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Research article

Sectoral linkage analysis of three main air pollutants in China's industry: Comparing 2010 with 2002

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ABSTRACT

To investigate the driving forces of air pollution in China, the changes in linkages amongst inter-industrial air pollutant emissions were analyzed by hypothetical extraction method under the input-output framework. Results showed that the emissions of SO_2, soot and dust from industrial sources increased by 56.46%, 36.95% and 11.69% respectively in 2010, compared with 2002. As major contributors to emissions, the power and gas sectors were responsible for the growing SO_2 emissions, the nonmetal products sector for soot emissions, and the metals mining, smelting and pressing sectors for dust emissions. The increasing volume of emissions was mainly driven by the growing demand in the transport equipment and electrical equipment sectors. In addition, the expansion in the metals mining, smelting and pressing sectors could result in even more severe air pollution. Therefore, potential effective strategies to control air pollution in China are: (1) reducing the demand of major import sectors in the equipment manufacturing industry; (2) promoting R&D in low-emissions-production technologies to the power and gas sectors, the metals mining, smelting and pressing sectors, and the nonmetal products sector, and (3) auditing the considerable industrial scale expansion in the metals mining, smelting and pressing sectors and optimizing the industrial structure.

1. Introduction

Recently, the regional haze pollution in China, which is characterized by high concentrations of the fine particulate matter ($PM_{2.5}$), has attracted a growing public concern worldwide. According to the statistics of The World Bank (2016), the mean annual exposure of $PM_{2.5}$ (micrograms per cubic meter) in China has increased by 11% from 1990 to 2000, and by 23% from 2000 to 2010. According to the monthly site records of The National Meteorological Information Center of China Meteorological Administration, the number of hazy days in winter increased dramatically from 2002 to 2013 in eastern China (Wang et al., 2015). In North China and South China, the number of hazy days increased significantly from the beginning of this century (Ding and Liu, 2014).

A number of studies have been conducted to investigate the driving factors for the severer air pollution in China. Decomposition analysis is a common approach adopted by previous studies to examine the contribution of various factors to the air pollutant emissions (Chen and Duan, 2016; Dhakal, 2009; Feng et al., 2012; Liu et al., 2012a; Wang et al., 2011). The vast majority of these studies highlighted a series of common factors such as change of: production scale, energy efficiency, energy intensity, and end-of-pipe treatment technology (Dhakal, 2009; Fujii et al., 2013; Li et al., 2017; Lyu et al., 2016; Yang et al., 2016). By contrast, the role of industrial structural change is largely overlooked. Some scholars claimed that the industrial structure changes had limited impact on the pollutant emissions (Liu et al., 2012b; Zhao et al., 2010). However, the changes in industrial structure and their effects on energy consumption and air pollutant emissions cannot be ignored. In fact, since the accession to WTO at the end of 2001, significant changes have taken place in China's industrial structure. Some literature revealed these changes and corresponding environment effect (Guan et al., 2009; Minx et al., 2011; Tian et al., 2014; Wang et al., 2014).

According to the data from the National Bureau of Statics of the People's Republic of China, the contribution of heavy industry to the gross industrial output value increased from 61.06% in 2002 to 71.47% in 2010. However, since 2011, it experienced a slight

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decrease, from 71.95% in 2011 to 68.82% in 2015. Moreover, since the beginning of 2011, the US embassy continuously released the statistics of $PM_{2.5}$ emissions, which has drawn a growing public concern in China. Since then, more measures have been taken to deal with haze events. The change pattern in the period of 2002–2010 was different from that after 2011. This study focused on the period of 2002–2010 to investigate the influences of such industrial structure change on the air pollutant emissions.

This study aims to examine the driving force for the growing air pollution in China from the industrial structure perspective. Based on input-output theory (Leontief, 1966), main industrial sectors contributing to the growing air pollution are identified. Similarly, the effects of industrial structure changes on the air pollution in China are revealed. Consequently, corresponding policies could be developed to mitigate the air pollution and associated impacts.

2. Data sources and methodology

2.1. Data source and processing

(1) Emissions data

The regional haze in China is mainly attributable to the high concentration of $PM_{2.5}$ (the diameter of particulate matter less than 2.5 μm) in the atmosphere. So far, there are limited emissions data on $PM_{2.5}$ pollution in China and there are only temporal data on SO_2, soot and dust emissions. However, $PM_{2.5}$ pollution can be measured indirectly. Soot and dust are direct sources of $PM_{2.5}$. Similarly, local SO_2 emissions are the main sources of SO_4^{2-} in $PM_{2.5}$ (Yao et al., 2002) and sulfate is a major component of fine haze particles (Cheng et al., 2016). SO_2 would turn into secondary particles through complex physical and chemical processes after been emitted in gas form and become secondary sources of $PM_{2.5}$. As the main constituent of $PM_{2.5}$, secondary particles accounted for more than 55% of the $PM_{2.5}$ mass concentration (Yang et al., 2013). In addition to mitigating primary particulate emissions, reducing the emissions of secondary aerosol precursors plays a crucial role in controlling $PM_{2.5}$ levels in China (Huang et al., 2014). Therefore, the SO_2, soot and dust emissions data are used in this study since these three pollutant emissions can reflect the $PM_{2.5}$ emissions indirectly, as well as the impact of atmospheric pollutants on regional haze.

