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Carbon emission imbalances and the structural paths of Chinese regions

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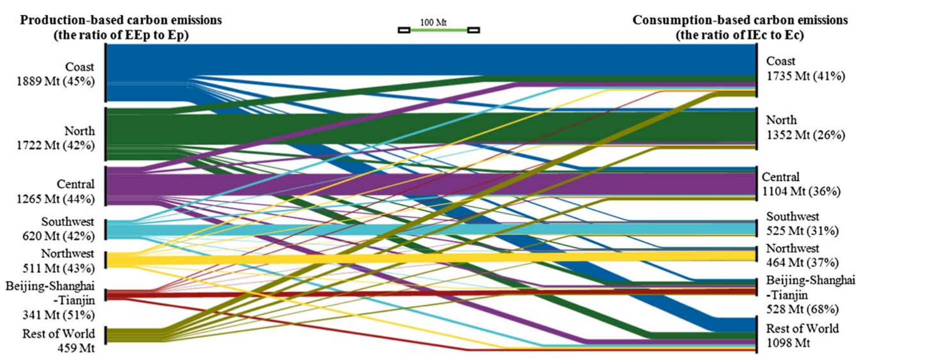
HIGHLIGHTS

- Consumption-based carbon emissions increased faster than the production-based one.
- Carbon emission imbalances of most Chinese regions have been reduced since 2007.
- Disparities in the regional per capita carbon footprint have widened since 2007.
- SPA shows most regions have larger imports/exports shares in upstream supply tiers.
- Beijing's carbon supply chains were a bit longer but less diverse than Shanghai.

GRAPHICAL ABSTRACT



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ABSTRACT

As the Chinese regions become more and more connected to each other and foreign countries, this study aims to address carbon imbalance and outsourcing issues in China. Using a production-based carbon emission inventory and a China-global multi-regional input-output model, this study estimates the consumption-based carbon emissions in 30 Chinese regions in 2007 and 2010. Our results reveal that the carbon imbalances of most Chinese provinces and cities have decreased between 2007 and 2010, but disparities in the regional per capita carbon footprint have widened. Our Structural Path Analysis (SPA) results shows that most Chinese regions have higher ratios of both imported (to consumption-based) and exported (to production-based) carbon emissions in further upstream supplier tiers than that of direct imports and exports in the first tier, thus it's vital to trace emissions in the upstream supply chain to understand emission outsourcing. Our result from four case study provinces suggests that Beijing should import more electricity products from nearby Hebei and Shandong rather than Inner Mongolia to lower its consumption-based carbon emissions given the smaller emission coefficients of their electricity production.

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1. Introduction

At the Paris climate conference (COP21) in December 2015, 195 countries adopted the Paris Agreement within the framework of the United Nations Framework Convention on Climate Change (UNFCCC). It is generally considered to be the historic turning point for reducing global warming [1]. Prior to and during the Paris conference, some countries submitted Intended Nationally Determined Contributions (INDCs), which represented the targets that each country should reach in order to achieve the global goal. As early as June 2015, China announced its INDCs and committed to the achievement of peak carbon dioxide emissions around 2030 and the reduction of carbon dioxide emissions per unit of GDP by 60–65% from 2005 levels by 2030 [2].

The ambitious climate mitigation goal of China can be achieved through region-level efforts. China has initiated low-carbon development pilots in 6 provinces and 36 cities, which include 42% of the total population, 57% of the GDP, and 56% of all carbon emissions [2]. In addition, the second session of the China-U.S. Climate-Smart/Low-Carbon Cities Summit was held in Beijing in June 2016 and was attended by participants from 17 U.S. cities, counties, and states and from 49 Chinese cities and provinces. The participating Chinese provinces and cities intend to perform enhanced actions to support the achievement and implementation of China's respective post-2020 national climate targets. During the Summit, the NDRC (National Development and Reform Commission) of China announced that the number of low-carbon development pilot cities in China will increase to 100 [3].

The newly launched 13th Five Year Plan (2015–2020) reported that China achieved a 20% reduction, which more than satisfied the 17% carbon intensity reduction goal proposed in the 12th Five Year Plan (2010–2015), and determined a new 18% mandatory goal for the next five years [4]. Each Chinese province was allocated mandatory energy reduction and carbon emission mitigation targets (see Supporting Information, i.e., SI, Table S1), which was slightly higher than that in the previous plan [5,6]. Annual achievement of the reduction of emission intensity by each local government was assessed by the central government as an important performance evaluation indicator. According to the report, the most rapidly developing provinces or cities, e.g., Beijing and Shanghai, easily achieved the goal, while a few less-developed provinces, e.g., Xinjiang and Qinghai, struggled to meet the requirement [7,8].

