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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]:

$$\mathrm{CO}_{2\mathrm{exp}} = \mathbf{c} \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{e}, \tag{1}$$

where $\mathrm{CO}_{2\mathrm{exp}}$ 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 $(\mathrm{D} \rightarrow \mathrm{U})$ or from upstream to downstream $(\mathrm{U} \rightarrow \mathrm{D})$:

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

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

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 $\mathbf{CO}_{2\mathrm{exp}}^{\mathrm{D}\rightarrow\mathrm{U}}$ 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 $\mathbf{CO}_{2\mathrm{exp}}^{\mathrm{U}\rightarrow\mathrm{D}}$ 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.

$$\mathrm{GDP}_{\mathrm{exp}} = \mathbf{v} \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{e}. \tag{4}$$

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

$$P = \mathrm{CO}_{2\mathrm{exp}}/\mathrm{GDP}_{\mathrm{exp}}. \tag{5}$$

This indicator captures the emissions a country makes per unit value-added export, thus, it can be considered a proxy to represent the potential environmental cost to a country of joining international trade. In the same manner, at the sector level, embodied value-added in exports are given by

$$\mathbf{GDP}_{\mathrm{exp}}^{\mathrm{D}\to\mathrm{U}} = \mathbf{v} \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathrm{diag}(\mathbf{e}), \tag{6}$$

$$\mathbf{GDP}_{\mathrm{exp}}^{\mathrm{U}\to\mathrm{D}} = \mathrm{diag}(\mathbf{v}) \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{e}. \tag{7}$$

Further, following the definition of P in Eq. (5), the carbon intensity of embodied emissions in exports at the sector level can be defined as follows:

$$\begin{aligned}\mathbf{P}^{\mathrm{D}\to\mathrm{U}} &= \mathbf{CO}_{2\mathrm{exp}}^{\mathrm{D}\to\mathrm{U}} // \mathbf{GDP}_{\mathrm{exp}}^{\mathrm{D}\to\mathrm{U}} \\ &= [\mathbf{c} \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathrm{diag}(\mathbf{e})] // [\mathbf{v} \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathrm{diag}(\mathbf{e})],\end{aligned} \tag{8}$$

$$\mathbf{P}^{\mathrm{U}\to\mathrm{D}} = \mathbf{CO}_{2\mathrm{exp}}^{\mathrm{U}\to\mathrm{D}} // \mathbf{GDP}_{\mathrm{exp}}^{\mathrm{U}\to\mathrm{D}} = \mathbf{c} // \mathbf{v}. \tag{9}$$

Here, we define "//" as an element-wise vector division operator. It is easy to see that the carbon intensity for embodied emissions in the export of a specific product depends on all upstream sectors' emission input coefficients $\mathbf{c}$ and value-added rates $\mathbf{v}$, while the carbon intensity for a specific sector's emissions embodied in all exports is equal to the conventional definition of the production based sectoral carbon intensity (sectoral emissions/sectoral value-added).

The analysis in this paper takes advantage of a novel database developed by Ma et al. [18]: the augmented 2007 Chinese national IO table (42 sectors). The layout of this IO table is shown in Supplementary Information 3. In order to estimate CO_2 emissions by sector and firm type based on this augmented Chinese IO table, the following steps are taken. We first follow the conventional method [31] to estimate China's CO_2 emissions from fuel combustion in physical terms using the 2008 Chinese energy balance table and IPCC emission factors. Combining this information with the energy input data in monetary terms (for four energy sectors: coal mining, washing and processing sector, oil and gas mining sector, petroleum processing, coking and nuclear fuel processing sector, and gas production and supply sector) from the conventional Chinese national IO table, the CO_2 emissions per RMB of energy use by energy sector can be estimated. Since the energy input data in monetary terms by sector and firm type is available in the augmented Chinese IO table, assuming that there is no difference in the energy price across firms (all firms face the same market price for a specific type of energy – a strong but necessary assumption lacking more detailed and reliable energy price data), CO_2 emissions by sector and firm type can be estimated. It should be noted that the above estimation method fully takes into account both the absolute amount of energy inputs and the structure of energy mixture by sector and firm type. This is different from Dietzenbacher et al. [20] who use the ratio of domestic intermediate inputs as a weight to estimate the carbon intensity by firm type. In addition, we start from the most detailed IO sector to estimate emissions rather than disaggregate the sectors in the energy balance table. This is also different from Su et al. [32] who emphasize the importance of estimation bias when disaggregating sectors in the energy balance table to match the more detailed IO sectors.