The emissions data in 2002 were drawn from the China Statistical Yearbook (National Bureau of Statistics of China, 2003) and the emissions data in 2010 were retrieved from the National Pollution Census Data of China (The First National Pollution Census Data Compilation Committee, 2011).

(2) Economic data

The Input-Output Table of China in 2002 and 2010 were used in this study, which were drawn from the National Bureau of Statistics. The industrial output data of 2002 and 2010 were derived from China Statistical Yearbook (National Bureau of Statistics of China, 2003, 2011).

According to the classification in the input-output table and the emission statistics, as well as the industrial output data, a total of twenty industrial sectors were formed (see SI Table S1).

2.2. Methodology

2.2.1. Hypothetical extraction method

As a well-recognized method to measure the importance of economic linkages, the Hypothetical Extraction Method (HEM) can be employed to identify flows of the embodied resources use and pollutant emissions (Wang et al., 2017). The HEM-based linkage analysis has been widely employed to analyze related issues associated with water and energy use (Duarte et al., 2002; Guerra and Sancho, 2010), atmospheric pollutant emissions (Wang et al., 2017); CO_2 emissions at the regional level such as China (Wang et al., 2013; Zhao et al., 2010, 2016), Italy (Ali, 2015) and South Africa (Zhao et al., 2015). Most of the previous research employed HEM to study the static linkages between inter-sector or inter-region air pollutants. However, few studies attempted to examine the effect of industrial structure changes on air pollution via HEM from a dynamic perspective. The composition of each sector's total emissions is analyzed via HEM. Consequently, the linkages of SO_2, soot and dust emissions amongst various industrial sectors of China are examined. As a result, key sectors are identified and a new index is proposed to analyze the effect of temporal changes in the key sectors on air pollutants (Fig. 1).

2.2.2. The composition of each sector's total emissions based on HEM

According to modified hypothetical extraction method presented by Duarte et al. (2002), the net backward linkage emissions (*NBLE*) reflects the real or net 'emissions imports' for sector s, representing the requirements of emissions from the other sectors $-s$ to obtain the final demand of sector s. The net forward linkage emissions (*NFLE*) is the real or net 'emissions exports' made by sector s, where the part of emissions is emitted by sector s and used by the other sectors to meet their demand.

$$NBLE_s = D_{-s}\Delta_{-s,s}y_s \quad (1)$$

$$NFLE_s = D_s\Delta_{s,-s}y_{-s} \quad (2)$$

where D_s represents direct emission intensity of the sector s; D_{-s} represents direct emission intensity of the other sectors except sector s; y_s is the final demand of sector s; y_{-s} is the final demand of the other sectors except sector s; $\Delta_{s,-s}$ and $\Delta_{-s,s}$ are calculated by the Leontief inverse matrix (complete demand coefficient matrix) in the input-output analysis: $(I\text{-}A)^{-1} = \begin{pmatrix} \Delta_{s,s} & \Delta_{s,-s} \\ \Delta_{-s,s} & \Delta_{-s,-s} \end{pmatrix}$.

Based on our previous research (Wang et al., 2013), the concepts of demand emissions (*DE*) and output emissions (*OE*) are a useful tool to discover the linkage between the demand and output among the sectors. *DE* is defined as the total emissions required to satisfy the demand of a sector. *OE* is defined as the total emissions as the output of a sector, which represents the direct emissions of a sector. *DE* and *OE* can reflect the linkage amongst various emissions from the perspective of total consumption and production respectively. Thus, *DE* and *OE* possess the following relations:

$$OE = D_s\Delta_{s,s}y_s + D_s\Delta_{s,-s}y_{-s} \quad (3)$$

$$DE = D_s\Delta_{s,s}y_s + D_{-s}\Delta_{-s,s}y_s \quad (4)$$

$$DE_s + DE_{-s} = OE_s + OE_{-s} \quad (5)$$

The difference between *OE* and *DE* represents the net effect of emissions embodied in the linkages between sector s and other sectors $-s$, namely net transferred emissions (*NTE*).

$$NTE_{s\rightarrow -s} = OE - DE = D_s\Delta_{s,-s}y_{-s} - D_{-s}\Delta_{-s,s}y_s \quad (6)$$

Then we can identify the 'key import sectors ($NTE<0$) and key export sectors ($NTE>0$)' according the value of *NTE*.

2.2.3. Indexes for the temporal change of key sectors

(1) Structural elasticity coefficient of emissions (SEC)