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China's "Exported Carbon" Peak: Patterns, Drivers, and Implications

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Key Points:
- Chinese export-embodied emissions peaked in 2008 at a level of 1,657 million tones
- The subsequent decline in export-embodied emissions was mainly due to the changing structure of Chinese production
- More attention should focus on ensuring that countries increasing their exports do so using low-carbon inputs

Supporting Information:
- Supporting Information S1

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Abstract Over the past decade, China has entered a "new normal" phase in economic development, with its role in global trade flows changing significantly. This study estimates the driving forces of Chinese export-embodied carbon emissions in the new normal phase, based on environmentally extended multiregional input-output modeling and structural decomposition analysis. We find that Chinese export-embodied CO_2 emissions peaked in 2008 at a level of 1,657 million tones. The subsequent decline in CO_2 emissions was mainly due to the changing structure of Chinese production. The peak in Chinese export-embodied emissions is encouraging from the perspective of global climate change mitigation, as it implies downward pressure on global CO_2 emissions. However, more attention should focus on ensuring that countries that may partly replace China as major production bases increase their exports using low-carbon inputs.

Plain Language Summary A large share of global CO_2 emissions is produced by making goods and services that are internationally traded, to which China is the largest contributor. We find that Chinese export-embodied CO_2 emissions peaked in 2008 at a level of 1,657 million tones. The peak in Chinese export-embodied emissions is encouraging from the perspective of global climate change mitigation, as it implies downward pressure on global CO_2 emissions. However, more attention should focus on ensuring that countries that may partly replace China as major production bases increase their exports using low-carbon inputs.

1. Introduction

A large share of global carbon dioxide (CO_2) emissions is produced making goods for international trade. The emissions embodied in international trade account for more than 20% of global emissions (Arce et al., 2016; Davis & Caldeira, 2010). Understanding the trends and drivers of trade-embodied CO_2 emissions is therefore of great importance as the world strives to peak and phase down CO_2 emissions in order to achieve global climate mitigation goals. Additionally, patterns of trade-embodied CO_2 also matter from a distributional perspective. Emissions embodied in the exports of developing countries are much larger than those of developed countries (Kander et al., 2015; Peters & Hertwich, 2008), and this pattern has introduced political controversy into the accounting of carbon emissions in the international climate regime, as well as the allocation of responsibilities among countries for mitigating climate change. China is the largest contributor to CO_2 emission flows from developing countries to developed countries (Peters, Davis, & Andrew, 2012). Therefore, it is particularly important to estimate the emissions embodied in Chinese exports and to analyze the determinants of changes in these emissions over time—the core aim of this paper. Specifically, we use a multiregional input-output (MRIO) model to estimate the CO_2 emissions embodied in Chinese exports from 2002 to 2015 and apply structural decomposition analysis (SDA) to assess the driving forces of changes in these emissions up to 2012.

Now is a particularly important time to consider these issues, as the structure of China's economy is changing dramatically, with profound impacts on its overall CO_2 emissions (Gao, 2012; Green & Stern, 2017)—a finding that has taken many observers by surprise. The role played by exports is a crucial piece of this wider puzzle. Exports have consistently played a critical role in driving rapid economic growth in China during in past decades. Accordingly, China's exports induce a large proportion of its total carbon emissions, as recent studies have confirmed (Liu et al., 2016; Mi, Meng, Guan, Shan, Liu, et al., 2017). However, closer examination of the period since the turn of the 21st century reveals a number of distinct shifts in the contribution of exports to China's economic growth and CO_2 emissions. A number of distinct periods can be identified based on these shifts for heuristic purposes.

From roughly the turn of the century to 2008, China's export-embodied CO_2 emissions increased rapidly. Exports contributed over 50% and 20% of total emission growth in China for the 2002–2005 (Guan et al., 2009) and 2005–2007 (Mi, Meng, Guan, Shan, Liu, et al., 2017) periods, respectively. However, the 2008 global financial crisis dramatically affected China's economy, especially by reducing the overseas demand for Chinese exports. China's export value declined by 7% from 2008 to 2009. China's government introduced a series of economic stimulus measures in 2008, commonly referred to as the Four Trillion Yuan stimulus package. In addition, China also took measures to stimulate its exports, such as raising export tax rebates. China's export value increased by 10% from 2010 to 2011 due to the stimulus package.

By the early 2010s, the effects of the stimulus package had begun to wane, and China's export value declined by 2.5% from 2012 to 2015. Since 2012/2013, China's government has articulated a new economic strategy to take advantage of emerging opportunities (including in low-carbon energy), arguing that China has entered a new normal phase of economic development marked by slower but higher quality economic growth (Grubb et al., 2015). The new normal involves a structural shift away from energy-intensive investment and heavy industry and toward less energy-intensive consumption, technological, and service sectors as the main drivers of growth (Green & Stern, 2017; Mi, Meng, Guan, Shan, Liu, et al., 2017). One desirable consequence of this wider economic transformation has been a dramatic change in the trajectory of China's total CO_2 emissions since 2013/2014 (Green & Stern, 2017), which now appear to have plateaued after rising rapidly for decades prior. A key motivation of the present study is to better understand the contribution of exports to China's CO_2 emissions in the context of this wider structural change.

To date, there have been no studies of Chinese export-embodied emissions in the new normal period covering years beyond 2012. A key contribution of this paper, therefore, is to fill this research gap using data spanning all of the above-mentioned periods right up to 2015. The model permits us to observe changes in patterns of overall, sectoral, and provincial-level export-embodied CO_2 emissions over a period that extends beyond the immediate aftermath of the global financial crisis and domestic stimulus package and thus to observe longer-term structural trends.

The SDA approach is applied to China's export-embodied emissions in the period of 2002–2012. Some researchers have used SDA to analyze the drivers of China's export-embodied emissions, including during this period. Xu et al. (2011), Su and Thomson (2016), and Pan et al. (2017) used the SDA approach to analyze the determinants of the changes in China's export-embodied emissions for 2002–2008, 2006–2012, and 1997–2012, respectively. However, these were all based on single-region input-output models, which cannot reflect regional variations and domestic interregional trade. In this study, the MRIO-based decomposition was used to investigate the determinants of changes in China's export-embodied emissions.

2. Methods and Data

2.1. Structural Decomposition Analysis Based on a Multiregional Input-Output Model

Environmentally extended input-output analysis is an approach to analyze the relationships between economic activities and environmental impacts within several economies (Feng et al., 2013; Meng et al., 2016; Mi et al., 2016). Environmentally extended input-output analysis can be used to calculate CO_2 emissions embodied in trade among nations or regions. The emissions embodied in exports can be calculated as follows (Meng et al., 2015):

$$C_{\text{exp}} = F(I - A)^{-1}E \tag{1}$$

where C_{exp} represents the emissions embodied in exports, F is the vector of the carbon intensity, $(I - A)^{-1}$ is the Leontief inverse matrix, and E is the vector of exports. We estimate CO_2 emissions embodied in China's exports from 2002 to 2015, although China's input-output tables (IOTs) are only available for 2002, 2005, 2007, 2010, and 2012. For years in which the IOTs are not available, we use those in nearby years as follows:

$$C_{\exp} = \begin{cases} F_t(I - A_t)^{-1}E_t & \text{if } t = 2002, 2005, 2007, 2010, 2012 \\ \frac{2}{3}F_t(I - A_{t-1})^{-1}E_t + \frac{1}{3}F_t(I - A_{t+2})^{-1}E_t & \text{if } t = 2003, 2008 \\ \frac{1}{3}F_t(I - A_{t-2})^{-1}E_t + \frac{2}{3}F_t(I - A_{t+1})^{-1}E_t & \text{if } t = 2004, 2009 \\ \frac{1}{2}F_t(I - A_{t-1})^{-1}E_t + \frac{1}{2}F_t(I - A_{t+1})^{-1}E_t & \text{if } t = 2006, 2011 \\ F_t(I - A_{2012})^{-1}E_t & \text{if } t = 2013, 2014, 2015 \end{cases}, \quad (2)$$

where F_t is the vector of the carbon intensity in year t, $(I - A_t)^{-1}$ is the Leontief inverse matrix in year t, and E_t is the vector of exports in year t.