Furthermore, it should be noted that better estimates for the carbon content of coal are available based on detailed coal mining data than the ones provided by the IPCC [33]. However, most existing research concerning the measure of embodied CO_2 emissions in Chinese exports are based on the IPCC factors thus to be able to compare our results with the existing literature, the IPCC factor was used in this paper. When using Liu et al. [33] emission factors we find that there is no significant change in our main conclusions at both national and sectoral levels. Uncertainties in estimation may happen due to data quality, assumption, parameter, and method used [33,34]. Indeed, adding more firm heterogeneity information is one way to reduce the uncertainty compared to using the conventional IO tables.

3. Results

3.1. Firm ownership and types of trade are important determinants of carbon intensities

In this paper, we estimate carbon emissions in Chinese exports by separating all firms located in mainland China into four categories in terms of ownership (Chinese-owned versus foreign-owned) and types of traded goods (processing trade versus non-processing trade): Chinese-owned firms conducting non-processing trade (CN), foreign-owned firms conducting non-processing trade (FN), Chinese-owned firms conducting processing trade (CP), and foreign-owned firms conducting processing trade (FP). Fig. 1 shows the estimation results of CO_2 emissions, GDP share and carbon intensity by firm type at the national level (aggregating all 42 sectors shown in Supplementary Information 1). Obviously, Chinese-owned firms conducting non-processing trade make the dominant contribution to both China's GDP (86.8%) and its CO_2 emissions (92.7%) with highest carbon intensity (1.9 kg per US$). The contributions to Chinese GDP and CO_2 emissions by foreign-owned firms conducting non-processing trade are respectively, 10.4% and 6.8% with relatively lower carbon intensity (1.1 kg per US$) than China's national average (1.7 kg per US$: the upper dotted line of the figure, estimated by using the conventional Chinese IO table). In addition, we find that firms engaged in processing trade contribute only a very small portion of China's total GDP and CO_2 emissions, with much lower carbon intensity (0.8 and 0.2 kg per US$ for Chinese and foreign-owned firms conducting processing trade, respectively).

The difference of CO_2 emissions and carbon intensity across firms at the national level shown in Fig. 1 depends on at least two factors: (1) Different types of firms may sell very different types of products according to market entry regulations or their market strategies in China. (2) Different types of firms, which are allocated to the same IO sector, may use different technologies to produce their products. To explain this in detail, we pick the top five sectors whose emissions account for 80.9% of China's national emissions (aggregating all the other 37 sectors into one sector) and show the estimation results of production-based CO_2 emissions and GDP at the sector level for different types of firms along with their carbon intensity in Table 1. Not surprisingly a large share (31.4%) of China's CO_2 emissions are from producing Electricity and steam which are almost entirely (98.1%) produced by Chinese-owned firms conducting non-processing trade. This can partly explain why CN has the largest share in total emissions with the highest carbon intensity as shown in Fig. 1. From Table 1, we also find that both Chinese and foreign-owned firms conducting non-processing trade have higher carbon intensity at all sector levels than firms conducting processing trade. This is because production for processing trade uses a higher share of imported intermediate goods.

