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Carbon footprints and embodied CO_2 transfers among provinces in China

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ABSTRACT

China is the top CO_2 emitter with enormous regional variation in economic development, resource endowment, and consumption patterns, which leads to great variations in regional CO_2 emissions and embodied CO_2 transfer among provinces. Analyzing the mechanisms responsible for carbon footprint (CF) and embodied CO_2 transfer among provinces via trade could help policy makers allocate emission responsibilities and reduction targets. Based on a multi-regional input–output model, this paper investigates the CFs and embodied CO_2 transfer in/among 30 provinces of China in 2007 and 2010, and analyzes emissions from different perspectives. Results indicate that China's CF grew from 5230 Mt in 2007 to 6922 Mt in 2010, with an annual growth rate of 9.8%. The provinces with the large CFs and per capita CF were mainly those locate in eastern, developed regions along the coast and several highly populated ones. CO_2 emissions due to capital formation contributes the most to the CFs and the increment in this period, and this was followed by urban consumption. Significant embodied CO_2 transfer were observed to drift from the developing and energy-abundant provinces like Hebei and Inner Mongolia, to the developed coastal provinces. Total embodied CO_2 transfer account for 43.9% of the national CF in 2007, and decreased to 41.0% in 2010. In order to control CO_2 emissions and make reduction allocations for provinces, interprovincial embodied CO_2 transfer and practical capacities need to be taken into account.

1. Introduction

Due to its rapid economic development and industrialization over the last three decades, China has become the world's top total CO_2 emitter [1]. It is also the top emitter from a consumption-based perspective, accounting for 23% of the total global consumption-based emissions in 2013 [2]. An increasing amount of attention is being paid to energy conservation and emission reduction in China and elsewhere around the world. In China, the government has presented its reduction targets and promises on a couple of occasions. More specifically, in 2009, the Chinese government promised to lower its CO_2 emissions per unit GDP by 40–45% by 2020 compared to the 2005 level [3]. In 2014, the government asserted that China would reach a peak in CO_2 emissions around 2030 but would endeavor to peak at an earlier date. Meanwhile, it would increase the share of non-fossil fuels used in primary energy consumption to around 20% by 2030 [4]. In June 2015, the Chinese government submitted its 'intended nationally determined contribution' (INDC) to the UN, and promised to lower its CO_2 emissions per unit GDP by 60–65% and increase forest stock volume by 4.5 billion cubic meters by 2030 compared to the 2005 level [5]. In the meantime, China would launch a nationwide emission trade system (ETS) in 2017 [6]. Overall, a multitude of actions have shown the determination of the Chinese government to address climate change.

China is a country with a vast territory. The various provinces show great variation in their economic development status, population density and scale, industrial structure, resource endowment, and residential lifestyle [7]. Huge interregional trade occurs in resources, commodities, and services as a result of the uneven distribution in different kinds of resources. This is particularly so between the developed eastern regions and the energy abundant, but poor, inland regions, which can be associated with a large amount of CO_2 transfer in the domestic supply chain [8]. That is to say, due to the separation between places of production and consumption of products and services, CO_2 emissions show considerable spatial variation, which results in large amounts of 'embodied' (other authors have also used the terms 'virtual' or 'hidden') CO_2 transfer. Thus, there is 'interregional carbon leakage' due to interregional trade within China, in which few trade barriers exist. In order to achieve its ambitious reduction targets, the Chinese government needs to allocate and tailor specific reduction targets to the various provinces. But with increased consumption capacity, the

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interregional trade flows increase as well, along with enlarged CO_2 transfer. This leads to large variation in consumption-based emissions among provinces. Thus, just considering the production perspective by itself brings barriers to the allocation of regional emission rights and responsibilities and the relevant emission policies made for the provinces. Therefore, it is important to consider not only the actual emission bases but the embodied emission transfer from the consumption perspective as well.

Carbon footprint (CF) is a useful indicator of consumption-based emission. It can provide new insights into, and methods to evaluate, the total CO_2 emissions from consumption activities and embodied CO_2 transfer [9,10]. The consumption-based CO_2 emission not only captures the direct and indirect emissions associated with commodities and services production [11], but also objectively assesses the emission level associated with consumption-driven economic growth and products or services that meet demands. It reflects the emission responsibilities allocated to the provinces where commodities and services are ultimately consumed [12], makes consumers aware of the effects of their lifestyles and consumption patterns on greenhouse gas (GHG) emission [13], and helps the design of policies and strategies on climate change that can be widely adopted [10,14]. As an indicator, CF extends the range of policy and research application of carbon emissions considerably [15], and provides supporting information for assigning emission responsibilities on a national, sectoral, and supply chain, etc. basis [11]. Thus, it has been widely employed [10,11,13,16].

