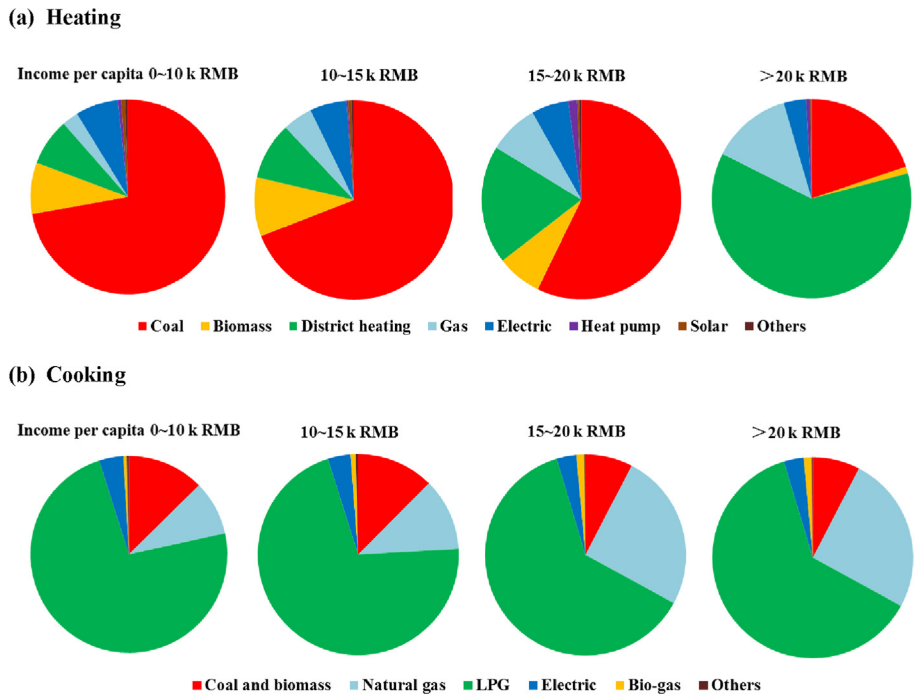

Fig. 2. Heating and cooking energy use patterns as a function of income: (a) heating and (b) cooking.

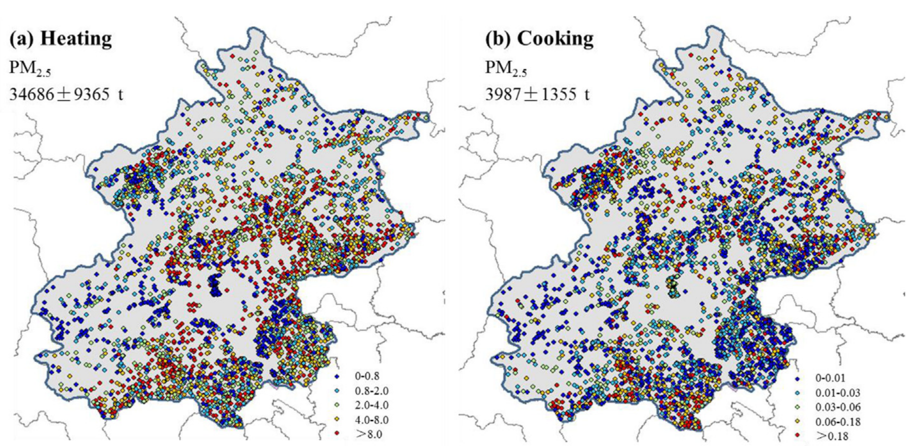

Fig. 3. Emissions of $PM_{2.5}$ from household heating and cooking in each village in Beijing (Unit: t): (a) heating and (b) cooking.

3.3. Temporal and spatial distributions

Figure S7 shows the monthly distributions of several emission sources in Beijing (NBS, 2016a,b). The emissions from other sources (industry, transportation, etc.) can be obtained from our previous studies (Zhao et al., 2017). The monthly variations in emissions from industrial-related sources (power plant, steel, cement, and industry process) and transportation are small, but for sources such as heating, open biomass burning and agriculture, the emissions vary dramatically in each month. There is no household heating demand from the second half of March to the first half of November.

