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Temporal and spatial heterogeneity of carbon intensity in China's construction industry

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ABSTRACT

As a basic, forerunner industry, as well as a major energy consumer, the construction industry is now facing the dual pressures of energy conservation and emissions abatement. Employing 2005–2014 data, the study estimates the sector's carbon intensity in 30 provinces in China using an improved accounting framework. Moran's I index and a dynamic evolution model, based on the kernel density function, are employed to depict the temporal and spatial heterogeneity in this industry's emissions patterns. We find that significant features of spatial cluster exist in neighboring provinces of China in the space dimension, and the sector's annual average carbon intensity can be classified into four agglomeration areas, namely, high and high (H-H), low and high (L-H), low and low (L-L) and high and low (H-L). From the carbon intensity accounting perspective, building material is the main contributor to the spatial pattern. In the time dimension, for the sampling periods of 2005–2008, 2008–2011, and 2011–2014, the decomposition difference of the sector's carbon intensity in 24 provinces is widening, except for 6 provinces including Inner Mongolia, Guangxi, and Ningxia. The results of the kernel density function analysis show that the critical areas to cut carbon emissions in the construction industry are the H-H agglomeration areas and the provinces in these areas should borrow ideas from those in L-L agglomeration areas for this purpose. In conclusion, province-specific policies based upon temporal and spatial heterogeneity are proposed to achieve China's emissions abatement target as soon as possible.

1. Introduction

Greenhouse gases (GHG) are generally associated with social and economic development; however, excessive emissions pose a significant threat to human health (Monahan and Powell, 2011). The control of carbon dioxide-dominated GHG emissions has become the central way for countries to achieve green development. The construction sector accounts for nearly 36% of the worldwide carbon emissions (Chau et al., 2012).

In China, the total anthropogenic CO_2 emissions from the construction sector increased from 3905×10^4 t in 1995–$103{,}721 \times 10^4$ t in 2010, representing 28%-34% of its total carbon emissions from energy consumption (Chuai et al., 2015). Indirect carbon emissions from other industrial sectors induced by the construction sector represented approximately 97% of the total anthropogenic carbon emissions of the sector (Cao et al., 2016). Accordingly, the construction industry, which is an important source of carbon emissions, should have a more targeted reduction responsibility for emissions to aid in the current government goals. To enable this, there is significant reference value for government departments in analyzing the regional distribution characteristics of carbon intensity and the dynamic evolution in China's construction industry in recent years.

Numerous studies have shown that the construction industry has the greatest potential for carbon emissions reduction, and this concept has attracted many researchers to the field (Sattary and Thorpe, 2016; Seo et al., 2015; & rge-Vorsatz and Novikova, 2008). In terms of low-carbon development in China's construction industry, researchers have studied the barriers (Lam et al., 2015; Shaikh et al., 2014; Wang et al., 2014), policies (Jagannathan, 2014; Kibert and Fard, 2012; Lee and Chong, 2016; Li et al., 2017; Yuan et al., 2011), and applicable technologies (Li et al., 2016; Martínez et al., 2016; Watson et al., 2015; Yang et al., 2016) that can improve the energy efficiency of building.

To estimate carbon emissions from the construction industry, many researchers use life-cycle analysis (Bonamente and Cotana, 2015; Chou and Yeh, 2015; Kneifel, 2010; Lamnatou et al., 2015; Lamnatou et al., 2014; Onat et al., 2014; Sim and Sim, 2017) to estimate the emissions of various infrastructure including residential buildings (Onat et al., 2014), commercial buildings (Kneifel, 2010), office buildings (Chou and Yeh, 2015), and dams (Liu et al., 2012). There are also methods for estimating the variability in GHG emissions using the stochastic carbon

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emissions estimation (SCE2) method (Lim et al., 2016), and process-based and input-output analytical methods (Zhang and Wang, 2016). The main models are the top gas recycling-oxygen blast furnace (TGR-OBF) model (Jin et al., 2017), the life-cycle carbon emissions (LCCE) model (Ogunjuyigbe et al., 2016; Roh and Tae, 2016), the stochastic impacts by regression on population, affluence, and technology (STIRPAT) model (Liddle, 2015), and the ecological input-output model (Salvo et al., 2015; Ukidwe and Bakshi, 2007). In terms of the accounting boundary for carbon emissions, existing research focuses on the carbon emissions of energy consumption (Dimoudi and Tompa, 2008; Shen and Sun, 2016), which often directly use fossil fuels to account for emissions (Amiri et al., 2013; Chen et al., 2011; Spork et al., 2015) but not fully consider the carbon emissions of building materials or electricity consumption; In the extant accounting methods, the national average electricity carbon emissions factor is often used, which cannot account for the differences in regional resource endowment.

As China covers a vast territory, regional development is not balanced (Pan et al., 2017; Tang et al., 2015; Xiao et al., 2015). Examining spatial and temporal distribution characteristics, Chuai et al. (2015) studied the differences in spatial and temporal carbon emissions (including direct and indirect carbon emissions) by grid in China's construction industry from 1995 to 2010. The results show significant regional differences. Coastal regions show a dramatic build-up and expansion, greater carbon storage losses from vegetation, and greater anthropogenic carbon emissions. Consequently, studies on regional differences and time series on the construction industry carbon emissions are urgently needed to help assess reductions plans.

