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March 30, 2016

Abstract: 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 firm 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 of 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.

Keywords: embodied CO_2 emissions, carbon intensity, supply chains, ownership, processing trade

JEL classification: E01, F18; C67; F64, H23

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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 firm 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 of 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.

Keywords: embodied CO_2 emissions in exports, carbon intensity, supply chain, firm heterogeneity, ownership, processing trade

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China has been the world's largest emitter of CO_2 since 2006[1] (BP, 2015). 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] (Rogelj et al., 2009). Recent evidence[3] (Meng et al., 2014) shows that about 30% (1,971 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] (Peters et al., 2007; Weber et al., 2008; Guan et al., 2008; Guan et al., 2009). 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[5, 8-14] (e.g., Weber et al., 2008; Christopher et al., 2008; Pan et al., 2008; Su and Ang, 2010; Xu et al., 2011; Feng et al., 2012; Su and Ang, 2013, 2014). 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[15] (see Miller and Blair, 2009) 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 depends heavily on the sector's position in supply chains[3] (Meng et al., 2014). 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[16] (EUSME, 2011), 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 iPhone 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 they do 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[17] (Ma et al., 2015) and given the higher carbon intensity of domestic production[18] (Liu et al., 2015), 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. (2012)[19] and Su et al. (2013)[20] 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, the target years of their data are 1997 and 2002, and there is no explicit information about firm ownership. Jiang et al. (2015)[21] 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. (2015)[17]. In this paper, we use the same database (Ma et al., 2015), but investigate embodied emissions in Chinese exports from detailed supply-chain perspectives at the national, sector, and inter-firm level.

We first show the production-based emissions[22-25] (see IPCC, 2006; Peters, 2008; Peters and Hertwich, 2008, Davis and Caldeira, 2010), 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 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. (2013)[26] and Prell et al. (2014)[27] 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.

Results

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). Figure 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 level (1.7 kg per US$: the upper dotted line of the figure, estimated by using the conventional Chinese IO table). In addition, we can find that firms engaged in processing trade contribute only a very small portion of China's total GDP and CO_2 emissions, with much lower carbon intensity (0.8 and 0.2 kg per US$ for Chinese and foreign-owned firms conducting processing trade, respectively).

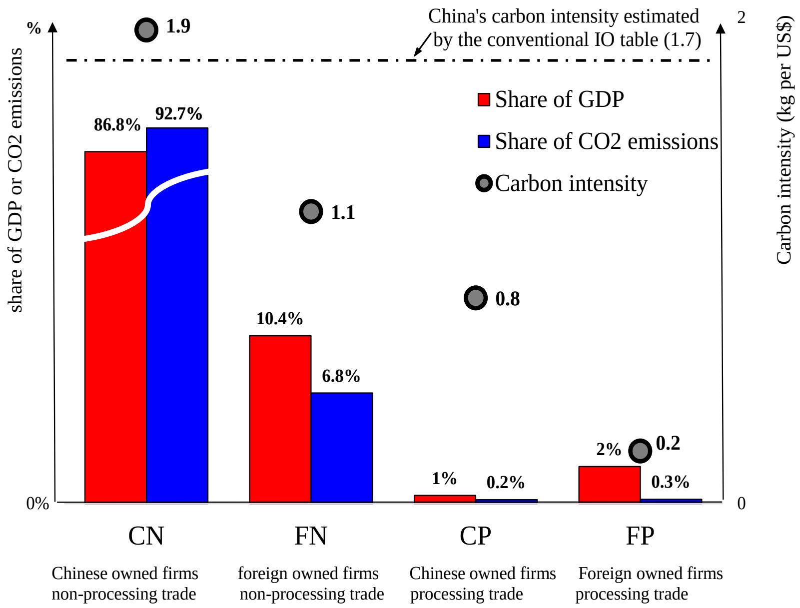


Figure 1 | China's CO_2 emissions, GDP and carbon intensity by firm type

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

CO2 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	4,119	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$)	CN	CP	FN	FP	Sum	Share by industry	Share of foreign-owned firms
Electricity and steam	113,954	0	1,751	107	115,812	3.3%	1.6%
Metal smelting products	143,957	696	11,398	760	156,812	4.5%	7.8%
Chemical	128,481	2,027	29,890	5,145	165,542	4.7%	21.2%
Non-metallic mineral products	73,224	108	8,048	973	82,352	2.4%	11.0%
Transportation and warehousing	192,659	0	4,302	0	196,961	5.6%	2.2%
Other sector aggregate	2,384,630	14,980	307,080	73,185	2,779,875	79.5%	13.7%
Sum	3,036,906	17,811	362,469	80,170	3,497,355	100.0%	12.7%
Share by firm type	86.8%	0.5%	10.4%	2.3%	100.0%		
Carbon intensity (Kt/Million US$)	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.

The difference of CO_2 emissions and carbon intensity across firms at the national level shown in Figure 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 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 Figure 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 more imported intermediate goods rather than producing these goods inside China.

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 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 Figure 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%.

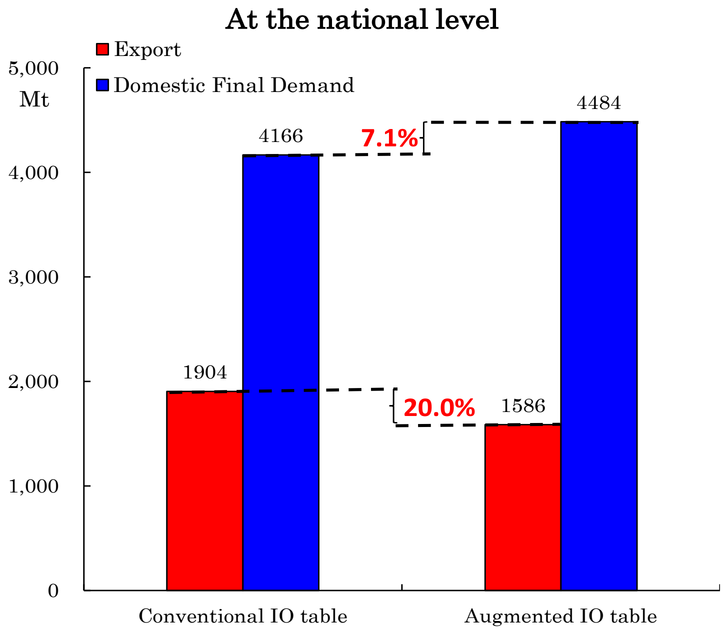


Figure 2 | Discrepancy in the estimation of embodied CO2 emissions in Chinese exports when ignoring firm heterogeneity information

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 backward and forward linkages defined in literature related to "Trade in Value-added"[28, 29] (Koopman et al., 2014; Wang et al., 2013). Figure 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 Figure 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 are relatively smaller as there is very small amount of electricity directly being exported to other 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 Figure 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.

