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A top-bottom method for city-scale energy-related CO_2 emissions estimation: A case study of 41 Chinese cities

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ABSTRACT

China has become the world's largest energy consumer, accounting for approximately 30% of global CO_2 emissions. City contributions make up 84% of China's commercial energy consumption. However, energy consumption data for most Chinese cities are not accessible. Many studies have focused on the estimation of carbon emissions at the provincial or national level; city-level carbon emissions are not well studied. In order to solve this problem, this research constructed a top-bottom method for city-scale energy-related carbon emissions estimation in China. Typically, cities are considered the constituent units of a province. Relying on provincial energy balance tables and utilizing the available city-level socioeconomic data as indicators, we scaled down provincial energy consumption to the city level. We compared our estimation results with city-level point-source data, and found that for the 41 Chinese cities to which we applied this method, the difference was within 10%, while for 25 of these cities, the difference was within 5%. Thus, we believe our method is reasonably accurate. We also subdivided the city carbon emissions into three major energy categories (coal-related, oil-related, and gas-related) and found that the difference could be attributed mainly to coal-related energy emissions. The results of the uncertainty analysis indicated that the uncertainty of the coal emission factor was the largest, thus demonstrating that it is critical not only to choose appropriate indicators to characterize coal-based industrial carbon emissions, but also to identify accurate emission factors for coal-related fossil fuels. Both analyses demonstrated China's coal-dominant energy structure. We believe our method is practical and can provide detailed data support for the establishment of city-level carbon emission inventories, furthermore, it will also be helpful for Chinese cities to negotiate carbon reduction responsibilities and allocating carbon reduction tasks.

1. Introduction

As the largest carbon emitter in the world (Guan et al., 2009), China has promised to reduce its CO_2 emissions intensity (CO_2 emissions per GDP) by 60%–65%, based on 2005 levels, by 2030 (Mi et al., 2016). China will also reach its carbon emissions peak by 2030. Because China is in the process of rapid urbanization and economic growth (Hubacek et al., 2011), the continuous improvement of living standards will inevitably lead to continuous growth in carbon emissions (Shan et al., 2018; Wang and Zhao, 2018). To accomplish this goal, the Chinese government faces enormous pressure. As the main consumer of energy, cities are often the key CO_2 emitters, it's estimated that 35 largest Chinese cities contribute 40% of China's total carbon emissions in 2006 (Dhakal, 2009). At the same time, due to the strong urban authority and strong governance of cities, it is the most appropriate scale at which to carry out a carbon mitigation plan (Liu et al., 2011; Xi et al., 2011), thus, it is crucial to determine the city-level carbon emissions.

Obtaining accurate city-level carbon emissions data is the first step in developing an emissions reduction policy (; Chen et al., 2015; Lu and Chen, 2017; Shao et al., 2016) . At present, the commonly used estimation method is based on the

Abbreviations: EBT, energy balance table; EF, emission factor; IC, intermediate conversion; L, loss; TFC, total final consumption; NEU, non-energy use.

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Intergovernmental Panel on Climate Change (IPCC) model of fossil energy consumption data (European Commission, 2014; United Nations Framework Convention on Climate Change (UNFCCC)) , which estimates the energy-related carbon emissions of a specific area based on the carbon emission factors of different energy sources (Lei et al., 2011; Wiedmann et al., 2009). China has comprehensive energy consumption data in the form of energy balance tables (EBTs) at the national and provincial levels (Liu et al., 2015) , thus, many scholars have used the IPCC (2006) model to analyze national and provincial carbon emissions characteristics. However, with the exception of a few municipalities directly under the central government and developed cities, most cities' statistical departments do not release energy consumption data, the carbon emission data released by the provincial statistical departments is often the synthesis of all cities in the province, and they don't separately release related city-level carbon emissions data too. Many city-level carbon emissions accounting or estimation rely on field research to obtain energy consumption and other relevant data. However, such methods are time consuming and labor intensive. There is an urgent need to establish an easy and relatively accurate method to estimate energy-related carbon emissions at the city level. At present, energy statistics at the provincial level are relatively comprehensive, the energy balance table, which has been used in many studies, has been compiled since the 1980s and has been very reliable (Shan et al., 2017).

Therefore, based on the existing energy consumption data and related socioeconomic data at both the provincial and city level for 2012, we used a top-bottom reference approach to estimate energy consumption and carbon emissions in 41 cities. According to the IPCC's suggestion, "to apply both a sectoral approach and the reference approach to estimate a country's CO_2 emissions from fuel combustion and to compare the results of these two independent estimates" (Volume 2, Chapter 6, Page 5. 2006), we compared the results of our estimation with those of a previous sectoral approach and found that the difference was within 10%, which confirmed the rationality and operability of our method. This paper can provide scientific methods and reasonable ideas for compiling carbon emission inventories of Chinese cities that are continuous in both time and space scales. And the method we constructed can also provide reliable data support to allocate carbon emission reduction tasks and negotiating reduction responsibilities between cities.