However, studies have rarely focused on the regional differences. It is fortunate that studies on the temporal and spatial distribution of carbon emissions in other fields (Cao et al., 2016; Hamilton and Lovette, 2015; Ruijven et al., 2016; Xiong et al., 2016a; Yuan et al., 2016) can provide a useful reference for the study of temporal and spatial heterogeneity of carbon emissions in the construction industry. Shi et al. (2016) established a correlation between nighttime light index panel data and carbon emissions data and proposed a method of indirect measurement and analysis of temporal and spatial changes of CO_2 emissions in China using the night light index. Xiong et al. (2016b) analyzed the trends of carbon emissions in the Xinjiang Autonomous Region in China from 1991 to 2014 in three stages based on efficiency factors and economic factors. Hamilton and Lovette spatiotemporally calculated the carbon values of the mangrove forests and estimated the amount of carbon lost due to direct displacement by aquaculture (Hamilton and Lovette, 2015). Fu et al. (2015) used Moran's I spatial autocorrelation statistics to test the spatial autocorrelation between carbon intensity in each region over the years, and concluded that there was a significant spatial autocorrelation between the provincial carbon intensities. Chen et al. (2015) analyzed the spatial pattern of per capita carbon emissions in China using Moran's I index. The results show that in temporal and spatial terms, the spatial autocorrelation of per capita carbon emissions in China has gradually become stronger, and the spatial agglomeration is characterized by an inter-planar distribution.

Based on the above analysis, this study performs the following: First, we redefine the accounting boundary of carbon emissions in the construction industry and improve the calculation method for the carbon intensity value (Section 2). On the one hand, the accounting boundary is widened to include three parts, building materials, fossil fuels, and electricity, which enables including more details and overcomes the shortcomings of existing research in only accounting for fossil fuels. On the other hand, we account for differences in electricity carbon emissions in the provincial construction industry and eliminate calculation errors caused by differences in regional resource endowment. Second, the study conducts a multidimensional perspective analysis to consider temporal and spatial differences of carbon intensity in China's construction industry (Section 3). In spatial terms, it is essential to analyze the agglomeration characteristics of carbon intensity and its underlying mechanism in the regional construction industry. In temporal terms, it is essential to analyze the dynamic evolution process and variation. Finally, based on the characteristics of temporal and spatial heterogeneity, the study proposes a regional carbon emissions reduction strategy for the construction industry suitable for policy decisions of the Chinese government departments (Section 4).

2. Methods and data sources

2.1. Calculation of carbon intensity

The calculation method for the carbon intensity of the construction industry as a whole is different from that for a single building or a certain type of building. The single building usually needs to establish a full life cycle measurement model to calculate its carbon emissions based on on-site statistical survey data of detailed energy and building materials consumption (Li, 2012; Liu, 2013; Zhang and Sun, 2015; Zhang et al., 2010). Moreover, a certain type of building analysis often chooses a typical carbon emissions stage (such as the construction stage, the use stage, or recovery and cleaning stage) using engineering measured data to model the calculation (Hua et al., 2014; Jiang, 2012; Wang, 2012b). However, the calculation method for the carbon intensity of construction industry is not uniform (Suzuki et al., 1995; Chen et al., 2011; Huang et al., 2017). Due to the limited data, the calculation method is usually relatively rough, which generally estimates the carbon intensity based on the terminal energy consumption of the construction industry (Hiwatashi and Oka, 2005; Nag and Parikh, 2005). This calculation method is simple, but ignores the implied carbon emissions generated by the consumption of building materials. Some studies have shown that the indirect carbon emissions from the production of cement, steel, and other building materials are significantly higher than the direct carbon emissions from terminal energy consumption (Zhang and Liu, 2013). Considering the reality in China, indirect carbon emissions accounted for about 90% of its total emissions (Feng et al., 2014). Therefore, indirect carbon emissions are essential in the calculation of the carbon intensity of the construction industry (Qi et al., 2012). In addition, in the calculation for the carbon intensity of the construction industry, there are few studies taking into account the regional differences in resource endowments (such as the inconsistencies in the generation of power in each region). In this study, these shortcomings are addressed.

The carbon intensity of the construction industry is calculated for each region in China from three aspects: fossil fuels, building materials, and electricity. The calculations are as shown in Eqs. (1) and (2):

$$CI = \frac{C}{GDP} \tag{1}$$

$$C = C_F + C_E + C_M \tag{2}$$

where CI is the carbon intensity of the construction industry, C is the carbon dioxide emissions of the construction industry, and GDP is the actual growth in the construction industry based on the 2000-year values. C_F, C_E, and C_M, respectively, represent carbon dioxide emissions of fossil fuels, electricity, and building materials used in this industry.

2.1.1. Calculation of fossil fuels carbon emissions

The calculation of carbon dioxide emissions (C_F) for fossil fuels, which is consistent with current conventional algorithms, is based on the reference method provided by the Intergovernmental Panel on Climate Change (IPCC, 2007), where the specific types of fossil fuels are determined by the actual terminal energy consumption requirements of the construction industry, as shown in Eqs. (3) and (4):

$$C_F = \sum_{i=1}^{11} (CO_2)_i = \sum_{i=1}^{11} E_i \times NCV_i \times CEF_i \tag{3}$$

$$CEF_i = CC_i \times COF_i \times (44/12) \times 10^3 \tag{4}$$