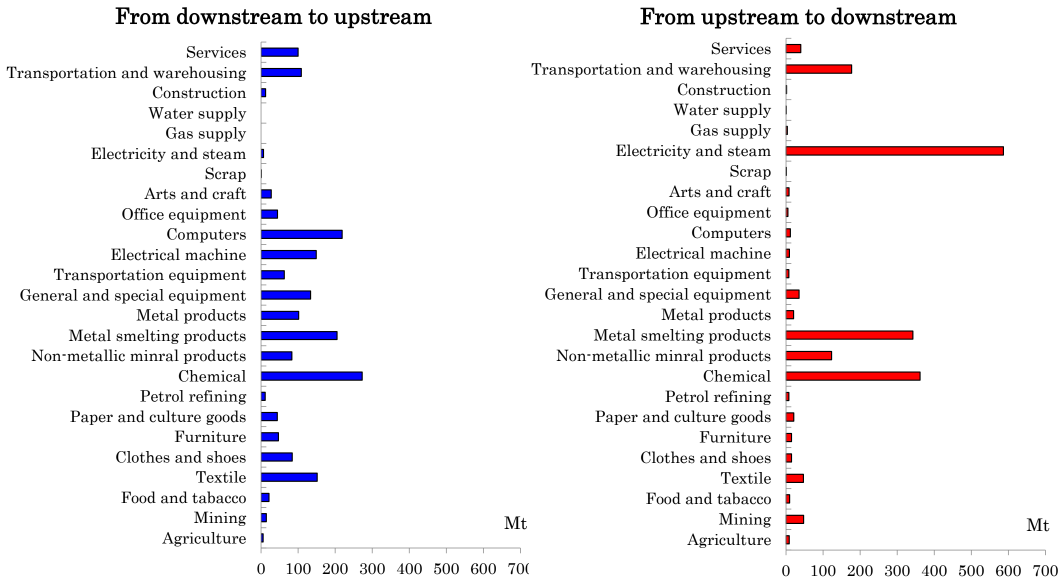


Figure 3 | Tracing embodied CO_2 emissions in Chinese exports throughout domestic supply chains

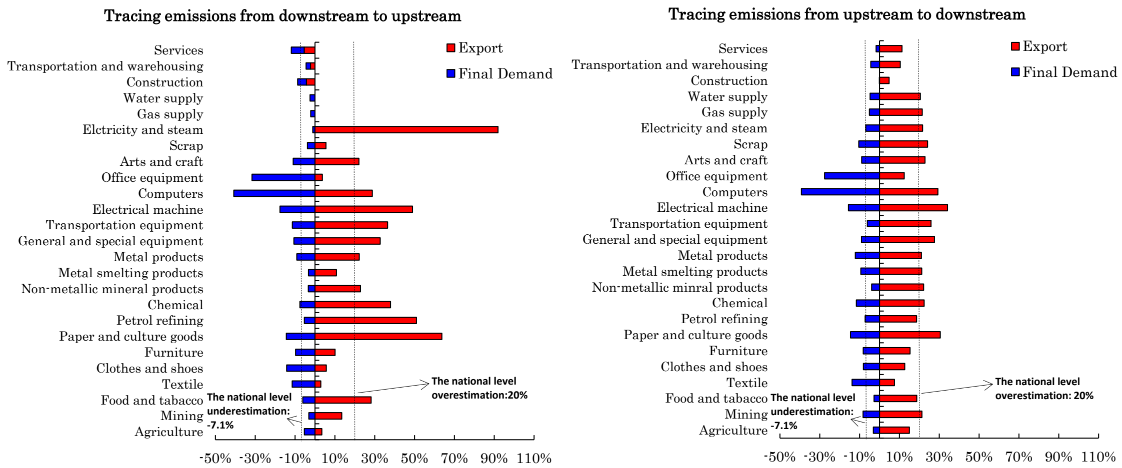


Figure 4 | Error in estimating embodied CO_2 emissions in Chinese exports at the sector level using backward linkage (left panel) and forward linkage analysis (right panel)

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

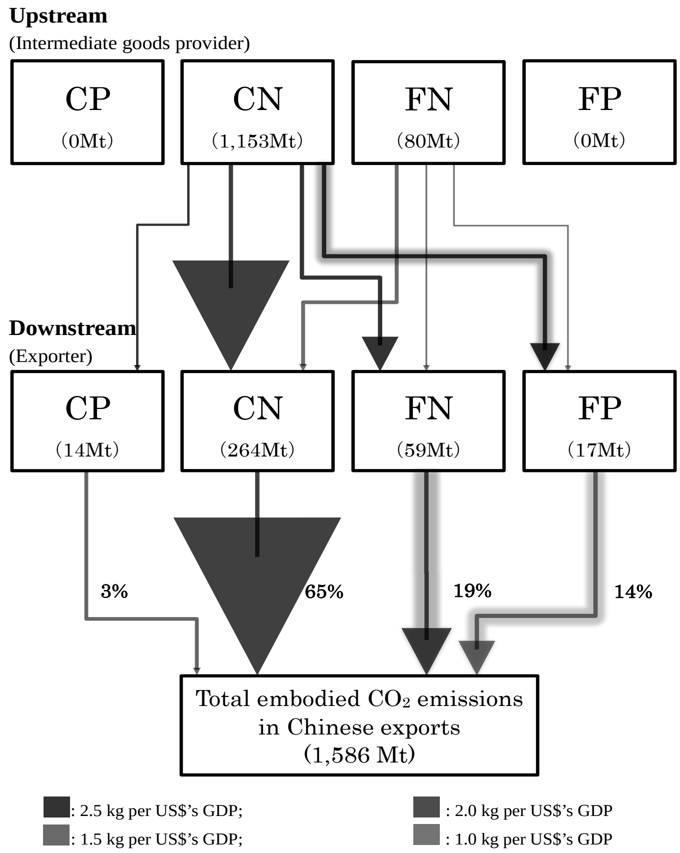
In order to give a more detailed explanation to the occurrence of the discrepancies shown in Figures 2 and 4, we calculated embodied CO_2 emissions per unit of export for product by firm type. The estimation results are shown in Table 2. Clearly, CN's figures for most sectors are larger than the figures 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 the 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 conducting processing trade. This overestimation is dominant for 2 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.

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

Firm type / Sector	Based on the augmented IO table: CN	CP	FN	FP	Based on the conventional IO table
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.

Embodied CO_2 emissions in foreign-owned firms' exports are mainly from Chinese-owned firms' domestic sources



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, for downstream indicate the direct emissions happened in the production process of producing exporting goods.

Figure 5 | Flow of CO_2 emissions induced by Chinese exports along supply chains

Foreign-owned firms' CO_2 emissions generated in their production process 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 channels of domestic supply chains. In one channel, 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 supply chains of export production. On the other hand, domestic value-added embodied in exports is also induced through the same channels. 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 equations (5), (8), and (9) in the Method section).

Figure 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 parts, upstream and downstream as shown in Figure 5. The downstream firms include only those exporting firms closer to foreign consumers 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).

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 CO2 emissions in Chinese exports at the national level with huge differences resulting 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.

Furthermore, 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 foreign 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.