The mandatory goal for each province during the 13th Five Year Plan has been set according to its development stage, resources endowment, strategic position, eco-environmental protection, and so on [6]. In the future, scientific and accurate carbon emission data of Chinese regions need also to be taken into consideration to fairly attribute carbon emission reduction goal and efficiently achieve the INDC. The territorial emission inventory under UNFCCC plays a key role in current carbon emission management [9,10]. However, in recent years the growing inter-provincial trading led to more and more carbon transfer and imbalance issues in China [11–14]. For example, it is found that more than half of China's emissions are related to goods that are consumed outside of the province where they are produced in 2007 [15]. Therefore the consumption-based carbon emission inventory must be taken into consideration when properly identifying responsibility and assigning quotas [16].

Input-output analysis (IOA) has been frequently utilized to estimate consumption-based carbon emission [17–20]. Among all the existing studies, the single-regional input-output (SRIO) analysis was applied to analyze GHG emissions of final demand in a national or regional economy [19–21] while the multi-regional input-output (MRIO) analysis was employed to calculate carbon emissions embodied in trade among different countries or regions [17,18,22–26]. According to IOA, all carbon emissions are driven by final demand, and thus, emissions associated with the production of goods and services are ultimately attributed to final consumption activities. Transmission chains from production-based carbon emission sources to consumption-based destinations can be very complex due to the deepening modern industry division, but they can be mathematically traced through production layers by the Structural Path Analysis (SPA) method [27–31]. A study by Liu et al. found that the huge emissions embodied in Chinese exports are in part due to the very high emissions intensity in a few provinces and industry sectors [32]. For a Chinese region, it would be also very important to uncover the key pathways that lead to its major carbon emissions, which can be identified by SPA. From the production perspective, a region may reduce its export supply chains, which drive the most carbon emissions, to lower its on-site carbon emissions. In contrast, from the consumption perspective, a region may choose to purchase alternative products that are produced with low carbon intensive technologies to reduce its carbon footprint.

Against this general background, this paper first accounts for and analyzes the consumption-based carbon emissions of 30 Chinese provinces and cities, based on which the carbon emission imbalance of each Chinese region is assessed. The results can assist policymakers in the task of properly allocating carbon emission mitigation targets among Chinese regions. This paper also demonstrates the methods of identifying key carbon emission structural paths of production-based and consumption-based carbon emissions from each province or city. It can provide assistance for designing efficient carbon emission reduction strategies for each region.

2. Methods and data

2.1. Methods

2.1.1. Multi-regional input-output (MRIO) analysis

MRIO analysis has attracted widespread interest for addressing global environmental issues [33–35]. In an MRIO model, the same types of products developed from different economies are treated as entirely different products, and different regions are connected through an interregional trade matrix. With a given MRIO table, the total output vector $\mathbf{x}$ of the MRIO model, according to input-output theory [36,37], is represented as

$$\mathbf{x} = \mathbf{Ax} + \mathbf{y} \quad \text{and} \quad \mathbf{x} = (\mathbf{I}-\mathbf{A})^{-1}\mathbf{y} \tag{1}$$

in which $\mathbf{A}$ is the technical coefficients matrix and $\mathbf{y}$ represents the final demand matrix. When subjected to Leontief's demand-pull model, the carbon emissions flow $\mathbf{E}$ driven by final demand can be calculated accordingly from

$$\mathbf{E} = \boldsymbol{\varepsilon}\mathbf{x} = \boldsymbol{\varepsilon}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y} = \mathbf{my}, \tag{2}$$

in which the vector $\boldsymbol{\varepsilon}$ represents the direct carbon emission coefficients, $\mathbf{I}$ is an identity matrix, and $\mathbf{m} = \boldsymbol{\varepsilon}(\mathbf{I} - \mathbf{A})^{-1}$ are designated as carbon emission multipliers [38]. The emissions embodied in exports (EEE) and imports (EEI) can be then calculated from

$$\text{EEE} = \mathbf{me} \quad \text{and} \quad \text{EEI} = \mathbf{mi}, \tag{3}$$

where $\mathbf{e}$ and $\mathbf{i}$ represent the exports and imports matrices, respectively.

The indicator of per capita consumption-based carbon emissions, i.e., the carbon footprint, is used to evaluate the inequalities among different Chinese provinces and cities. In addition, an indicator of the CII (carbon emission imbalance index) is formulated in this work in order to assess the carbon emission trade imbalance of Chinese regions. For carbon emission net importers, this indicator is defined as the proportion of consumption-based carbon emissions that is net imported from other economies:

$$\text{when } E_{\text{consumption}} > E_{\text{production}}, \quad CII = (E_{\text{consumption}} - E_{\text{production}})/E_{\text{consumption}}. \tag{4}$$

For carbon emission net exporters, it is defined as the proportion of production-based carbon emissions that is net exported to other economies: