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Household consumption of coal and related sulfur, arsenic, fluorine and mercury emissions in China

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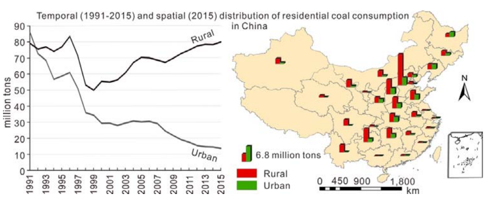
GRAPHICAL ABSTRACT



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ABSTRACT

Coal is vital to China's economic development. However, the burning of coal pollutes the air and can cause manifold health problems. This study focused on domestic coal consumption patterns and any concomitant trends in sulfur, arsenic, fluorine and mercury emissions in China during the 1991–2015 period. The most recently published domestic coal consumption statistics were collected, and data covering the emission levels and concentrations of sulfur, arsenic, fluorine and mercury released during the burning of domestic coal were obtained. We found that domestic coal consumption distribution patterns in China were spatially consistent with levels of atmospheric pollution. In 2015, the emissions of sulfur, arsenic, fluorine and mercury from domestic coal-burning amounted to 0.88 million tons, 213.28 t, 11,618.73 t and 15.89 t, respectively. These results showed a marked increase in rural emissions since 2002, and represented a total five times larger than urban emissions in 2015. Further, after 2008, there was a sharp increase in sulfur, arsenic, fluorine and mercury emissions from domestic coal-burning, in sharp contrast to the decrease in emissions from coal-fired power plants. These findings highlight the environmental impact of domestic coal consumption on rural communities, accelerating the need for more effective air pollution controls.

1. Introduction

China accounted for half of the world's coal consumption in 2015 (BP statistical review of world energy BP, 2016). Coal is the basic energy source driving China's national economic development (Chen et al., 2016). As such, coal accounted for 64% of China's primary energy consumption in 2015, while oil and natural gas only accounted for 18.1% and 5.9%, respectively (Compilatory Group of China development report CGCDR, 2016). China's current energy reserves (*i.e.*, as a nation it is rich in coal, but has fewer oil reserves, and very little gas) mean that coal is going to be the most important energy source over the next few decades (Chen et al., 2013). However, burning coal causes severe environmental problems (Sun et al., 2007; Wang et al., 2014), especially the emission of harmful and toxic elements (*e.g.* sulfur, arsenic, fluorine and mercury) into the environment (He et al., 2016) and the consequent danger to human health (HosgoodIII et al., 2013; Zhang and Smith, 2007).

Chinese SO_2 emissions make a significant contribution to global SO_2 emissions (Yan and Wu, 2017). Nearly 90% of Chinese SO_2 emissions come from coal burning (Lu et al., 2010). Harmful pollutants, such as

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Mercury (Hg), fluorine (F) and arsenic (As), are also emitted when coal is burnt indoor. Hg is a heavy metal pollutant with a high toxicity. Chinese anthropogenic Hg emissions from the burning of coal are the highest in the world, accounting for approximately one third of total global emissions (Zhang et al., 2017). Significant rates of endemic fluorosis and arsenicosis occur in 12 Chinese provinces and more than 14 million people suffer from these serious conditions (Ministry of Health, People's Republic of China MHPRC, 2015; Selinus et al., 2013). A reduction in the levels of toxic elements emitted during the burning of coal has become an environmental priority.

Most coal in China is used by the industrial sector (Emrouznejad and Yang, 2016; Pian et al., 2016). During period of the "Tenth Five Year Plan", the "Eleventh Five Year Plan" and the "Twelfth Five Year Plan" (*i.e.*, 2001–2015), the Chinese government brought in more rigorous controls on pollutants emitted by industry and coal-fired power plants. This was done by promoting the development of clean coal technology, and through the installation of industrial desulfurization and dust removal equipment (Li et al., 2016). The emission of harmful elements from coal-fired power plants has therefore decreased significantly since 2006 (Tian et al., 2014; Wang et al., 2012).

The domestic coal-burning is second only to industrial coal consumption in China (Department of Energy Statistics in National Bureau of Statistics of China DESNBSC, 2016). In 2015, China's population reached 1.374 billion. The rural population accounted for 43.9% of this total, *i.e.*, 0.603 billion (National Bureau of Statistics of China NBSC, 2016). Across vast swathes of rural, and even suburban areas, > 90% homes do not have central heating facilities (Duan et al., 2014). Moreover, domestic coal-burning stoves tend to be very simple in design, with no desulfurization or dust removal functions (Cheng et al., 2017; Zhi et al., 2015).

Although there have been numerous studies of the toxic effects of pollution from coal-fired power plants (Su et al., 2011; Tang et al., 2012; Tian et al., 2014), there has been relatively little comprehensive spatiotemporal research into domestic coal consumption in China and its attendant sulfur (S), As, F and Hg emissions. As it is vital that emissions are reduced as part of a sustainable future, this paper seeks to redress this research imbalance.