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[15,30] (Miller and Blair, 2009; Murray and Wood, 2010). Due to its ability to provide a life cycle perspective from 'cradle to grave' by accounting for impacts of the full upstream supply chain IOA has become an important approach for estimating embodied emissions in trade[4,6,7,12] (e.g., Peters et al., 2007; Guan et al., 2008, 2009; Feng et al., 2012). Using an environmentally extended IO model (EIO), embodied CO_2 emissions in exports at the national level can be estimated as follows[15] (for details see Miller and Blair, 2009):

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

where, $CO_{2\,exp}$ is a scalar representing the total CO_2 emissions embodied in exports; $\mathbf{c}$ is a 1×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×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×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 ($D \rightarrow U$) or from upstream to downstream ($U \rightarrow D$):

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

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 $\mathbf{CO}_{2\,exp}^{D\rightarrow U}$ 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 $\mathbf{CO}_{2\,exp}^{U\rightarrow D}$ 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 equation (1) by the value-added rate $\mathbf{v}$ (a 1×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.

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

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

$$P = CO_{2\,\text{exp}}/\text{GDP}_{\text{exp}}. \tag{5}$$

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

$$\mathbf{GDP}_{\text{exp}}^{\text{D}\to\text{U}} = \mathbf{v} \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \text{diag}(\mathbf{e}), \tag{6}$$
$$\mathbf{GDP}_{\text{exp}}^{\text{U}\to\text{D}} = \text{diag}(\mathbf{v}) \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{e}. \tag{7}$$

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

$$\mathbf{P}^{\text{D}\to\text{U}} = \mathbf{CO}_{2\,\text{exp}}^{\text{D}\to\text{U}} // \mathbf{GDP}_{\text{exp}}^{\text{D}\to\text{U}} = [\mathbf{c} \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \text{diag}(\mathbf{e})] // [\mathbf{v} \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \text{diag}(\mathbf{e})], \tag{8}$$
$$\mathbf{P}^{\text{U}\to\text{D}} = \mathbf{CO}_{2\,\text{exp}}^{\text{U}\to\text{D}} // \mathbf{GDP}_{\text{exp}}^{\text{U}\to\text{D}} = \mathbf{c} // \mathbf{v}. \tag{9}$$

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. (2015)[17]: 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] (Peters et al., 2006) 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 types: 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 type 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 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.

Supplementary Information 1 | Sector classification

42 Sectors	Sector name	25 Sectors	Sector name
1	Agriculture	1	Agriculture
2	Coal mining	2	Mining
3	Crude oil and gas mining		
4	Metal mining		
5	Non-metal and other mining		
6	Food and tabacco	3	Food and tabacco
7	Textile	4	Textile
8	Clothes and shoes	5	Clothes and shoes
9	Furniture	6	Furniture
10	Paper and culture goods	7	Paper and culture goods
11	Petrol refining	8	Petrol refining
12	Chemical	9	Chemical
13	Non-metallic mineral products	10	Non-metallic mineral products
14	Metal smelting products	11	Metal smelting products
15	Metal products	12	Metal products
16	General and special equipment	13	General and special equipment
17	Transportation equipment	14	Transportation equipment
18	Electrical machine	15	Electrical machine
19	Computers	16	Computers
20	Meters and office equipment	17	Meters and office equipment
21	Arts and craft	18	Arts and craft
22	Scrap	19	Scrap
23	Electricity and steam supply	20	Electricity and steam
24	Gas supply	21	Gas supply
25	Water supply	22	Water supply
26	Construction	23	Construction
27	Transportation and warehousing	24	Transportation and warehousing
28	Post services		
29	Telecommunication, computer services and software	25	Services
30	Trade		
31	Hotel		
32	Finance		
33	Real Estate		
34	Leasing services		
35	Research		
36	Technical services		
37	Water, environment and public services		
38	Resident and other services		
39	Education		
40	Health, social security and welfare services		
41	Culture, sport and entertainment		
42	Public administration		

Supplementary information 2 | Additional results

Figure 5 gives the inter-firm relations at the national level for embodied emissions in exports. As mentioned in the Method section, at the national level, there is no difference in estimating embodied emissions in exports whether tracing emissions from downstream to upstream or vice versa. However, at the sector level, these two different approaches explain embodied emissions in exports in very different ways.

Table S1 shows the inter-firm relation of embodied emissions in exports traced from upstream to downstream at the sector level. For ease of explanation, we first compare the estimation results for Chinese-owned firms (CN) and foreign-owned firms (FN) involved in non-processing trade as shown in Table S1a. The figures in the second column of this table represent the amount of emissions generated by a specific sector of CN or are embodied in exports by the 4 types of downstream firms (at the head of the table) through domestic supply chains. Clearly, CN's Electricity and steam, and Transportation sectors are the most important contributors to export-related emissions, especially for CN. This is also reflected in Figure 5, which shows that the largest stream of carbon is associated with CN's exports. The Electricity and steam, and Transportation sectors for CN also contribute a large amount of emissions to FN and FP's exports. This can also be confirmed from Figure 5, in which two wide carbon flows from CN go to FN and FP's exports. Compared with CNs' sectors, the most heavily emitting sectors of FN are the Chemical and Metal sectors. Their emissions are mostly caused during production of FN's exports followed by production of CN and FP's exports. This fact can also be easily confirmed by referring to Figure 5. In addition, in Table S1a, we also show the embodied value-added in exports and the corresponding carbon intensity information in the last two columns. According to equation (9), at the sector level, the intensity (embodied emissions in exports / embodied value-added in exports) depends on the emitter's conventional intensity (sectoral emissions / sectoral GDP), independently of which exporters is considered. Therefore, the intensity figures in Table S1a are equal to those shown in Table 1.

For CP and FP's emissions embodied in exports, the relevant results are shown in Table S1b. Since firms conducting processing trade do not provide intermediate inputs to other firms in domestic supply chains, the emissions by Chinese-owned firms (CP) and foreign-owned firms (FP) involved in processing trade reflect only their own usage of energy in producing exports (i.e., there is no inter-firm transaction in Table S1b). This can also be seen in Figure 5. Thus, CP and FP's emissions are embodied in only their own exports.

Table S2 shows the inter-firm relations of embodied emissions in exports traced from downstream to upstream at the sector level. We also first compare CN and FN as shown in Table S2a. The figures in the second column of this table represent the amounts of emissions that are induced in the 4 types of upstream firms by CN or FN's exports of a specific product (on the left side of the table). Clearly, the exports of Textile, Chemical, Metal product and General and specific equipment are, for both CN and FN, the most important drivers of embodied emissions in domestic supply chains. The large figure for textiles is mainly due to the large scale of exports (13.4% of total Chinese exports), since producing textiles does not need much energy (carbon intensity is 1.1 Kt/Million US$) or high carbon intermediate inputs. The large figure for Chemical and Metal products is because of the relatively large scales of their exports (8.4% and 4.1% of total Chinese exports) and higher carbon intensity (5.6 and 5.7 Kt/Million US$). The large figure for General and specific equipment is due to the relatively large scale of exports (6.5% of total Chinese exports) as well as the large demand for high carbon intermediate inputs in its production process. On the other hand, the difference between the impacts of CN and FN's exports is that most emissions induced by CN's exports are from CN itself, while a large portion of emissions induced by FN's exports is also from CN. The main reason for this is that a large portion of the intermediate inputs (electricity, chemicals, non-metallic mineral products and so on) used in FN's export production is provided by CN. In addition, from the intensity information shown in the most right most section of this table, it is easy to see that for getting one unit of value-added through exports, there is no significant difference between CN and FN for most sectors (see the last column labeled 'sum'). However, for many sectors, FN's exports are more carbon intensive in inducing CN's emissions than CN's exports. This is why in Figure 5 the carbon flow from CN to FN is much darker than that from CN to CN. In addition since CP and FP never provide intermediate goods to CN and FN, no emissions from CP and FP are induced by CN and FN's exports.