3.2. Ignoring firm heterogeneity information leads to a significant error in estimating embodied CO_2 emissions in Chinese exports

In this paper, we assume that the estimation of production-based CO_2 emissions depends on only the amount of energy used, no matter what type of firm uses this energy. In other words, there is no difference in CO_2 emissions generated by different types of firms when they burn the same amount of a specific type of energy. Therefore, the difference of energy efficiency across firms is reflected in the magnitude of energy use per output. This also

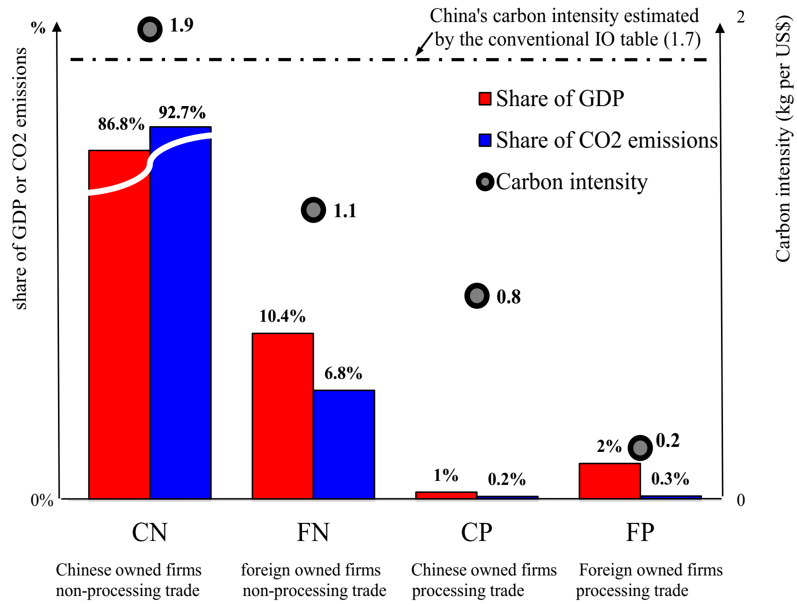

Fig. 1. China's CO_2 emissions, GDP and carbon intensity by firm type.

Table 1
Production-based CO_2 emissions, GDP share and carbon intensity.

CO_2 emissions (Kt)	CN	CP	FN	FP	Sum	Share by industry	Share of foreign-owned firms
Electricity and steam	1,888,357	0	14,707	336	1,903,400	31.4%	0.8%
Metal smelting products	825,538	1,212	69,102	503	896,355	14.8%	7.8%
Chemical	723,971	8,465	136,624	3,236	872,296	14.4%	16.0%
Non-metallic mineral products	620,405	535	60,713	291	681,944	11.2%	8.9%
Transportation and warehousing	546,028	0	13,293	0	559,321	9.2%	2.4%
Other sector aggregate	1,021,002	4119	119,543	12,127	1,156,791	19.1%	11.4%
Sum	5,625,301	14,331	413,982	16,493	6,070,107	100.0%	7.1%
Share by firm type	92.7%	0.2%	6.8%	0.3%	100.0%		
GDP (million US$)	CN	CP	FN	FP	Sum	Share by industry	Share of foreign-owned firms
Electricity and steam	113,954	0	1751	107	115,812	3.3%	1.6%
Metal smelting products	143,957	696	11,398	760	156,812	4.5%	7.8%
Chemical	128,481	2027	29,890	5145	165,542	4.7%	21.2%
Non-metallic mineral products	73,224	108	8048	973	82,352	2.4%	11.0%
Transportation and warehousing	192,659	0	4302	0	196,961	5.6%	2.2%
Other sector aggregate	2,384,630	14,980	307,080	73,185	2,779,875	79.5%	13.7%
Sum	3,036,906	17,811	362,469	80,170	3,497,355	100.0%	12.7%
Share by firm type	86.8%	0.5%	10.4%	2.3%	100.0%		
Carbon intensity (Kt/Million US$)	CN	CP	FN	FP	National average		
Electricity and steam	16.6		8.4	3.1	16.4		
Metal smelting products	5.7	1.7	6.1	0.7	5.7		
Chemical	5.6	4.2	4.6	0.6	5.3		
Non-metallic mineral products	8.5	5.0	7.5	0.3	8.3		
Transportation and warehousing	2.8		3.1		2.8		
Other sector aggregate	0.4	0.3	0.4	0.2	0.4		
National average	1.9	0.8	1.1	0.2	1.7		