In recognition of the advantages of consumption-based accounting evaluation, much of the previous literature has studied the issue of CF and embodied CO_2 transfer about China on different levels. Using different versions of the Global Trade Analysis Project (GTAP) database, the CFs of various nations (including China) and the CO_2 emission transfer embodied in international trade have been examined by various scholars. Liu et al. [17] analyzed the emissions embodied in exports from China's provinces using GTAPv8. They showed that, in 2007, China transferred 58% of the total emissions embodied in export to the top three importers: US (24%), EU (25%), and Japan (9%). Qi et al. [18] reached similar conclusions using the same dataset. Using GTAPv7, Davis and Caldeira [19] found that, in 2004, China was the largest net exporter, and second-largest consumption-based CO_2 emitter after the US, transferring 1.4 Gt CO_2 abroad (mainly to the US, Japan, and Western Europe). For more examples at the multinational level, see Refs. [16,20,21]. Xu et al. [22] assessed air emissions and energy transfer in bilateral trade between China and the US. Li and Hewitt [23] focused on carbon emissions embodied in trade between China and the UK in 2004, and noted that the UK reduced emissions by 11% through trade with China — however, global emissions volume increased. Liu et al. [24] and Dong et al. [25] analyzed CO_2 emissions embodied in bilateral trade between China and Japan in 1990 and 2000 using an Asian input–output table. Some studies have analyzed CF and embodied CO_2 transfer within China at the regional level. Meng et al. [26] investigated the interregional spillover effects of CO_2 emissions in China for 2002 and 2007 based on a multi-regional input–output (MRIO) model. They found that the eastern coast was then the largest domestic CO_2 'importer', the northwest the largest 'exporter', and the central region the hub of CO_2 emissions. Yao et al. [27] accounted for the CF from regional household consumption, distribution, and transformation of household CF among eight regions in China in 2007 using the MRIO approach. Using one production-based and two consumption-based accounting principles, Liu et al. [28] analyzed the regional CFs and carbon flows embodied in interregional trades for the same eight regions in China in 2002 and 2007. Jiang et al. [29] examined regional CF and interregional embodied carbon flows in China in 2007 using an emissions embodied in bilateral trade (EEBT) method.

In contrast, only a few studies have investigated CF and embodied CO_2 transfer at the provincial level. Shi et al. [30] estimated the CFs of 30 provinces in China based on provincial input–output tables in 2002 and 2007, and carbon transfer based on China's interregional input–output (IRIO) 2002 database. Feng et al. [31] analyzed CO_2 emissions outsourced by provinces through trade within China. However, an in-depth analysis of CO_2 emissions from a consumption perspective in China has not been established, and systematic analyses of variations of provincial CFs have not been conducted. For specific mitigation targets need to eventually materialize in each province, but they are in very different stages of development and there is great variation in their socio-economic situations even though they are in the same region. Provincial indicators can support the associated environmental policy making and allocation of specific mitigation targets for the different provinces, and can also help grant some tendentious policies for exceptional ones. Analysis of the embodied CO_2 transfer among provinces will reveal the spatial distribution across the regions of China and will not only explicitly explain how interprovincial trade affects CO_2 emissions in the various provinces [29], but give a better indication of the reduction responsibility they should assume from a consumption perspective. The mechanisms responsible for absorption of the embodied CO_2 transfer can clearly expound the sources of the resulting CF [32], and the transfer mechanisms may constitute an empirical practical basis for establishing a nationwide ETS in the near future. In addition, their features can provide a foundation for cooperation between specific producing and consuming provinces. Therefore, in the current paper, our aim is to solve the aforementioned problems, and provide policy makers the basis for provincial emission reduction responsibilities allocation and effective CO_2 reduction schemes. We quantitatively survey the CF and embodied CO_2 transfer at a provincial level, and then analyze the emissions from different perspectives, which is a particularly crucial and necessary step.

The reminder of this paper is organized as follows. Section 2 describes the methodology used to account for the CF and embodied CO_2 transfer among Chinese provinces. Section 3 presents the data sources and approaches used to manage the data. Section 4 gives the results and a discussion of them, and Section 5 considers policy implications. Finally, conclusions are drawn in Section 6.

2. Methodology

In this paper, we use a multi-regional input–output model to account for the provincial CFs and embodied CO_2 transfers in China. The MRIO model involves fluxes corresponding to production within a region, inflow, and outflow between regions, and the final consumption. In such an MRIO framework, different regions are connected by interregional transactions.

For the region r in a non-competitive MRIO framework, the basic expression representing linear equilibrium can be written

$$x^r = \sum_s A^{rs} x^s + \sum_s y^{rs} \tag{1}$$

where x^r is a column vector representing the output in region r, $A^{rs} = (a_{ij}^{rs})$ is the input coefficient matrix (given by $a_{ij}^{rs} = z_{ij}^{rs}/x_j^s$, in which z_{ij}^{rs} is the inter-sector monetary flux from sector i in region r to sector j in region s, and x_j^s is the total output of sector s in region j), and y^{rs} is the final consumption of imported commodities in region s from region r. Thus, y^{rr} represents the final regional consumption of products and services produced in region r and finally consumed in region r. The consumption y includes rural household consumption, urban household consumption, government expenditure, capital formation, and change of inventories.

Suppose there are m regions, and each region contains n sectors. Then, the above equation can be extended in matrix form:

$$\begin{bmatrix} x^1 \\ x^2 \\ \vdots \\ x^m \end{bmatrix} = \begin{bmatrix} A^{11} & A^{12} & \cdots & A^{1m} \\ A^{21} & A^{22} & \cdots & A^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ A^{m1} & A^{m2} & \cdots & A^{mm} \end{bmatrix} \begin{bmatrix} x^1 \\ x^2 \\ \vdots \\ x^m \end{bmatrix} + \sum_s \begin{bmatrix} y^{1s} \\ y^{2s} \\ \vdots \\ y^{ms} \end{bmatrix} \tag{2}$$