For emissions embodied in CP and FP's exports, detailed results are shown in Table S2b. It is easy to see that the important drivers of emissions are the export of Clothes, Chemicals, Transportation equipment, Electrical products, and Computers for CP, and Clothes, Paper, Metal products, Computers, and Office equipment for FP. Similar to the situation seen in Table S2a, most emissions embodied in CP and FP's exported products are from CN. One difference is that emissions induced by some exported products, like Petrol, Chemicals, and Non-metallic mineral products, are only from CP or FP itself. This is due to the fact that intermediate inputs including energy goods used in CP and FP for producing these exports are mainly from imports rather than from domestic firms (this can be confirmed from the original data). In addition, according to the intensity figure (the last column of the table), the potential environmental cost in terms of emissions per unit of value-added from exports for CP and FP is much lower than that for CN and FN.

Table S1a | Embodied CO_2 emissions in exports traced from upstream to downstream (non-processing trade)

Exporter by firm type / Emitter by firm type and sector		Embodied emissions in exports (Kt)					Embodied value-added in exports (Million US$)					Intensity of embodied emissions in exports (Kt/Million US$)				
		CN	CP	FN	FP	Sum	CN	CP	FN	FP	Sum	CN	CP	FN	FP	Sum
CN	1 Agriculture	5,158	160	1,477	565	7,360	38,739	1,202	11,091	4,242	55,274	0.1	0.1	0.1	0.1	0.1
CN	2 Mining	26,124	751	6,968	4,546	38,389	33,846	946	8,748	5,851	49,391	0.8	0.8	0.8	0.8	0.8
CN	3 Food and tabacco	4,399	104	1,049	516	6,068	8,988	212	2,143	1,054	12,397	0.5	0.5	0.5	0.5	0.5
CN	4 Textile	28,596	611	3,341	1,322	33,870	25,767	550	3,011	1,192	30,519	1.1	1.1	1.1	1.1	1.1
CN	5 Clothes and shoes	7,585	86	456	283	8,410	10,901	123	656	407	12,087	0.7	0.7	0.7	0.7	0.7
CN	6 Furniture	6,875	104	1,212	762	8,952	6,437	97	1,135	713	8,381	1.1	1.1	1.1	1.1	1.1
CN	7 Paper and culture goods	8,541	366	2,291	2,158	13,356	7,014	301	1,882	1,772	10,969	1.2	1.2	1.2	1.2	1.2
CN	8 Petrol ref.	4,216	105	953	662	5,936	9,206	230	2,081	1,445	12,962	0.5	0.5	0.5	0.5	0.5
CN	9 Chemical	163,586	4,851	35,626	31,635	235,699	29,031	861	6,322	5,614	41,829	5.6	5.6	5.6	5.6	5.6
CN	10 Non-metallic mineral products	58,749	1,633	10,460	14,949	85,791	6,934	193	1,235	1,764	10,126	8.5	8.5	8.5	8.5	8.5
CN	11 Metal smelting products	174,563	5,862	41,374	32,480	254,280	30,440	1,022	7,215	5,664	44,341	5.7	5.7	5.7	5.7	5.7
CN	12 Metal products	8,821	236	1,576	1,984	12,616	8,976	240	1,603	2,019	12,838	1.0	1.0	1.0	1.0	1.0
CN	13 General and special equipment	16,683	377	2,845	1,863	21,767	16,807	379	2,866	1,877	21,929	1.0	1.0	1.0	1.0	1.0
CN	14 Transportation Equipment	3,430	154	594	305	4,484	8,657	389	1,499	770	11,315	0.4	0.4	0.4	0.4	0.4
CN	15 Electrical machine	3,038	92	537	618	4,284	7,575	229	1,338	1,540	10,682	0.4	0.4	0.4	0.4	0.4
CN	16 Computers	1,022	46	187	803	2,058	5,374	240	985	4,222	10,821	0.2	0.2	0.2	0.2	0.2
CN	17 Office equipment	986	25	162	191	1,365	1,998	50	329	387	2,765	0.5	0.5	0.5	0.5	0.5
CN	18 Arts and Craft	3,654	64	391	381	4,491	2,893	51	310	302	3,556	1.3	1.3	1.3	1.3	1.3
CN	19 Scrap	565	24	178	131	898	7,788	327	2,451	1,799	12,365	0.1	0.1	0.1	0.1	0.1
CN	20 Electricity and steam	301,983	11,164	92,124	72,737	478,008	18,223	674	5,559	4,389	28,846	16.6	16.6	16.6	16.6	16.6
CN	21 Gas supply	1,833	68	561	454	2,917	312	12	95	77	496	5.9	5.9	5.9	5.9	5.9
CN	22 Water supply	192	8	59	52	311	562	24	171	152	909	0.3	0.3	0.3	0.3	0.3
CN	23 Construction	1,173	8	59	49	1,289	1,573	10	79	65	1,728	0.7	0.7	0.7	0.7	0.7
CN	24 Transportation and warehousing	125,344	2,044	15,796	13,404	156,589	43,984	723	5,575	4,734	55,016	2.8	2.8	2.8	2.8	2.8
CN	25 Services	21,252	411	3,131	2,915	27,709	99,254	2,407	17,065	18,714	137,440	0.2	0.2	0.2	0.2	0.2
FN	1 Agriculture	112	4	117	14	247	1,747	60	1,833	213	3,854	0.1	0.1	0.1	0.1	0.1
FN	2 Mining	204	7	512	41	764	438	15	1,480	89	2,022	0.5	0.5	0.3	0.5	0.4
FN	3 Food and tabacco	636	21	1,156	105	1,918	1,109	37	2,014	182	3,342	0.6	0.6	0.6	0.6	0.6
FN	4 Textile	4,084	189	4,167	409	8,848	4,317	200	4,405	432	9,354	0.9	0.9	0.9	0.9	0.9
FN	5 Clothes and shoes	856	47	1,942	154	2,999	1,322	72	2,998	238	4,631	0.6	0.6	0.6	0.6	0.6
FN	6 Furniture	422	15	2,131	108	2,676	364	13	1,836	93	2,305	1.2	1.2	1.2	1.2	1.2
FN	7 Paper and culture goods	183	10	695	61	950	316	18	1,200	105	1,638	0.6	0.6	0.6	0.6	0.6
FN	8 Petrol Ref	189	5	127	33	354	400	11	270	70	751	0.5	0.5	0.5	0.5	0.5
FN	9 Chemical	20,350	880	21,146	5,738	48,113	4,452	192	4,626	1,255	10,526	4.6	4.6	4.6	4.6	4.6
FN	10 Non-metallic mineral products	2,847	143	9,580	1,309	13,880	377	19	1,270	174	1,840	7.5	7.5	7.5	7.5	7.5
FN	11 Metal smelting products	8,967	438	14,555	2,428	26,388	1,479	72	2,401	400	4,353	6.1	6.1	6.1	6.1	6.1
FN	12 Metal products	794	45	2,074	377	3,289	809	46	2,114	384	3,354	1.0	1.0	1.0	1.0	1.0
FN	13 General and special equipment	1,308	57	3,730	284	5,378	1,478	65	4,216	321	6,080	0.9	0.9	0.9	0.9	0.9
FN	14 Transportation Equipment	285	21	547	42	895	909	67	1,747	133	2,856	0.3	0.3	0.3	0.3	0.3
FN	15 Electrical machine	296	19	918	129	1,362	762	50	2,366	333	3,511	0.4	0.4	0.4	0.4	0.4
FN	16 Computers	544	75	800	1,311	2,730	2,098	288	3,087	5,056	10,529	0.3	0.3	0.3	0.3	0.3
FN	17 Office equipment	103	5	271	39	418	179	9	475	68	731	0.6	0.6	0.6	0.6	0.6
FN	18 Arts and Craft	308	17	965	102	1,393	271	15	849	90	1,225	1.1	1.1	1.1	1.1	1.1
FN	19 Scrap	33	1	14	8	57	651	28	277	155	1,111	0.1	0.1	0.1	0.1	0.1
FN	20 Electricity and steam	2,234	83	1,372	540	4,228	266	10	163	64	503	8.4	8.4	8.4	8.4	8.4
FN	21 Gas supply	61	2	19	15	97	13	1	4	3	21	4.5	4.5	4.5	4.5	4.5
FN	22 Water supply	76	3	23	20	122	270	12	82	73	437	0.3	0.3	0.3	0.3	0.3
FN	23 Construction	1	0	6	0	7	5	0	17	1	23	0.3	0.3	0.3	0.3	0.3
FN	24 Transportation and warehousing	1,386	50	2,054	326	3,815	448	16	661	106	1,231	3.1	3.1	3.1	3.1	3.1
FN	25 Services	2,061	82	5,003	574	7,720	10,684	447	16,474	3,409	31,014	0.2	0.2	0.3	0.2	0.2