The monthly distributions of major air pollutants in Beijing are shown in Fig. 4(a)-(d) (emissions for other sources are from the literature Zhao et al., 2017). Emissions from household heating considerably contribute to SO_2 and $PM_{2.5}$ total emissions and have significant effects on NOx and NMVOC emissions in winter (Dec., Jan., and Feb.). For $PM_{2.5}$ and SO_2, household heating emissions account for approximately 70% and 60% of the total emissions of each respective pollutant in winter. This result suggests that household heating is the most important emission source in winter. Household heating is not a critical source of NOx at the annual scale compared with transportation and industry combustion; however, household heating significantly contributes to NOx emissions (approximately 14%) in winter months. Household heating is the second largest emission source of NMVOCs in winter (accounting for approximately 20%), following industry solvent use. In summer, there are no heating activities, and household cooking is the most important residential source, accounting for nearly 10% of total $PM_{2.5}$ and SO_2 emissions in July. The residential emissions by month are shown in Table S4.

The spatial distributions of household heating and cooking emissions are shown in Figs. 3 and 4(e) (f). Urban Beijing is

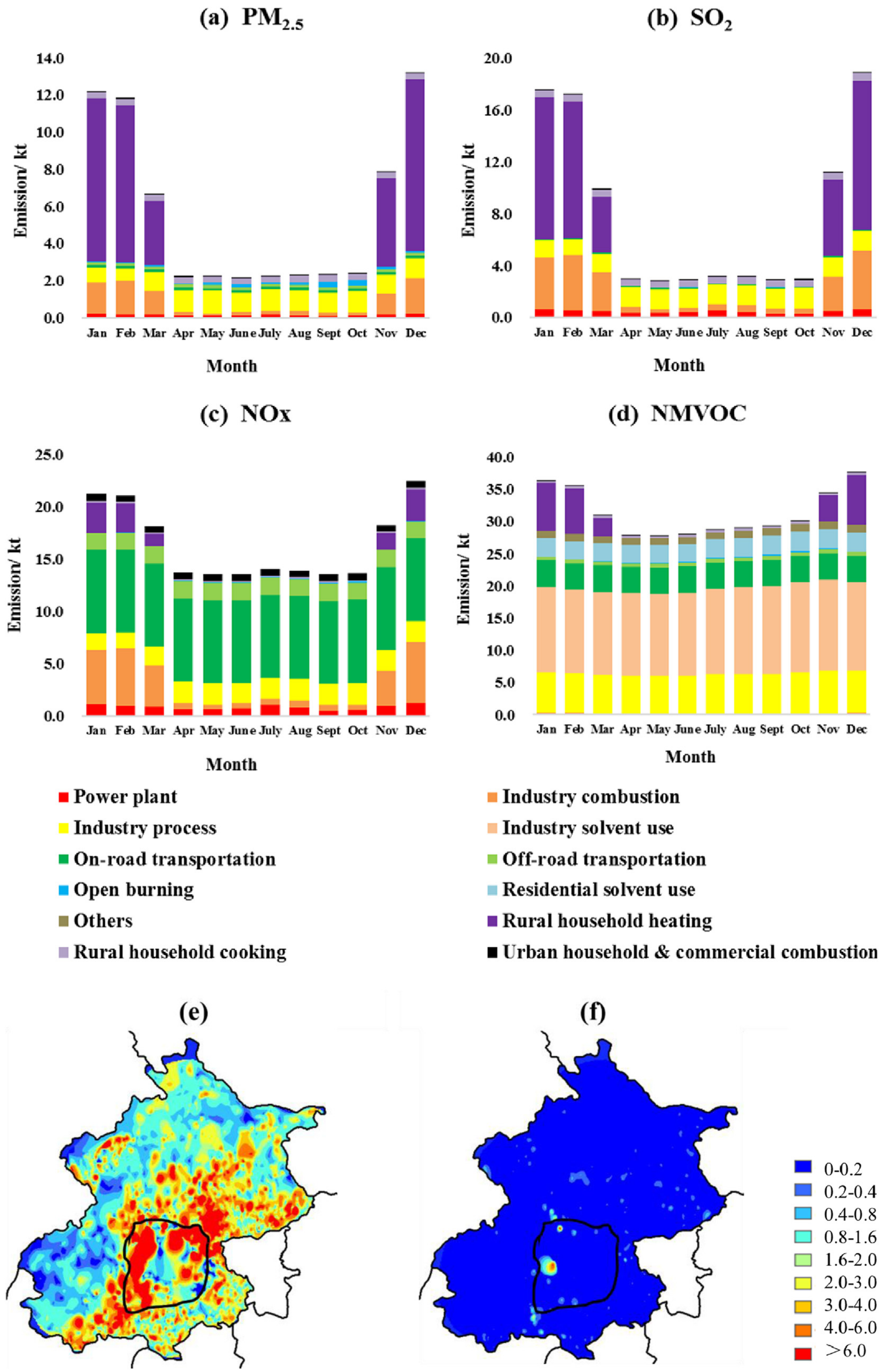

Fig. 4. Monthly and spatial distributions for air pollutants in Beijing: (a) $PM_{2.5}$ emissions by month, (b) SO_2 emissions by month, (c)NO_X emissions by month, (d) NMVOC emissions by month, (e) Household $PM_{2.5}$ emissions in Jan. (t), and (f) Household $PM_{2.5}$ emissions in July (t). (The black circle: Sixth Ring Road).