This study looked at the following areas: (1) the quantities of coal consumed domestically in China in 2015, and any spatial patterns arising; (2) the preliminary estimation of S, As, F, and Hg emissions resulted from the burning of domestic coal during the 1991–2015 period, comparing to China's total SO_2 emissions and the As, F, and Hg emissions from coal-fired power plants; and (3) the proposition of policy recommendations were put forward to develop a more effective atmospheric pollution control measure in China.

This study may be important for three reasons. First, based on recently-published statistical data, existing records and newly-measured data, it provides an important record of the environmental impact of domestic coal consumption in China. Second, to the best of our knowledge, this is the first study to explore the spatiotemporal relation between domestic coal consumption and air pollution. Third, this research explores new perspectives in the hope of developing a better understanding of atmospheric pollution in China, and therefore could significantly influence the direction of future research. On the one hand, the results of this study has the potential of drawing the attention of environmental scientists to the importance of the increasing levels of toxic elements being emitted from rural household coal combustion. On the other hand, in the energy policy field, this research provides the basic data necessary for a more complete understanding of the nature of the heavy air pollution arising from rural household coal burning, and may help the Chinese government formulate more effective national pollution control policies.

The paper is structured as follows. Section 2 briefly presents the reviews of the related national policies and literatures. Section 3 explains the data collection, methodology and sampling. The results are presented in Section 4. Section 5 provides a discussion based on the results of Section 4. The last section covers conclusions, policy recommendations, limitations of the paper and future research directions.

2. Background

2.1. Coal burning-related environmental protection polices in China

In the 1970s, the Chinese State Council held the first National Conference on Environmental Protection, focusing on the air pollution caused by industrial sources. During the 1980s, in response to the country's economic reform and open door policies, the Chinese economy grew rapidly, fueling a growing demand for energy. Urban coal consumption, and therefore rates of air pollution, increased. The government therefore introduced basic pollution prevention and control measures, principally aimed at monitoring and controlling the levels of soot in the air; it also required that improvements be made in the urban energy structure and urban gas pipelines. In the 1990s, however, coal consumption increased further with the rapid development of the Chinese thermal power industry. Parts of southwestern and southern China were increasingly affected by acid rain, and cities began to experience high levels of SO_2 pollution. In response to these developments, the national government required the thermal power plants, together with large and medium-sized enterprises, to install desulfurization and dust removal equipment; cities were mandated to establish "coal free zones" in order to control both emissions and the attendant pollution (Yi et al., 2014).

During the "Tenth Five Year Plan" (2001–2005), the Chinese government imposed limits on the S content of coal used in urban areas, and began large-scale projects such as the "West to East" Gas Transmission and Electricity Transmission Project. During the "Eleventh Five Year Plan" (2006–2010), the emphasis was placed on saving energy and reducing emissions; further, highly polluting fuel "no burning zones" were more strictly demarcated and enforced within urban environments, and especially city centers, in an attempt to improve air quality. Coal-fired power plants were the primary focus of attempts to control SO_2 emissions, and flue gas desulphurization facilities became mandatory throughout the national energy infrastructure. During the "Twelfth Five-Year Plan" (2011–2015), regional $PM_{2.5}$ and SO_2 air pollution grew more serious, with pollution in the form of haze increasingly the problem. The government then began to explore capping total coal consumption across key cities, regions and industries.

In 2013, the Chinese State Council issued "Ten Specific Measures" and an "Air Pollution Prevention Action Plan", requiring the closure or renovation of small coal-fired boilers, and an accelerated desulfurization and denitration of dust emissions by key industries. There was a drive to improve the ability to detect $PM_{2.5}$ concentrations and the air quality during the day in 338 prefecture level cities, and establish a pollution source emission inventory, based proportionally on the pollution emitted by key cities. Further, during the "Thirteenth Five-Year Plan" (2016–2020), the number of good air quality days and $PM_{2.5}$ concentrations has been defined for prefecture level cities, and the "coal to gas project" has continued to be promoted in key cities.

The nearly 40 years' worth of regulations designed to protect the environment from the ill effects of burning coal chart the Chinese government's increasingly stringent desire to restrict the emissions from thermal power plants and industrial boilers. In key cities, a series of environmental protection measures have been implemented, from the establishment of "coal free zones" to the "West to East Gas Transmission Project", as alternatives to the use of coal. Despite these efforts, however, air quality monitoring in cities above prefecture level has recorded increasingly serious levels of air pollution since 2002, and the annual mean number of hazy days has continued to increase. This would suggest that existing controls have failed to address fully other significant sources of pollution.

In China, 0.603 billion people still live in rural communities. Due to a lack of centralized heating facilities, > 60 million domestic stoves are