Table S1b | Embodied CO_2 emissions in exports traced from upstream to downstream (processing trade)

Emitter by firm type and sector \ Exporter by firm type		Embodied emissions in exports (Kt)					Embodied value-added in exports (Million US$)					Intensity of embodied emissions in exports (Kt/Million US$)				
		CN	CP	FN	FP	Sum	CN	CP	FN	FP	Sum	CN	CP	FN	FP	Sum
CP	1 Agriculture	0	0	0	0	0	0	0	0	0	0					
CP	2 Mining	0	0	0	0	0	0	0	0	0	0					
CP	3 Food and tabacco	0	190	0	0	190	0	596	0	0	596		0.3			0.3
CP	4 Textile	0	619	0	0	619	0	1,161	0	0	1,161		0.5			0.5
CP	5 Clothes and shoes	0	571	0	0	571	0	1,363	0	0	1,363		0.4			0.4
CP	6 Furniture	0	81	0	0	81	0	338	0	0	338		0.2			0.2
CP	7 Paper and culture goods	0	419	0	0	419	0	790	0	0	790		0.5			0.5
CP	8 Petrol Ref	0	90	0	0	90	0	411	0	0	411		0.2			0.2
CP	9 Chemical	0	8,457	0	0	8,457	0	2,025	0	0	2,025		4.2			4.2
CP	10 Non-metallic mineral products	0	536	0	0	536	0	108	0	0	108		5.0			5.0
CP	11 Metal smelting products	0	1,213	0	0	1,213	0	696	0	0	696		1.7			1.7
CP	12 Metal products	0	155	0	0	155	0	286	0	0	286		0.5			0.5
CP	13 General and special equipment	0	237	0	0	237	0	838	0	0	838		0.3			0.3
CP	14 Transportation Equipment	0	454	0	0	454	0	1,933	0	0	1,933		0.2			0.2
CP	15 Electrical machine	0	408	0	0	408	0	1,816	0	0	1,816		0.2			0.2
CP	16 Computers	0	284	0	0	284	0	3,693	0	0	3,693		0.1			0.1
CP	17 Office equipment	0	267	0	0	267	0	969	0	0	969		0.3			0.3
CP	18 Arts and craft	0	308	0	0	308	0	502	0	0	502		0.6			0.6
CP	19 Scrap	0	1	0	0	1	0	1	0	0	1		0.6			0.6
CP	20 Electricity and steam	0	0	0	0	0	0	0	0	0	0					
CP	21 Gas supply	0	0	0	0	0	0	0	0	0	0					
CP	22 Water supply	0	0	0	0	0	0	0	0	0	0					
CP	23 Construction	0	0	0	0	0	0	0	0	0	0					
CP	24 Transportation and warehousing	0	0	0	0	0	0	0	0	0	0					
CP	25 Services	0	35	0	0	35	0	277	0	0	277		0.1			0.1
FP	1 Agriculture	0	0	0	0	0	0	0	0	0	0					
FP	2 Mining	0	0	0	0	0	0	0	0	0	0					
FP	3 Food and tabacco	0	0	0	89	89	0	0	0	928	928				0.1	0.1
FP	4 Textile	0	0	0	464	464	0	0	0	2,729	2,729				0.2	0.2
FP	5 Clothes and shoes	0	0	0	1,084	1,084	0	0	0	3,999	3,999				0.3	0.3
FP	6 Furniture	0	0	0	859	859	0	0	0	1,628	1,628				0.5	0.5
FP	7 Paper and culture goods	0	0	0	1,304	1,304	0	0	0	4,779	4,779				0.3	0.3
FP	8 Petrol ref.	0	0	0	52	52	0	0	0	219	219				0.2	0.2
FP	9 Chemical	0	0	0	3,230	3,230	0	0	0	5,134	5,134				0.6	0.6
FP	10 Non-metallic mineral products	0	0	0	291	291	0	0	0	975	975				0.3	0.3
FP	11 Metal smelting products	0	0	0	505	505	0	0	0	763	763				0.7	0.7
FP	12 Metal products	0	0	0	801	801	0	0	0	2,732	2,732				0.3	0.3
FP	13 General and special equipment	0	0	0	130	130	0	0	0	4,509	4,509				0.0	0.0
FP	14 Transportation equipment	0	0	0	60	60	0	0	0	1,592	1,592				0.0	0.0
FP	15 Electrical machine	0	0	0	773	773	0	0	0	6,918	6,918				0.1	0.1
FP	16 Computers	0	0	0	3,773	3,773	0	0	0	34,877	34,877				0.1	0.1
FP	17 Office equipment	0	0	0	2,429	2,429	0	0	0	5,994	5,994				0.4	0.4
FP	18 Arts and craft	0	0	0	258	258	0	0	0	1,057	1,057				0.2	0.2
FP	19 Scrap	0	0	0	1	1	0	0	0	20	20				0.0	0.0
FP	20 Electricity and steam	0	0	0	338	338	0	0	0	108	108				3.1	3.1
FP	21 Gas supply	0	0	0	0	0	0	0	0	0	0					
FP	22 Water supply	0	0	0	0	0	0	0	0	0	0					
FP	23 Construction	0	0	0	0	0	0	0	0	0	0					
FP	24 Transportation and warehousing	0	0	0	0	0	0	0	0	0	0					
FP	25 Services	0	0	0	48	48	0	0	0	1,184	1,184				0.0	0.0