This paper is organized as follows. In Section 2, we provide a literature review of common city-level carbon emissions estimation methods. In Section 3, our city-level carbon emissions estimation method and relevant issues are introduced. Section 4 presents the validation results and other findings. We also discuss the advantages and disadvantages of the method in Section 5.

2. Literature review

In recent years, many scholars and research institutions have developed an interest in accounting methods for city-level carbon emissions (; Dodman, 2009; Hillman and Rawaswami, 2010) . Due to different research purposes and the lack of data, many methods have been proposed for carbon emissions estimation (Brondfield et al., 2012; Xu et al., 2018). From a methodological point of view, these methods can be divided into the different categories.

Since CO_2 emissions from energy consumption comprise the majority of city carbon emissions, many scholars use EBTs or energy consumption data to calculate the carbon emissions of a study area. Shan et al. (2017) developed a set of methods for constructing CO_2 emissions inventories for Chinese cities based on the EBTs, which cover 47 socioeconomic sectors, 17 fossil fuels, and 9 primary industry products. Zhao et al. (2012) used Shanghai as an example and discussed a method to calculate CO_2 emissions using the EBT. They also discussed the issues that should be focused on when analyzing the characteristics of emission sources. Sun et al. (2015) discussed the use of EBTs to calculate the amount of CO_2 emissions and the uncertainties. The drawbacks of this approach were that they solely concentrated on the provincial or municipal level (such as Beijing, Shanghai, Tianjin, and Chongqing), or on core cities (such as Guangzhou). Municipalities directly under the control of the central government have a status that is equivalent to that of a provincial unit with abundant and comprehensive relevant data. However, a typical prefecture-level city does not have as many resources and data, so these methods are not applicable for calculating carbon emissions of ordinary prefecture-level cities.

Some studies used a bottom-up approach to obtain carbon emissions data for the study area by collecting sectoral energy consumption data (Wang et al., 2012, 2014) or point source carbon emission data (Cai et al., 2018). The limitations of such methods are as follows: first, the process of data collection is difficult, and large amounts of time, manpower, and material resources are consumed; second, the research objects are not the same among different studies; and third, the time scales are generally different and the status of social sectors are not consistent. As a result, the comparability and applicability of these studies are deteriorating, so this method cannot be used as a universal method to calculate city-scale carbon emissions.

The use of carbon satellites or other spatial datato reflect carbon emissions in different regions is another relatively new method (Wang et al., 2014; Zhao et al., 2018). The annual global emissions data released worldwide have become the cornerstone of the global climate change negotiations. However, such studies are mainly conducted in developed western countries by organizations such as the Netherlands Environmental Assessment Agency (PBL), Emissions Database for Global Atmospheric Research (EDGAR), Carbon Dioxide Information Analysis Centre (CDIAC), and the European Commission's Joint Research Centre (JRC). The disadvantage of this kind of study is that the resolution is limited by atmospheric greenhouse gas (GHG) monitoring equipment, which generally has a resolution of $1^\circ \times 1^\circ$ (or 10 km × 10 km). Therefore, its application is often concentrated at global, regional, or national scales, and it is rarely used at smaller city scales at present due to poor accuracy. However, the spatial data can be used for cross-validation of city-scale carbon emissions.

In addition, the input-output model and its' related extended models are also used in the accounting of city consumption-based carbon emissions (Mi et al., 2016, 2017; Davis and Caldeira, 2010), even LCA model can also be used to calculate carbon emissions (Cong et al., 2014). However, these methods cannot be commonly used at city level because of their own defects (Chen et al., 2017).

In summary, due to the lack of basic city-level data, unclear official statistics, and practical difficulties, few of the above methods are adoptable and they cannot provide detailed data for many cities. Meanwhile, these data are not consistent or systematic (Shan et al., 2017). Some studies also revealed that because of the lack of data transparency and accuracy of the energy-related data, China has been frequently questioned when attending global negotiations and allocating responsibilities (Guan et al., 2012; Liu et al., 2015; Zheng et al., 2018). Based on previous research and taking full account of data availability, we developed a feasible method to calculate carbon emissions from city-level energy consumption based on provincial EBTs. We applied this method to 41 Chinese cities. In order to verify the accuracy of our method, we conducted cross-validation with point-source data from the China High Resolution Emission Database (CHRED). We also conducted a Monte Carlo uncertainty analysis to ensure that our method was applicable and accurate.