Note: CN denotes Chinese-owned firms conducting non-processing trade, FN denotes foreign-owned firms conducting non-processing trade, CP denotes Chinese-owned firms conducting processing trade, and FP denotes foreign-owned firms conducting processing trade.

means that introducing firm heterogeneity information to the conventional IO table does not change the estimation of production-based emissions at either the sector or national levels, but it may provide different estimation results for embodied CO_2 emissions in exports and domestic final demands. As shown in Fig. 2, at the national level, using the conventional IO table causes an overestimation of embodied CO_2 emissions in Chinese exports by about 20% and an underestimation of embodied CO_2 emissions in China's domestic final demands by about 7%.

At the sector level, there are two approaches to tracing emissions in exports throughout domestic supply chains: from downstream to upstream and from upstream to downstream. These are also referred to as backward and forward linkages defined in the literature related to "Trade in Value-added" [35,36]. Fig. 3 are the estimation results using these two different input–output approaches. It shows that by tracing emissions from downstream to upstream (the left side of Fig. 3), emissions embodied in exports are mainly contributed from manufacturing sectors, (e.g., Chemical, Computer, Metal smelting, Textile, and Machinery and equipment), while embodied emissions in exports from the Electricity and steam sector are relatively smaller as there is a very small amount of electricity directly being exported to other

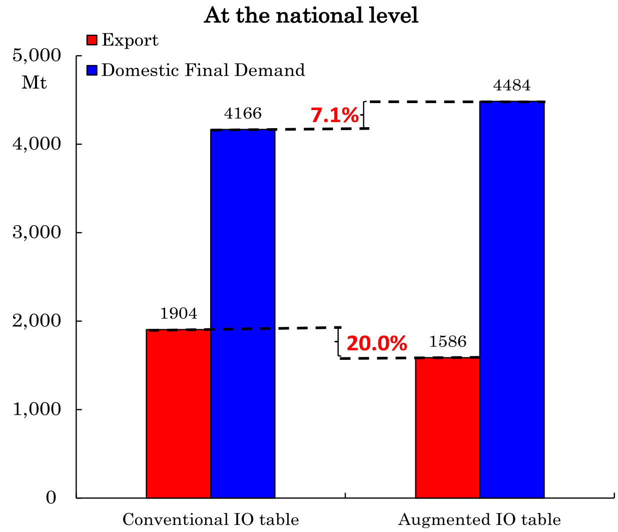

Fig. 2. Discrepancy in the estimation of embodied CO_2 emissions in Chinese exports when ignoring firm heterogeneity information.

countries. For example, more than 99% of Chinese electricity is for domestic use rather than for exports in 2007. However, when we look at emissions in the upstream supply chain for export production, (the right side of Fig. 3), the electricity sector is the single largest emitting sector accounting for 30.4% of the total emissions associated with China's exports. This is not only because the carbon intensity of this sector is the highest, but also reflects the fact that electricity is used as an intermediate input in numerous downstream sectors and ultimately supports all Chinese exports.

The impact of introducing firm heterogeneity to estimating embodied emissions in Chinese exports at the sector level for both approaches is shown in Fig. 4. The degree of discrepancy across sectors shows large variation. Some sectors' discrepancies are much larger than that the national level. In addition, we can find a huge difference between the two approaches.