Table S2a | Embodied CO_2 emissions in exports traced from downstream to upstream (non-processing trade)

Emitter by firm type / Experter by firm type and sector		Embodied emissions in exports (Kt)					Embodied value-added in exports (Million US$)					Intensity of embodied emissions in exports (Kt/Million US$)				
		CN	CP	FN	FP	Sum	CN	CP	FN	FP	Sum	CN	CP	FN	FP	Sum
CN	1 Agriculture	4,258	0	288	0	4,545	6,219	0	228	0	6,447	0.7		1.3		0.7
CN	2 Mining	10,620	0	368	0	10,989	5,158	0	254	0	5,412	2.1		1.5		2.0
CN	3 Food and tabacco	8,716	0	513	0	9,229	8,729	0	577	0	9,306	1.0		0.9		1.0
CN	4 Textile	108,249	0	8,409	0	116,658	58,155	0	6,438	0	64,593	1.9		1.3		1.8
CN	5 Clothes and shoes	47,259	0	4,282	0	51,542	30,905	0	3,856	0	34,761	1.5		1.1		1.5
CN	6 Furniture	23,001	0	1,370	0	24,371	12,388	0	990	0	13,378	1.9		1.4		1.8
CN	7 Paper and culture goods	11,966	0	699	0	12,665	5,871	0	478	0	6,349	2.0		1.5		2.0
CN	8 Petrol ref.	5,967	0	201	0	6,168	3,632	0	151	0	3,783	1.6		1.3		1.6
CN	9 Chemical	137,021	0	6,773	0	143,795	34,658	0	3,021	0	37,679	4.0		2.2		3.8
CN	10 Non-metallic mineral products	48,967	0	1,249	0	50,215	9,375	0	622	0	9,997	5.2		2.0		5.0
CN	11 Metal smelting products	147,433	0	4,201	0	151,635	35,849	0	2,296	0	38,144	4.1		1.8		4.0
CN	12 Metal products	51,337	0	2,456	0	53,793	17,479	0	1,300	0	18,779	2.9		1.9		2.9
CN	13 General and special equipment	67,206	0	3,502	0	70,708	27,276	0	2,273	0	29,549	2.5		1.5		2.4
CN	14 Transportation equipment	27,466	0	1,766	0	29,232	13,306	0	1,326	0	14,632	2.1		1.3		2.0
CN	15 Electrical machine	44,622	0	2,824	0	47,447	17,373	0	1,659	0	19,032	2.6		1.7		2.5
CN	16 Computers	18,499	0	1,407	0	19,906	10,523	0	1,524	0	12,047	1.8		0.9		1.7
CN	17 Office equipment	5,525	0	395	0	5,921	2,743	0	302	0	3,045	2.0		1.3		1.9
CN	18 Arts and craft	13,762	0	824	0	14,586	6,493	0	547	0	7,040	2.1		1.5		2.1
CN	19 Scrap	78	0	4	0	82	291	0	4	0	295	0.3		0.9		0.3
CN	20 Electricity and steam	2,001	0	15	0	2,016	216	0	12	0	228	9.3		1.3		8.8
CN	21 Gas supply	0	0	0	0	0	0	0	0	0	0					
CN	22 Water supply	0	0	0	0	0	0	0	0	0	0					
CN	23 Construction	11,872	0	697	0	12,568	4,299	0	318	0	4,617	2.8		2.2		2.7
CN	24 Transportation and warehousing	106,502	0	1,916	0	108,418	43,877	0	2,063	0	45,940	2.4		0.9		2.4
CN	25 Services	76,040	0	4,178	0	80,219	76,462	0	4,928	0	81,390	1.0		0.8		1.0
FN	1 Agriculture	537	0	123	0	660	319	0	1,308	0	1,628	1.7		0.1		0.4
FN	2 Mining	1,154	0	502	0	1,656	318	0	1,382	0	1,699	3.6		0.4		1.0
FN	3 Food and tabacco	5,741	0	1,338	0	7,080	4,739	0	2,088	0	6,827	1.2		0.6		1.0
FN	4 Textile	19,477	0	4,897	0	24,374	9,291	0	4,663	0	13,955	2.1		1.1		1.7
FN	5 Clothes and shoes	12,192	0	2,959	0	15,151	6,580	0	3,754	0	10,334	1.9		0.8		1.5
FN	6 Furniture	9,781	0	2,660	0	12,441	4,473	0	2,195	0	6,668	2.2		1.2		1.9
FN	7 Paper and culture goods	3,056	0	845	0	3,901	1,296	0	1,236	0	2,532	2.4		0.7		1.5
FN	8 Petrol ref.	1,036	0	117	0	1,153	504	0	197	0	702	2.1		0.6		1.6
FN	9 Chemical	25,650	0	16,713	0	42,363	7,648	0	4,118	0	11,765	3.4		4.1		3.6
FN	10 Non-metallic mineral products	7,596	0	9,082	0	16,678	2,099	0	1,357	0	3,456	3.6		6.7		4.8
FN	11 Metal smelting products	19,543	0	12,348	0	31,890	5,542	0	2,374	0	7,916	3.5		5.2		4.0
FN	12 Metal products	18,385	0	2,741	0	21,126	5,022	0	2,321	0	7,343	3.7		1.2		2.9
FN	13 General and special equipment	24,637	0	4,756	0	29,393	7,970	0	4,675	0	12,646	3.1		1.0		2.3
FN	14 Transportation equipment	9,332	0	1,097	0	10,429	3,545	0	1,963	0	5,508	2.6		0.6		1.9
FN	15 Electrical machine	22,094	0	2,256	0	24,351	6,843	0	2,929	0	9,772	3.2		0.8		2.5
FN	16 Computers	15,868	0	1,749	0	17,617	6,147	0	3,267	0	9,414	2.6		0.5		1.9
FN	17 Office equipment	2,622	0	444	0	3,066	920	0	573	0	1,493	2.9		0.8		2.1
FN	18 Arts and craft	3,972	0	1,151	0	5,123	1,591	0	949	0	2,541	2.5		1.2		2.0
FN	19 Scrap	11	0	4	0	15	8	0	66	0	74	1.4		0.1		0.2
FN	20 Electricity and steam	454	0	696	0	1,150	80	0	88	0	168	5.7		7.9		6.8
FN	21 Gas supply	0	0	0	0	0	0	0	0	0	0					
FN	22 Water supply	0	0	0	0	0	0	0	0	0	0					
FN	23 Construction	42	0	8	0	49	12	0	17	0	29	3.6		0.5		1.7
FN	24 Transportation and warehousing	747	0	1,707	0	2,454	392	0	577	0	969	1.9		3.0		2.5
FN	25 Services	19,482	0	5,729	0	25,211	10,105	0	14,769	0	24,874	1.9		0.4		1.0

