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'Made in China': A reevaluation of embodied CO_2 emissions in Chinese exports using firm heterogeneity information

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HIGHLIGHTS

- Firms in the same IO sector for China may have very different carbon intensity.
- Firm heterogeneity information significantly improves carbon footprint estimation.
- Embodied CO_2 emissions in Chinese exports may be overestimated by 20% for 2007.
- The competitiveness of China's exports relates to upstream firms' externalities.

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ABSTRACT

Emissions embodied in Chinese exports might be lower than commonly thought, which would increase China's responsibility for carbon emissions under a consumption-based approach. Using an augmented Chinese input–output table in which information about firm ownership and type of traded goods are explicitly reported, we show that ignoring firm heterogeneity causes embodied CO_2 emissions in Chinese exports to be overestimated by 20% at the national level, with huge differences at the sector level, for 2007. This is because different types of firms that are allocated to the same sector of the conventional Chinese input–output table vary greatly in terms of market share, production technology and carbon intensity. This overestimation of export-related carbon emissions would be even higher if it were not for the fact that 80% of CO_2 emissions embodied in exports of foreign-owned firms are, in fact, emitted by Chinese-owned firms upstream in the supply chain. The main reason is that the largest CO_2 emitter, the electricity sector located upstream in Chinese domestic supply chains, is strongly dominated by Chinese-owned firms with very high carbon intensity.

1. Introduction

China has been the world's largest emitter of CO_2 since 2006 [1]. Not only the absolute level of China's CO_2 emissions but also its rapid growth (the average annual growth rate of Chinese emissions was about 6% between 1995 and 2014) brings a great and urgent challenge to achieve global climate change mitigation targets, such as limiting the average global surface temperature increase to 2 °C (3.6 °F) above the pre-industrial average [2]. Recent evidence Meng et al. [3] shows that about 30% (1971 Mt) of Chinese CO_2 emissions in 2009 were associated with the production of exports. Exports have been a main cause of the increase of Chinese CO_2 emissions over time [4–7]. Therefore, a better understanding of the source and structure of emissions embodied in Chinese exports is a precondition both in setting climate policies concerning "carbon leakage" through international trade and in reaching political consensus about sharing the responsibility between developed and developing economies.

The estimation of embodied CO_2 emissions in Chinese exports has attracted much interest [7–15]. However, existing studies on this topic have some drawbacks in both methodology and data used. With regards to methodology, Leontief's input–output (IO) models [16] provide a widely used tool set to measure embodied emissions in exports, but only rather recently have these models been employed for detailed supply chain analyses of embodied carbon emissions. The role that a sector plays in embodied emissions

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depends heavily on the sector's position in supply chains [3]. In this paper we not only elucidate how a specific export sector induces emissions in domestic supply chains (tracing emissions from downstream to upstream), but also reveals how emissions emitted in a specific sector contribute to producing exports (tracing emissions from upstream to downstream).

In terms of data, most studies rely on national or regional IO tables which aggregate different types of firms into the same IO sector, implicitly assuming that all firms use the same technology to produce goods and services. This assumption may be acceptable for countries whose production technologies at the sector level have lower variation across firms. However, for the case of China, and developing countries more generally, this assumption may lead to large errors in estimating embodied emissions in exports because of the potentially large differences in production technologies and energy efficiency across firms according to ownership (e.g., Chinese-owned or foreign-owned), know-how, technological and financial endowment, and types of trade (e.g., processing or non-processing trade). According to the regulations used by Chinese customs [17], processing trade refers to importing all or part of raw and auxiliary materials, parts and components, accessories, and packaging materials from abroad duty free, and re-exporting the finished products after processing or assembling by enterprises within mainland China (e.g., Foxconn assembles iPhones for Apple in China and exports the phones to the US). This definition implies that firms conducting processing trade use more imported intermediate goods than those from domestic production. This is very different from firms conducting normal trade, whose intermediate inputs are mainly produced domestically. Given the fact that more than 43% of Chinese exports in 2007 are processing trade [18], and given the higher carbon intensity of domestic production [19], the level of emissions embodied in processing trade should be less than that in non-processing trade.