In order to provide a more detailed explanation these discrepancies shown in Figs. 2 and 4, we calculated embodied CO_2 emissions per unit of export by firm type. The estimation results are shown in Table 2. Clearly, CN's figures for most sectors are larger than the figures estimated from the conventional IO table, while CP, FN, and FP's figures are smaller than that of estimation from the conventional IO table. Therefore, using the assumption of average production technology (i.e., ignoring firm heterogeneity) to estimate embodied CO_2 emissions in Chinese exports will give an underestimation for Chinese-owned firms conducting non-processing trade but a significant overestimation for foreign-owned firms and firms involved in processing trade. This overestimation is dominant for two reasons: One is based on the fact that 42.9% of Chinese exports were processing trade, of which 84.2% were produced by foreign-owned firms. Another factor is that the gap in carbon intensity between FP and the national average from the conventional IO is larger than the difference between CN and the national average, thus the overestimation will be much larger than the underestimation.

3.3. Embodied CO_2 emissions in foreign-owned firms' exports are mainly from domestic production in China

Foreign-owned firms' CO_2 emissions only account for 7.1% of China's total CO_2 emissions (see Table 1), but according to our estimation, CO_2 emissions induced by foreign-owned firms account for 32.4% of the total embodied CO_2 emissions in Chinese exports. To explain this phenomenon, we need a supply chain-based analysis. Embodied CO_2 emissions in exports can be induced mainly through two stages of domestic supply chains. In one stage, emissions may be directly induced in the production process by firms that directly produce exports. In the other, emissions may be indirectly induced in the production process of intermediate goods by firms who are located upstream in the export supply chains. On the other hand, domestic value-added embodied in exports is also induced through the same stages. This provides a useful tool for investigating the carbon intensity of embodied CO_2 emissions in Chinese exports along domestic supply chains (a detailed definition is given by Eqs. (5, 8, and 9) in Section 2).

Fig. 5 shows both emission flows induced by exports and their carbon intensity along each flow in the domestic supply chains. For simplicity, we separate the domestic supply chains into two

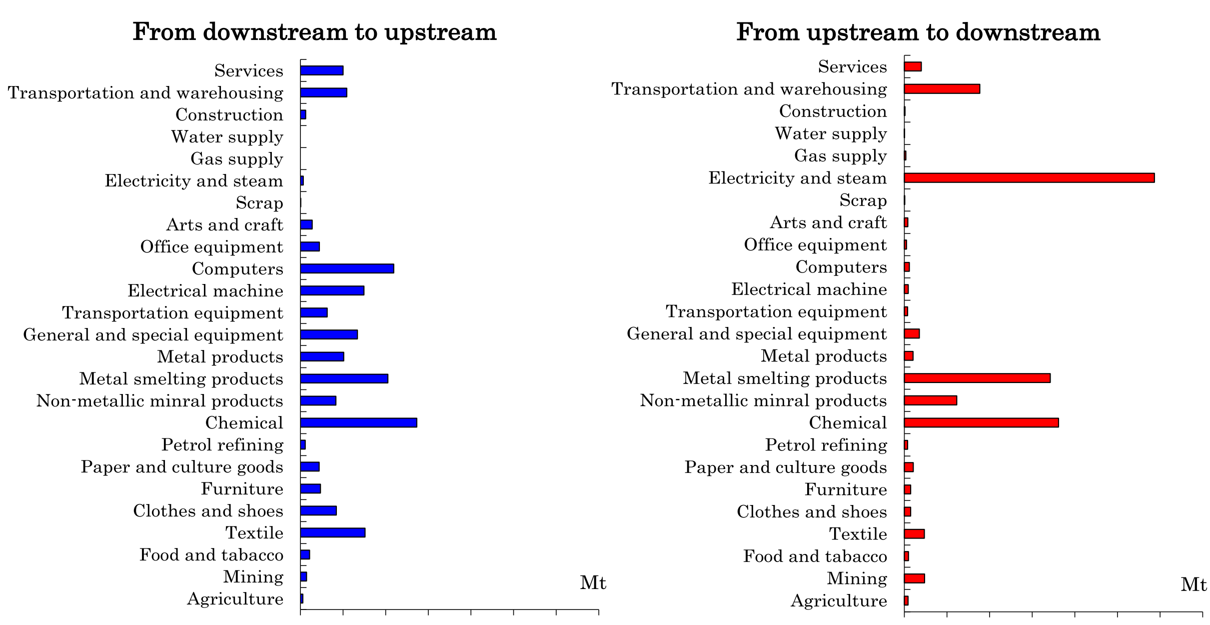

Fig. 3. Tracing embodied CO_2 emissions in Chinese exports throughout domestic supply chains.

