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Original Articles

Spatiotemporal simulation and comprehensive evaluation of atmospheric coal-related PAHs emission reduction in China

Likun Liang[a], Xuan Ru[a], Jingyue Wei[a], Zhudong Lin[a], Chaohai Wei[a,b,*], Yu Qian[c], Fusheng Li[d]

[a] School of Environment and Energy, South China University of Technology, Guangzhou 510006, PR China
[b] The Key Lab of Pollution Control and Ecosystem Restoration in Industry Clusters, Ministry of Education, Guangzhou 510006, PR China
[c] School of Chemical Engineering, South China University of Technology, Guangzhou 510006, PR China
[d] River Basin Research Center, Gifu University, 1-1 Yanagido, Gifu 501-1193, Japan

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ABSTRACT

As the world's largest consumer of coal, China is now facing serious pollution of atmospheric polycyclic aromatic hydrocarbons (PAHs) produced by coal utilization processes, i.e., coal-related PAHs, which should be of concern for relevant policy-makers. Based on the interrelationships among coal-related PAHs emission, coal consumption and socio-economic development, this study applied a coupled method of system dynamics (SD) and geographic information system (GIS) to successfully model the spatiotemporal changing processes of coal-related PAHs emission reduction in China's 31 provinces. In these models, four different policies including industry structure adjustment, energy consumption structure adjustment, industrial emission control and household emission control were quantitatively designed to evaluate the emission reduction differences from national and provincial perspectives. And then, cluster analysis was used to identify the provinces with similar policy effects. The results indicated that, without any policy stimulation, atmospheric coal-related PAHs emission in China would maintain a gradual growth trend. The implementation of energy consumption structure adjustment had better national emission reduction effect than the other three policies, while not all provinces could succeed in emission reduction when the four policies were implemented, respectively. Besides, the different policy effects among provinces resulted from their development discrepancies in industry structure, energy structure and emission source characteristics. Therefore, to simultaneously realize the maximum national emission reduction effect and the integrated emission reduction for different provinces, all provinces should take energy consumption structure adjustment as the guiding policy and consider their targeted policies as supplementary. In short, the coupled SD-GIS method can be used to comprehensively analyze the spatiotemporal variations of unconventional atmospheric pollutants and the specific impacts of pollution control policies, which will provide a theoretical basis for local governments to reasonably direct the coordinated development of regional economy, energy structure and environmental quality.

1. Introduction

Polycyclic aromatic hydrocarbons (PAHs) are highly toxic persistent organic pollutants (POPs), which have posed serious threat to ecosystem and human health (Johnson et al., 2015; Agudelo-Castaneda et al., 2017). Since atmosphere is one of the most important media of PAHs distribution, extensive studies on atmospheric PAHs have been conducted around the world, focusing on pollution monitoring, transport/transformation, risk assessment, source apportionment and emission inventory (Shen et al., 2013a,b; Yang et al., 2015; Chen et al., 2017). Given the important values of emission inventory for scientific research and policy formulation, many researchers have estimated the emission inventories of atmospheric PAHs for various countries and regions (Galarneau et al., 2007; Zhang and Tao, 2009).

At the current stage, emission inventories are mainly applied to the fundamental researches on formation causes, distribution processes, influential factors and emission trends of PAHs pollution as well as the policy proposals for pollution prevention and control (Van der Gon et al., 2007; Mu et al., 2013; Liu et al., 2018). It is noteworthy that, based on the developed PAHs emission inventories, most researchers merely adopt some relatively simple statistical methods such as correlation analysis or linear-regression analysis to study certain influential factors or the changeable emission trends (Ravindra et al., 2008; Shen et al., 2013a,b). Besides, the policy proposals for PAHs pollution

* Corresponding author at: School of Environment and Energy, South China University of Technology, 382 Waihuan East Road, Guangzhou Higher Education Mega Center, Guangzhou 510006, PR China.
E-mail address: cechwei@scut.edu.cn (C. Wei).

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governance are mainly based on some qualitative analyses (Jimenez et al., 2017). However, the formation of any anthropogenic pollution can result from mutual influences of different factors for environment, energy, economy, population, climate and other relevant aspects (Barker et al., 2010; Ju et al., 2017). To the best of our knowledge, PAHs in the environment mostly come from the anthropogenic utilization processes of different energy resources such biomass, natural gas, coal and petroleum (Fan et al., 2014; Zheng et al., 2017). Therefore, as a component of anthropogenic pollution, atmospheric PAHs emission from different energy utilization processes may also be potentially influenced by multi-faceted factors.

In addition, it has been reported that indoor biomass burning is the most important anthropogenic source of atmospheric PAHs emission for many countries (Shen et al., 2013a,b), which has aroused widespread attention (Shen et al., 2014; Orecchio et al., 2016). Nevertheless, since PAHs emission from coal utilization processes (hereafter called "coal-related PAHs emission") in China, the world's largest consumer of coal (BPC, 2017), contributes to 24.9%–38.0% of the total PAHs emission (Zhang et al., 2007; Shen et al., 2013a,b), coal consumption has become the second largest contributor of atmospheric PAHs emission only next to indoor biomass burning. The comparison of atmospheric PAHs emission from major energy utilization processes in different countries and regions (Table S1) suggests that the coal-related PAHs pollution in China is comparatively severe. Meanwhile, because coal will still be the most major energy in China for a long time (NDRC and NEA, 2016), this serious trend of coal-related PAHs pollution will probably continue. It has also been confirmed that great spatial distribution differences exist in the PAHs emission from coking, industrial and domestic coal combustion in China (Xu et al., 2006). The emission status of coal-related PAHs in China summarized above indicates that this emission problem is an environmental issue featured with both temporal variations and spatial differences. Moreover, some researches have already inferred that there may be positive or negative correlation relationships between coal-related PAHs emission and certain economic, social or energy factors (e.g., GDP, population structure or energy structure) analyzed by some simple statistical methods (Shen et al., 2010; Jiang et al., 2013).

According to theoretical analysis of the potential influential factors for coal-related PAHs emission, it is easily understandable that the coal-related PAHs come from coal consumption processes which can help promote the economic development of relevant industries. Meanwhile, sustaining the economic growth requires more corresponding energy resources such as coal, which will result in increasingly serious PAHs pollution as well as greater threat for human health and ecological environment. The above qualitative analyses imply that some potential promoting/restraining interrelationships may exist between coal-related PAHs emission and the relevant factors for energy, economy, environment and other aspects. Facing such an open, dynamic and complex environmental issue, it is necessary to systematically and comprehensively study the relevant factors that can affect coal-related PAHs emission in China.

As an appropriate approach used for qualitatively and quantitatively analyzing the specific influences of different policies (Ahmad et al., 2016), system dynamics (SD) is good at dealing with complex time-varying system problems and has been widely applied to various studies in the environmental field (Zhu et al., 2015; Sukholthaman and Sharp, 2016). Currently, close attention is also paid to the applications of SD model for some conventionally monitored pollutants, such as CO_2 and $PM_{2.5}$ in the atmospheric environment (Ercan et al., 2016; Zhou and Zhou, 2017); but few researchers are considering its applications for the unconventional atmospheric pollutants, such as PAHs, a class of toxic POPs. Furthermore, the SD model, a "top-down" model, is inappropriate to represent a spatially changing process, because it can't deal with the spatial situation of variables in a system. As for issues with both temporal and spatial features, some researchers have introduced the extensively used technology of geographic information system (GIS), a "bottom-up" spatial analysis approach, to compensate the deficiency of SD in spatial analysis (Guan et al., 2011; Galicia and Cheu, 2013). Given the strength of SD in representing temporal processes with its restricted spatial modeling capabilities, and the competency of GIS for spatial analysis with its limited representation of temporal variations, the method of SD coupled with GIS is expected to realize a synergetic feedback in both space and time.

In order to scientifically forecast the varying emission trends and quantitatively propose the corresponding control policies for coal-related PAHs emission in China, this paper adopted the coupled SD-GIS method to develop the atmospheric coal-related PAHs emission (ACPAHE) models for China's 31 provinces, based on systematic consideration of the interrelationships among various potential socio-economic, energy and environment factors. In these models, different scenarios were designed to evaluate the emission reduction differences of coal-related PAHs from provincial and national perspectives. And then, cluster analysis was used to identify the provinces with similar policy effects. The main objectives of this study were to: 1) analyze the reasons for spatial response differences of coal-related PAHs emission reduction to various scenarios, 2) investigate the temporal variations of coal-related PAHs emission in China and the reasons for national emission reduction differences under various scenarios, and 3) propose targeted policies for the provinces with similar policy effects.

2. Methodology

2.1. Study area and data sources

China has 34 provincial administrative units (hereafter called "provinces" for short). Due to the limitation of statistical data for Hong Kong, Macao and Taiwan, we only investigated 31 provinces as shown in Fig. S1. The data on different indicators for these 31 provinces were collected as follows: the data on socio-economic indicators were derived from China Statistical Yearbook (2001–2016); the data on coal/energy related indicators were derived from China Coal Industry Yearbook (2001–2016), China Energy Statistical Yearbook (2001–2016) and the related research publication on coal industry (CNCA, 2011).

Furthermore, according to a previous investigation for potential emission sources and the source division basis from related literatures (Zhang and Tao, 2009; Shen et al., 2013a,b), the emission sources of 16 US EPA priority-controlled PAHs studied in this paper were divided into industrial sources and household sources. The industrial sources included coal processing for beehive coking and industrial coking as well as coal combustion for thermal power and other industries, while the household sources included anthracite combustion and bitumite combustion. PAHs emissions from different sources were calculated by emission factor method, and the data on emission factors of the four industrial sources and the two household sources were collected from Zhang and Tao (2009) and Shen et al. (2013a,b), respectively.

2.2. Establishment of SD model

2.2.1. System boundary and system structure

According to systematic analysis of interrelationships among coal-related PAHs emission, coal consumption and socio-economic development, a causal loop diagram (CLD) with three subsystems (i.e., socio-economy subsystem, coal consumption subsystem and coal-related PAHs emission subsystem) and four feedback loops (i.e., two reinforcing loops and two balancing loops) was developed using Vensim®PLE software. The main component variables in the three subsystems are provided in Table S2. The main feedback mechanisms within and among different subsystems are depicted in the simplified CLD (Fig. 1). Reinforcing loop-1 (R1) and balancing loop-1 (B1) are the feedback loops within the socio-economy subsystem and the coal consumption subsystem, respectively. Reinforcing loop-2 (R2) is the interactive