surrounded by polluted rural areas, especially in winter. In addition, there are 380 thousand village households (24.8% of total village households) and 1.35 million village residents (32.1% of total village residents) living in the urban area surrounded by the Sixth Ring road. These villages are denoted as "city villages" (mainly in districts such as Haidian, Fengtai and Chaoyang). Due to the short distance to the downtown of Beijing and coal control in urban areas, natural gas and district heating are popular heating and cooking methods in these "city villages". However, 770 kt of household heating coal is used inside the circle of the Sixth Ring road (20.0% of total heating coal), and 107 kt of coal is used in "city villages" for cooking (18.6% of total cooking coal). Therefore, the household emissions in urban areas (within the circle of the Sixth Ring road) are considerable and account for 16.1%–20.1% of the emissions from household heating and cooking.

3.4. Environmental implications of control strategies

Since there are many villages within the Sixth Ring road, and urban Beijing is surrounded by polluted suburbs, expanding the area of household coal restrictions is likely an effective way to improve air quality in urban Beijing. Table S5 and Fig. 5 show $PM_{2.5}$ household emissions and proportions in Jan. under different control scenarios. If the household coal use is restricted within the circle of the Sixth Ring road (Fig. 5(b)), the heating emissions of NO_X, NMVOCs, SO_2, and $PM_{2.5}$ will decrease by 2.09 kt, 5.05 kt, 8.66 kt, and 5.59 kt, respectively. Moreover, the cooking emissions of NO_X, NMVOCs, SO_2, and $PM_{2.5}$ will decrease by 0.30 kt, 0.77 kt, 1.23 kt, and 0.75 kt, respectively. Although the reductions account for only approximately 20% of total household emissions, they may result insignificant improvements in air quality in urban areas. If household coal combustion is forbidden within 10 km of the Sixth Ring road (approximately 40 km from downtown Beijing), the household $PM_{2.5}$ emissions will decrease by half, and the circle established by the *Encircling cities in rural areas* concept will move outward.

In recent years, the Beijing government has established substantial measures to improve energy use patterns and efficiency and reduce emissions from household emissions, especially for heating (Beijing Daily, 2017). The Beijing government built 700 "no-coal villages" in Chaoyang, Haidian and Mentougou Districts through energy replacement by the end of 2017. Prohibiting the usage of household coal played a great role on the improvement of air quality in Beijing in 2017. Fig S8 shows that air quality was significantly improved from 2015 to 2017 in winter in Beijing (China National Environmental Monitoring Centre, 2015, 2017). Despite this, the Ministry of Environmental Protection of China indicated that the contribution of coal combustion to air pollutants in BTH region was still more than 50% in autumn and winter in 2017 (MEP, 2017a). Since there is nearly no coal combustion in industrial sector in Beijing (MEP, 2017b), to further improve the winter air quality in Beijing, the next step is to replace all household coal with electricity or gas throughout the whole Beijing. If all household coal/biomass is replaced by natural gas, the emission reductions of NO_X, NMVOCs, SO_2, and $PM_{2.5}$ could reach 11.46 kt, 29.32 kt, 43.09 kt, and 34.67 kt, respectively (the reduction rates are 98.5%, 99.5%, 99.5%, and 99.6%, respectively).

Some technical problems need to be solved in the energy replacement policy. First is the gas source of natural gas supply. Compared with previous years, the consumption of natural gas in northern China has increased rapidly in 2017. The shortage of natural gas supply even led to the failure of some "coal to gas" projects (CRI online, 2017). To solve this problem, the Chinese government is making the best effort to excavate the productivity of gas field, and is actively coordinating the import of natural gas. On the other hand, the natural gas of Zhejiang, Fujian, Guangdong and other southern areas will be transferred to the northern areas in winter. During the winter peak period, there are more than 60 industrial enterprises stopped or limited to production from 2017 to 11-15 to 2018-3-15 in Beijing (BEIC, 2017), and the gas for industrial sector will be moderately reduced to better ensure the use of gas for the residential sector (CRI online, 2017; Beijing Morning Post, 2017). The second problem is the transportation of natural gas to the villages. Beijing has built more than 1100 natural gas pressure regulating station, and a total of nearly twenty thousand kilometers of natural gas pipeline. In 2020, the supply and transportation of natural gas for households in Beijing will be guaranteed (Beijing Morning Post, 2017).