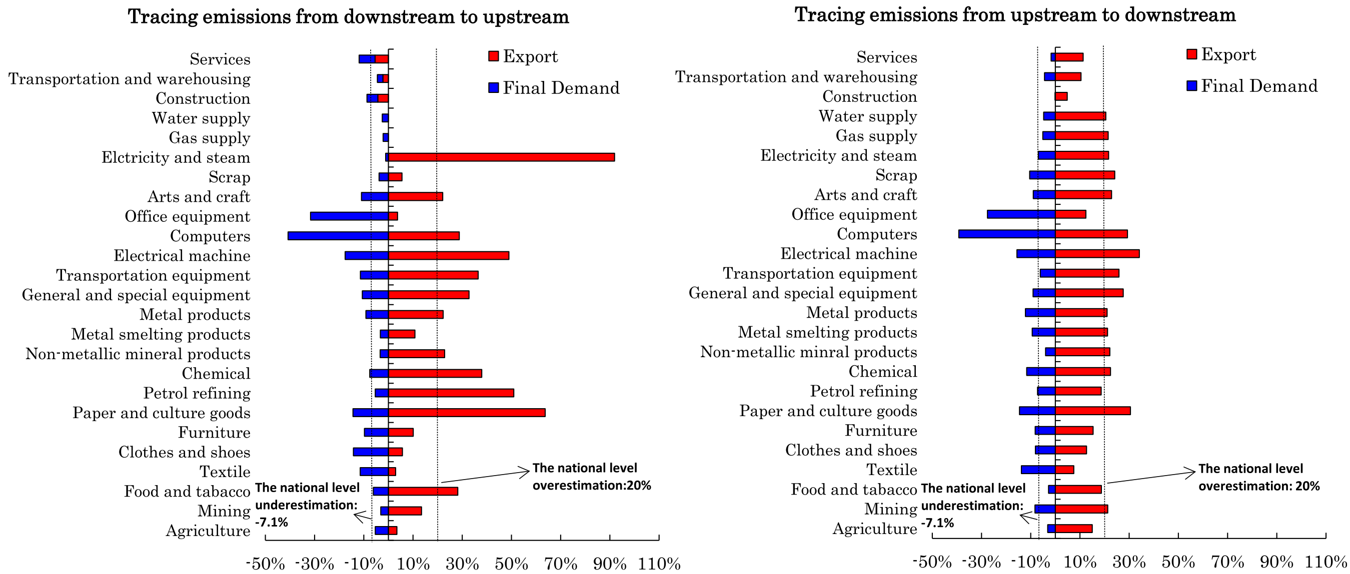

Fig. 4. Error in estimating embodied CO_2 emissions in Chinese exports at the sector level using backward linkage (left panel) and forward linkage analysis (right panel).

Table 2
Embodied CO_2 emissions per US$ of export by firm type.