Table S2b | Embodied CO_2 emissions in exports traced from downstream to upstream (processing trade)

Emitter by firm type / Exporter by firm type and sector		Embodied emissions in exports (Kt)					Embodied value-added in exports (Million US$)					Intensity of embodied emissions in exports (Kt/Million US$)				
		CN	CP	FN	FP	Sum	CN	CP	FN	FP	Sum	CN	CP	FN	FP	Sum
CP	1 Agriculture	0	0	0	0	0	0	0	0	0	0					
CP	2 Mining	0	0	0	0	0	0	0	0	0	0					
CP	3 Food and tabacco	0	190	0	0	190	0	596	0	0	596	2.1	0.3	0.1		0.3
CP	4 Textile	2,676	619	241	0	3,537	1,285	1,161	188	0	2,634	2.1	0.5	1.3		1.3
CP	5 Clothes and shoes	3,080	571	319	0	3,970	1,667	1,363	289	0	3,319	1.8	0.4	1.1		1.2
CP	6 Furniture	183	81	12	0	277	87	338	10	0	434	2.1	0.2	1.3		0.6
CP	7 Paper and culture goods	1,709	419	118	0	2,246	727	790	82	0	1,599	2.4	0.5	1.4		1.4
CP	8 Petrol Ref	0	90	0	0	90	0	411	0	0	411	2.3	0.2	0.0		0.2
CP	9 Chemical	0	8,457	0	0	8,458	0	2,025	0	0	2,025	2.2	4.2	0.6		4.2
CP	10 Non-metallic mineral products	0	536	0	0	536	0	108	0	0	108	2.2	5.0	0.0		5.0
CP	11 Metal smelting products	0	1,213	0	0	1,213	0	696	0	0	696	1.5	1.7	0.1		1.7
CP	12 Metal products	0	155	0	0	155	0	286	0	0	286	2.2	0.5	0.7		0.5
CP	13 General and special equipment	0	237	0	0	237	0	838	0	0	838	1.6	0.3	0.1		0.3
CP	14 Transportation equipment	5,336	454	362	0	6,152	2,028	1,933	274	0	4,235	2.6	0.2	1.3		1.5
CP	15 Electrical machine	7,421	408	484	0	8,313	2,299	1,816	288	0	4,402	3.2	0.2	1.7		1.9
CP	16 Computers	4,870	284	373	0	5,528	1,893	3,693	404	0	5,991	2.6	0.1	0.9		0.9
CP	17 Office equipment	2,747	267	213	0	3,227	955	969	160	0	2,083	2.9	0.3	1.3		1.5
CP	18 Arts and craft	1,208	308	88	0	1,604	487	502	59	0	1,048	2.5	0.6	1.5		1.5
CP	19 Scrap	0	1	0	0	1	0	1	0	0	1	2.1	0.6	0.6		0.6
CP	20 Electricity and steam	0	0	0	0	0	0	0	0	0	0					
CP	21 Gas supply	0	0	0	0	0	0	0	0	0	0					
CP	22 Water supply	0	0	0	0	0	0	0	0	0	0					
CP	23 Construction	0	0	0	0	0	0	0	0	0	0					
CP	24 Transportation and warehousing	0	0	0	0	0	0	0	0	0	0					
CP	25 Services	121	35	8	0	164	64	277	9	0	350	1.9	0.1	1.0		0.5
FP	1 Agriculture	0	0	0	0	0	0	0	0	0	0					
FP	2 Mining	0	0	0	0	0	0	0	0	0	0					
FP	3 Food and tabacco	0	0	0	89	89	0	0	0	928	928	2.1		0.1	0.1	0.1
FP	4 Textile	2,213	0	197	464	2,874	1,082	0	160	2,729	3,971	2.0		1.2	0.2	0.7
FP	5 Clothes and shoes	7,181	0	743	1,084	9,008	3,892	0	674	3,999	8,565	1.8		1.1	0.3	1.1
FP	6 Furniture	4,111	0	292	859	5,262	1,889	0	214	1,628	3,731	2.2		1.4	0.5	1.4
FP	7 Paper and culture goods	6,121	0	422	1,304	7,847	2,607	0	295	4,779	7,681	2.3		1.4	0.3	1.0
FP	8 Petrol ref.	0	0	0	52	52	0	0	0	219	219	2.3		0.0	0.2	0.2
FP	9 Chemical	0	0	0	3,230	3,230	0	0	0	5,134	5,134	1.6		0.3	0.6	0.6
FP	10 Non-metallic mineral products	0	0	0	291	291	0	0	0	975	975	2.1		0.1	0.3	0.3
FP	11 Metal smelting products	0	0	0	505	505	0	0	0	763	763	2.3		0.0	0.7	0.7
FP	12 Metal products	6,977	0	361	801	8,140	1,901	0	194	2,732	4,827	3.7		1.9	0.3	1.7
FP	13 General and special equipment	0	0	0	130	130	0	0	0	4,509	4,509	2.2		0.7	0.0	0.0
FP	14 Transportation equipment	0	0	0	60	60	0	0	0	1,592	1,592	1.8		0.2	0.0	0.0
FP	15 Electrical machine	17,815	0	1,155	773	19,742	5,526	0	695	6,918	13,139	3.2		1.7	0.1	1.5
FP	16 Computers	114,057	0	8,887	3,773	126,716	44,251	0	9,628	34,877	88,756	2.6		0.9	0.1	1.4
FP	17 Office equipment	26,031	0	2,021	2,429	30,480	9,066	0	1,521	5,994	16,581	2.9		1.3	0.4	1.8
FP	18 Arts and craft	984	0	70	258	1,312	402	0	49	1,057	1,509	2.4		1.4	0.2	0.9
FP	19 Scrap	0	0	0	1	1	0	0	0	20	20	2.1		0.3	0.0	0.0
FP	20 Electricity and steam	0	0	0	338	338	0	0	0	108	108	2.3		0.0	3.1	3.1
FP	21 Gas supply	0	0	0	0	0	0	0	0	0	0					
FP	22 Water supply	0	0	0	0	0	0	0	0	0	0					
FP	23 Construction	0	0	0	0	0	0	0	0	0	0					
FP	24 Transportation and warehousing	0	0	0	0	0	0	0	0	0	0					
FP	25 Services	277	0	19	48	344	147	0	20	1,184	1,351	1.9		1.0	0.0	0.3