For remote or mountainous rural areas where natural gas transportation is difficult, heat pump heating can be used instead of coal. According to "The development and utilization of geothermal energy "13th Five-Year" plan" (NDRC, 2017), air source heat pump, ground source heat pump, solar & air source heat pump, solar & ground source heat pump, and other new technologies and new equipment are encouraged to use in Beijing. The Office of the Beijing Municipal People's Government issued the "coal to clean energy" work plan for rural areas, it is pointed out that the households who install the air source heat pump or the ground source heat pump will be subsidized 100 RMB per square meter, and the maximum amount of subsidy per household is 12 thousand RMB (Office of the People's Government of Beijing, 2016). To ensure the heating power supply, the State Grid Beijing Electric Power

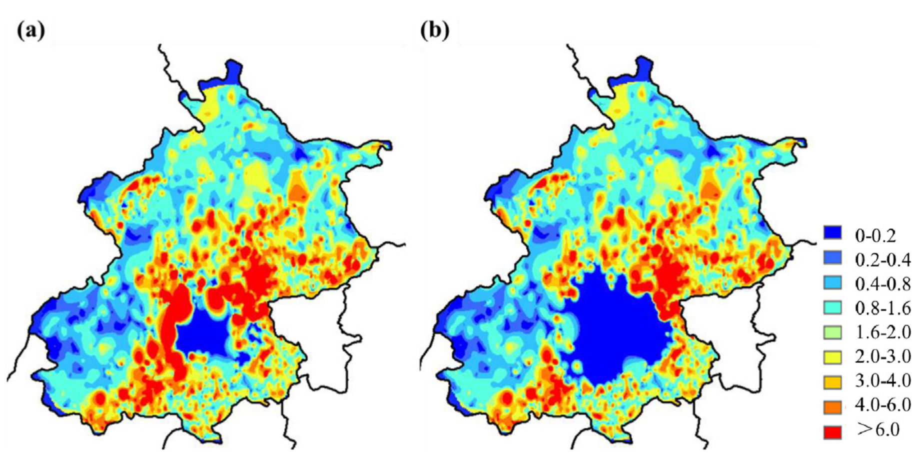

Fig. 5. Spatial distributions of household $PM_{2.5}$ emissions in Jan. if household coal is reduced within the (a) Fifth Ring road and (b)Six Ring road.

Company has applied the first nationwide intelligent power supply service command system relying on big data platform and integrated distribution equipment operation (State Grid, 2018), it can display the operation of distribution network equipment and monitor the power grid fault to ensure the reliability of power supply.

4. Conclusions

This study developed a village-based air pollutants emission inventory for Beijing household combustion in 2015 using the latest and most comprehensive energy consumption and emission factor data. Compared to previous studies, the temporal and spatial distribution of emission inventory are greatly improved. In terms of temporal distribution, household heating is the most important air pollutants emission source in winter in Beijing, contributing to ~70% of $PM_{2.5}$ and ~60% of SO_2 emissions in Dec., Jan., and Feb. In terms of spatial distribution, there are ~20% village households living in the urban area inside the Sixth Ring road ("city villages"). The emissions from these "city villages" may have a great impact on the air quality in urban Beijing due to the short distance.

Since downtown Beijing is surrounded by polluted suburbs, expanding the area of household coal restrictions is likely an effective way to improve air quality in urban Beijing. A coal forbiddance policy (e.g. "coal to gas") within the region encircled by the Sixth Ring road could gradually improve the air quality in urban Beijing. In the case of the availability of natural gas supply and energy transmission conditions, replacing coal with clean energy is the most effective way to further improving air quality in Beijing in winter.

Considering the natural gas supply in the whole region of northern China is very difficult, coal and biomass will still be important fuels for household combustion in many northern areas in the next few years. The village-based method in this study can be used to accurately quantify the emission from residential sources in other regions. The high spatial resolution inventory can help us to target areas that have highest emissions, and set up control priority strategies for these areas. In addition, the high precision of spatial and temporal distribution play an important role in the simulation of air quality models, which can quantitatively assess the impact of residential emissions on air quality.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (21625701 & 21521064) and the Ministry of Science and Technology of China 2016YFC0202700.We also thank the Beijing Association of New Energy and Renewable Energy for providing the valuable survey data.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.envpol.2018.03.036.

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