Firm type Sector	Based on the augmented IO table				Based on the conventional IO table
	CN	CP	FN	FP	
Agriculture	0.71	–	0.41	–	0.66
Mining	2.03	–	0.97	–	1.94
Food and tobacco	0.99	0.32	1.04	0.10	0.96
Textile	1.81	1.34	1.75	0.72	1.72
Clothes and shoes	1.48	1.20	1.47	1.05	1.39
Furniture	1.82	0.64	1.87	1.41	1.77
Paper and culture goods	1.99	1.40	1.54	1.02	1.86
Petrol refining	1.63	0.22	1.64	0.24	1.59
Chemical	3.82	4.18	3.60	0.63	3.76
Non-metallic mineral products	5.02	4.96	4.83	0.30	5.02
Metal smelting products	3.98	1.74	4.03	0.66	3.99
Metal products	2.86	0.54	2.88	1.69	2.81
General and special equipment	2.39	0.28	2.32	0.03	2.31
Transportation equipment	2.00	1.45	1.89	0.04	1.91
Electrical machine	2.49	1.89	2.49	1.50	2.39
Computers	1.65	0.92	1.87	1.43	1.56
Office equipment	1.94	1.55	2.05	1.84	1.82
Arts and craft	2.07	1.53	2.02	0.87	1.98
Scrap	0.28	0.55	0.21	0.04	0.26
Electricity and steam	8.85	–	6.83	3.14	8.99
Gas supply	–	–	–	–	–
Water supply	–	–	–	–	–
Construction	2.72	–	1.70	–	2.69
Transportation and warehousing	2.36	–	2.53	–	2.35
Services	0.99	0.47	1.01	0.25	0.94

Note: CN denotes Chinese-owned firms conducting non-processing trade, FN denotes foreign-owned firms conducting non-processing trade, CP denotes Chinese-owned firms conducting processing trade, and FP denotes foreign-owned firms conducting processing trade.

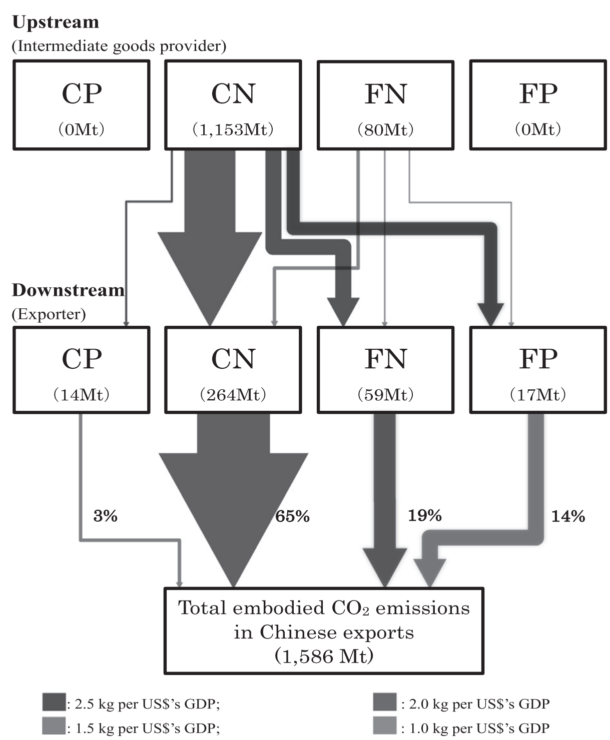

Fig. 5. Flow of CO_2 emissions induced by Chinese exports along supply chains. *Note:* CN denotes Chinese-owned firms conducting non-processing trade, FN denotes foreign-owned firms conducting non-processing trade, CP denotes Chinese-owned firms conducting processing trade, and FP denotes foreign-owned firms conducting processing trade. Figures in parentheses for upstream firms indicate the indirectly induced emissions downstream indicating the direct emissions happening in the production of exports.

stages, upstream and downstream as shown in Fig. 5. The downstream firms include only those exporting firms closer to foreign users than the upstream firms which provide intermediate goods to these exporting firms directly and indirectly. In the figure, arrow size represents the magnitude (in Mt) of embodied CO_2 flows; the shade of gray provides carbon intensity (kg per US$ value-added). Obviously, most CO_2 emissions in Chinese exports originally come from Chinese-owned firms conducting non-processing trade and are located upstream in the supply chain. This is due to the fact that intermediate goods (particularly electricity) with high carbon intensity used by downstream firms for exports are mainly produced by Chinese-owned firms. However, when comparing the carbon intensity of embodied emissions between different supply chain routes (expressed through the shade of gray in the upper part of this figure), one can see that the induced emissions by foreign-owned firms' exports are more carbon-intensive than those by Chinese-owned firms. (For detailed sectoral-level results concerning inter-firm flow of carbon induced by Chinese exports, one can refer to Supplementary Information 2).