Supplementary Information 3 | The augmented Chinese 2007 input-output table

		Demand on intermediate products				Domestic Final Demand	Export	Total Output
		Chinese-owned firms		Foreign-owned firms				
		Non-processing trade (CN)	Processing trade(CP)	Non-processing trade (FN)	Processing trade (FP)			
Chinese-owned firms	Non-processing trade (CN)	Z^{CNCN}	Z^{CNCP}	Z^{CNFN}	Z^{CNFP}	F^{CN}	E^{CN}	X^{CN}
	Processing trade (CP)	0	0	0	0	0	E^{CP}	X^{CP}
Foreign-owned firms	Non-processing trade (FN)	Z^{FNCN}	Z^{FNCP}	Z^{FNFN}	Z^{FNFP}	F^{FN}	E^{FN}	X^{FN}
	Processing trade (FP)	0	0	0	0	0	E^{FP}	X^{FP}
Import		Z^{MCN}	Z^{MCP}	Z^{MFN}	Z^{MFP}	F^{M}	0	0
Value-added		V^{CN}	V^{CP}	V^{FN}	V^{FP}			
Total Input		$(X^{CN})^{t}$	$(X^{CP})^{t}$	$(X^{FN})^{t}$	$(X^{FP})^{t}$			

Note: 1. Goods for non-processing includes domestic sales and normal exports. 2. Superscripts C and F represent Chinese-owned and foreign-owned firms respectively; M denotes imports; P and N indicate goods for processing trade and non-processing trade respectively. Z denotes intermediate input matrices, F denotes domestic final demands, E denotes exports, X represents gross output, and V is value added. For example an element in Z^{CNFN}, namely Z_{ij}^{CNFN} denotes the intermediate inputs produced by CN sector i and used by FN sectors j. It should be noted that the zero input from CP and FP to other firms is because all goods for processing are just used for exports according to the definition of processing trade (see EUSEM, 2011[16]). (The table has been modified from Ma et al., (2015)[17] who developed a constrained optimization method to construct the table by using the officially published Chinese 2007 IO table, the Annual Surveys of Industrial Production with firm-level information on balance sheet, production, ownership, etc. (from the National Bureau of Statistics of China) and the firm-level export and import data for 2007 (from China's General Administration of Customs)).

References

1. BP. BP Statistical Review of World Energy (2015).
2. Rogelj, J. *et al.* Halfway to Copenhagen, no way to 2°C. *Nature Reports Climate Change* **3,** 81–83 (2009).
3. Meng, B., Peters, G.P. & Wang, Z. Tracing CO_2 emissions in global value chains. *USITC Working Paper* (2014).
4. Peters, G.P., Weber, C.L., Guan, D. & Hubacek, K. China's growing CO_2 emissions - a race between lifestyle changes and efficiency gains. *Environ. Sci. Technol.* **41,** 5939–5944 (2007).
5. Weber, C.L., Peters, G.P., Guan, D. & Hubacek, K. The contribution of Chinese exports to climate change. *Energy Policy* **36,** 3572–3577 (2008).
6. Guan D., Peters, G.P., Weber, C.L. & Hubacek, K. The Drivers of Chinese CO_2 Emissions from 1980 to 2030. *Global. Environ. Change* **18,** 626–634 (2008).
7. Guan D., Peters, G.P., Weber, C.L. & Hubacek, K. Journey to world top emitter – an analysis of the driving forces of China's recent CO_2 emissions surge. *Geophys. Res. Lett.* **36,** L04709 (2009).
8. Christopher, L., Weber, H. & Scott, M. Quantifying the global and distributional aspects of American household carbon footprint. *Ecological Economics* 66, 379-391 (2008).
9. Pan, J., Phillips, J. & Chen, Y. China's balance of emissions embodied in trade: Approaches to measurement and allocating international responsibility. *Oxford. Rev. Econ. Pol.* **24,** 354–376 (2008).
10. Su, B. & Ang, B.W. 2010. Input–output analysis of CO2 emissions embodied in trade: the effects of spatial aggregation. Ecol. Econ. **70** (1), 10–18 (2010).
11. Xu, M., Li, R., John, C.C. & Chen, Y. CO_2 emissions embodied in China's exports from 2002 to 2008: A structural decomposition analysis. *Energy Policy* **39,** 7381–7388 (2011).
12. Feng, K., Siu, Y.L., Guan, D. & Hubacek, K. Analyzing drivers of regional carbon dioxide emissions for China a structural decomposition analysis. *J. Ind. Ecol.* **16,** 600–611 (2012).
13. Su, B. & Ang, B.W. Input–output analysis of CO_2 emissions embodied in trade: Competitive versus non-competitive imports. *Energy Policy* **56,** 83–87 (2013).
14. Su, B. & Ang, B.W. Input–output analysis of CO_2 emissions embodied in trade: A multi-region model for China. *Appl. Energy* **114,** 377–384 (2014).
15. Miller, R.E. & Blair, P.D. in *Input–Output Analysis: Foundations and Extensions* 2nd eds. (Cambridge Univ. Press, 2009).

16. EU SME Centre. Processing Trade in China (EUSME) (2011).
17. Ma, H., Wang, Z. & Zhu, K. Domestic content in China's exports and its distribution by firm ownership. *J. Comp. Econ.* **43,** 3–18 (2015).
18. Liu, Z. *et al.* Targeted opportunities to address the climate-trade dilemma in China. *Nature Clim. Change* (2015).
19. Dietzenbacher, E., Pei, J. & Yang, C. Trade, production fragmentation, and China's carbon dioxide emissions. *J. Environ. Econ. Manage* **64,** 88–101 (2012).
20. Su, B., Ang, B.W. & Low, M. Input–output analysis of CO_2 emissions embodied in trade and the driving forces. *Processing and normal exports. Ecol. Econ.* **88,** 119–125 (2013).
21. Jiang, X., Guan, D., Zhang, J., Zhu, K. & Green, C. Firm ownership, China's export related emissions, and the responsibility issue. *Energy Econ.* **51**, 466–474 (2015).
22. IPCC 2006 *IPCC Guidelines for National Greenhouse Gas Inventories* Vol.4 (IGES, 2006).
23. Peters, G.P. From production-based to consumption-based national emission inventories. *Ecol. Econ.* **65,** 13–23 (2008).
24. Peters, G.P. & Hertwich, E.G. Post-Kyoto greenhouse gas inventories: Production versus consumption. *Clim. Change* **86,** 51–66 (2008).
25. Davis, S.J. & Caldeira, K. Consumption-based accounting of CO_2 emissions. *PNAS* **107,** 5687–5692 (2010).
26. Meng, B., Xue, J., Feng, K., Guan, D. & Fu, X. China's inter-regional spillover of carbon emissions and domestic supply chains. *Energy Policy* **61,** 1305–1321(2013).
27. Prell, C., Feng, K., Sun, L., Geores, M. & Hubacek, K. The global economic gains and environmental losses of US consumption: A World-systems and Input-Output Approach. *Social Forces* **93,** 405–428 (2014).
28. Koopman, R., Wang, Z. & Wei, S.J. Tracing value-added and double counting in gross exports. *Am. Econ. Rev.* **104,** 459–494 (2014).
29. Wang, Z., Wei, S.J. & Zhu, K. Quantifying international production sharing at the bilateral and sector levels. *NBER Working Paper* **19677** (2013).
30. Murray, J. & Wood, R. (Eds.). *The Sustainability Practitioner's Guide to Input-Output Analysis*. Champaign, Illinois, USA: Common Ground Publishing (2010).
31. Peters, G.P., Weber, C.L. & Liu, J. Construction of Chinese energy and emissions inventory. *Norwegian University of Science and Technology working paper*, Trondheim (2006).

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