To our knowledge, very few studies have paid attention to the above firm heterogeneity in estimating CO_2 emissions in Chinese exports. Dietzenbacher et al. [20], Su et al. [21], Xia et al. [22] introduce information about a firm's involvement in the supply chain (processing and non-processing trade) into the estimation of embodied CO_2 emissions in Chinese exports and show that overestimation occurs when using conventional IO tables. However, there is no explicit information about firm ownership. Jiang et al. [23] use information about both firm ownership and type of trade to estimate embodied CO_2 emissions in Chinese exports for the year 2007 with an augmented Chinese national IO database compiled by Ma et al. [18]. However, there is no explicit consideration in Jiang et al. [23] on the overestimation of embodied emissions in Chinese exports from both upstream and downstream perspectives of the supply-chain. In this paper, we use the same database [18], but investigate embodied emissions in Chinese exports from detailed supply-chain perspectives at the national, sector, and inter-firm level which leads to more accurate estimates and allows us to identify the carbon hotspot in Chinese domestic supply chains for export production.

We first show the production-based emissions [24–27], GDP and emission intensity (emissions per GDP) for China at both sectoral and firm level. This can help us to clearly understand how different types of firms allocated in the same sector of the conventional Chinese IO table have different production functions in producing goods and services. This further provides important information for understanding the reasons behind the differences in CO_2 emissions embodied in Chinese exports when using conventional versus augmented IO tables. We provide supply-chain oriented analyses, which allows us to identify both the important emission drivers (e.g., which type of export induces more emissions?) and sources (e.g., which upstream sectors dominate emissions embodied in exports?) in Chinese exports. Furthermore, instead of the traditional carbon intensity index (sectoral emissions/sectoral GDP or output), we follow Meng et al. [28] and Prell et al. [29] in employing an alternative intensity index (embodied emissions in exports/embodied value-added in exports). This index can help to better understand the potential environmental costs in terms of emissions per unit value-added from international trade.

2. Method and data

Input–output analysis (IOA) is an accounting procedure and modeling approach that relies on national or regional input–output tables. A country's IO tables show the flows of goods and services and thus the interdependencies between suppliers and consumers along the production chain within an economy [16,30]. Due to its ability to provide a life cycle perspective from 'cradle to grave' by accounting for impacts of the full supply chain IOA has become an important approach for estimating embodied emissions in trade [4–6,12]. Using an environmentally extended IO model (EIO), embodied CO_2 emissions in exports at the national level can be estimated as follows [16]:

$$CO_{2exp} = \mathbf{c} \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{e}, \quad (1)$$

where CO_{2exp} is a scalar representing the total CO_2 emissions embodied in exports; $\mathbf{c}$ is a $1 \times n$ row vector of CO_2 emissions coefficients representing the CO_2 emissions per unit of economic output by sector; $\mathbf{A}$ is the $n \times n$ input coefficient matrix showing the share of intermediate input in total output; $(\mathbf{I}–\mathbf{A})^{-1}$ is the Leontief inverse matrix indicating the totally induced output by one unit production of final goods or exports through domestic supply chains; $\mathbf{e}$ is an $n \times 1$ column vector representing the exports by sector. According to different perspectives on supply chains, embodied emissions in exports at the sector level can be traced either from downstream to upstream $(D \to U)$ or from upstream to downstream $(U \to D)$:

$$\mathbf{CO}_{2exp}^{D\to U} = \mathbf{c} \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathrm{diag}(\mathbf{e}), \quad (2)$$

$$\mathbf{CO}_{2exp}^{U\to D} = \mathrm{diag}(\mathbf{c}) \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{e}. \quad (3)$$

In the traditional IO theory, the two different measures above have their own economic interpretations and thus play different roles in economic analysis. The measure $\mathbf{CO}_{2exp}^{D\to U}$ represents the CO_2 emissions of all sectors embodied in a specific export product. In other words, this measure looks at how a specific exporting product induces emissions of all sectors directly and indirectly through domestic upstream supply chains. In contrast, the measure $\mathbf{CO}_{2exp}^{U\to D}$ represents the CO_2 emissions of a specific sector embodied in all exports. In other words, this measure looks at how emissions of a specific sector located upstream are embodied in all its downstream sectors and finally exported to other countries. It is easy to see that there is, by definition, no difference at the national level between these two measures for embodied emissions in exports.

If we replace the emission coefficient $\mathbf{c}$ in Eq. (1) by the value-added rate $\mathbf{v}$ (a $1 \times n$ row vector representing the value-added per unit output by sector), the so-called embodied value-added (or GDP) in exports can also be estimated by the following way.

$$GDP_{exp} = \mathbf{v} \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{e}. \quad (4)$$

Further using Eqs. (1) and (4), an indicator P, of the carbon intensity of embodied emissions in exports can be defined as follows:

$$P = CO_{2exp}/GDP_{exp}. \quad (5)$$

This indicator captures the emissions a country makes per unit value-added export, thus, it can be considered a proxy to represent

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