4. Discussion and conclusion

We have shown that adding information about firm ownership and type of traded goods to the conventional 2007 Chinese IO table can significantly improve the accuracy and our understanding of the estimation of embodied CO_2 emissions in exports. Our results show that ignoring firm heterogeneity may cause a 20% overestimation of embodied CO_2 emissions in Chinese exports at the national level with huge differences at the sector level. This is mainly due to the fact that different types of firms which are allocated to the same sector of the conventional Chinese IO table vary greatly in terms of their market share, production technology and carbon intensity; however, this fact has been ignored in most existing estimations.

As shown in the paper, introducing firm heterogeneity information into a supply chain-based analysis can greatly enrich our understanding of the impact of economic globalization on the environment through international trade. For example, about 80% of embodied CO_2 emissions in foreign-owned firms' exports are mainly from Chinese-owned firms. An important fact behind this finding is that the electricity sector, which is the most important energy provider situated upstream in Chinese domestic supply chains, is under the strong control of Chinese-owned firms (enabled through high entry-barriers for foreign investors) resulting in high carbon intensities. On the other hand, the carbon intensity of foreign-owned firms for producing electricity is about half of that of Chinese-owned firms, but their share in China's electricity market is just 1.6% (see Table 1). China's accession to the WTO greatly enhanced foreign firms' participation in downstream sectors that are closer to final products such as computers, since historically these sectors were seen as 'sunrise industries' (i.e., industries that are new and growing fast and therefore expected to be important in the future), and thus had relatively lower levels of state control. At the same time, entry barriers for both foreign firms and private firms are still high in most upstream sectors, and particularly in the electricity sector. The higher entry barrier reduces the level of market competition as well as international technology transfer in the relevant upstream sectors. In addition, most energy-related upstream sectors in China are mainly controlled by state-owned firms with relatively high levels of support coming from government subsidies and carbon-reduction regulation is weaker than that applied internationally. As a result, more emissions happen in basic industries that are situated upstream of export production supply chains. In other words, the competitiveness of exports labeled as "Made in China" is partly due to the huge externalities generated by upstream firms.

With regards to China's national plan and targets on carbon emission mitigation, most policies in China focus on key sectors at both national and provincial levels, but rarely consider firm heterogeneity in terms of ownership, firm size and trading pattern as well as the interactions across different types of firms from a value-chain perspective. As shown in the paper, different types of firms located in the same IO sector may have very different technologies and carbon intensity, ignoring this difference not only causes large overestimation in consumption based emission indictors, but may also lead to uninformed policy making with negative, unexpected side effects.

The availability of Chinese IO data on firm heterogeneity was an important precondition to perform this type of research. The same method and estimation can also be applied to other countries, which would be especially relevant for many developing countries that also have a relatively large share of processing trade in their exports, such as Mexico and Vietnam, or have relatively large differences in terms of production technologies, energy efficiencies across types of firms. In other words, the large estimation discrepancy of embodied CO_2 emissions found in the case of China is likely to be an issue in other countries. We hope this study can provide a touchstone for attracting more attention to use firm-level information and supply-chain based analytical tools to have better understanding on energy use and global CO_2 emission mitigation.

Author contributions

Yu Liu and Bo Meng conceived and designed the research. Liu Yu calculated the data. Liu Yu, Bo Meng, Klaus Hubacek analyzed the data. Klaus Hubacek, Jinjun Xue, Kuishuang Feng performed the research. Yuning Gao contributed materials and calculation results for supplementary information. All authors contributed to writing the paper.

Competing financial interests

The authors declare no competing financial interests.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2016.06.088.

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