Structural decomposition analysis can be used to identify major shifts within an economy based on comparative static changes in key sets of factors (Hoekstra & Van Den Bergh, 2002; Skolka, 1989). It is used to decompose China's export-embodied emission changes into five factors, including population, efficiency, production structure, export structure, and export volume, and it can be expressed as follows:

$$\Delta C_{\exp} = \Delta pFLE_sE_v + p\Delta FLE_sE_v + pF\Delta LE_sE_v + pFL\Delta E_sE_v + pFLE_s\Delta E_v, \quad (3)$$

where Δ is the change in a factor, p is the population, F is the carbon emission intensity, L is the Leontief inverse matrix, $L = (I - A)^{-1}$, E_s is the export, and E_v is the per capita export volume. Each of the five terms in equation (3) refers to the associated contribution to emissions changes induced by one driver, keeping other factors constant. See Text S1 in the supporting information for more details on SDA (Malik & Lan, 2016; Wu & Wang, 2017).

2.2. Carbon Emission Inventory Construction

In this study, CO_2 emissions from both fuel combustion and cement production are considered. We construct a Chinese emission inventory using the reference approach provided by the Intergovernmental Panel on Climate Change (IPCC) as follows (Mi, Wei, et al., 2017):

$$C_{\text{fossil}} = D_{\text{fossil}} \times V \times H \times O, \quad (4)$$

where C_{fossil} represents the CO_2 emissions from fossil fuel combustion, D_{fossil} is the amount of energy consumption, V is the net calorific value, H is the carbon content, and O is the oxygenation. The emission factors used in this study are obtained from Liu et al. (2015) and shown in Table S1 in the supporting information.

The following equation is used to calculate CO_2 emissions from cement production (Shan, Guan, et al., 2017; Shan et al., 2016):

$$C_{\text{cement}} = D_{\text{cement}} \times G, \quad (5)$$

where C_{cement} represents the CO_2 emissions from cement production, D_{cement} is the amount of cement production, and G represents the CO_2 emitted when producing one unit of cement. The territorial-based CO_2 emissions for 30 Chinese provinces are shown in Table S2.

There are 45 sectors in the initial emission inventories, which is consistent with the Chinese energy statistical system. The emission inventories are adjusted into 30 sectors corresponding to the Chinese MRIO tables (Table S3). The sector of "others" in the emission inventories is disaggregated into four sectors in the Chinese MRIO tables (including hotel and restaurant, leasing and commercial services, scientific research, and other services). It is assumed that the carbon intensity (i.e., carbon emissions per unit of output) is the same in the four sectors for each province. See Text S2 for more details on carbon emission inventory construction (Mi, Meng, Guan, Shan, Song, et al., 2017; Shan, Zheng, et al., 2017).

2.3. Data Sources

This study required two main data sets: time series of MRIO tables and corresponding CO_2 emissions. The 2012 Chinese MRIO table was compiled by Mi, Meng, Guan, Shan, Song, et al. (2017), and other Chinese MRIO tables were obtained from the Chinese Academy of Sciences (Liu et al., 2012; Liu et al., 2014). All MRIO tables were deflated to 2012 prices (Mi, Meng, Guan, Shan, Liu, et al., 2017). The CO_2 emission inventory was constructed on the basis of energy consumption, cement production, and emission factor data. The energy consumption data for all economic sectors in all provinces were obtained from the China Energy

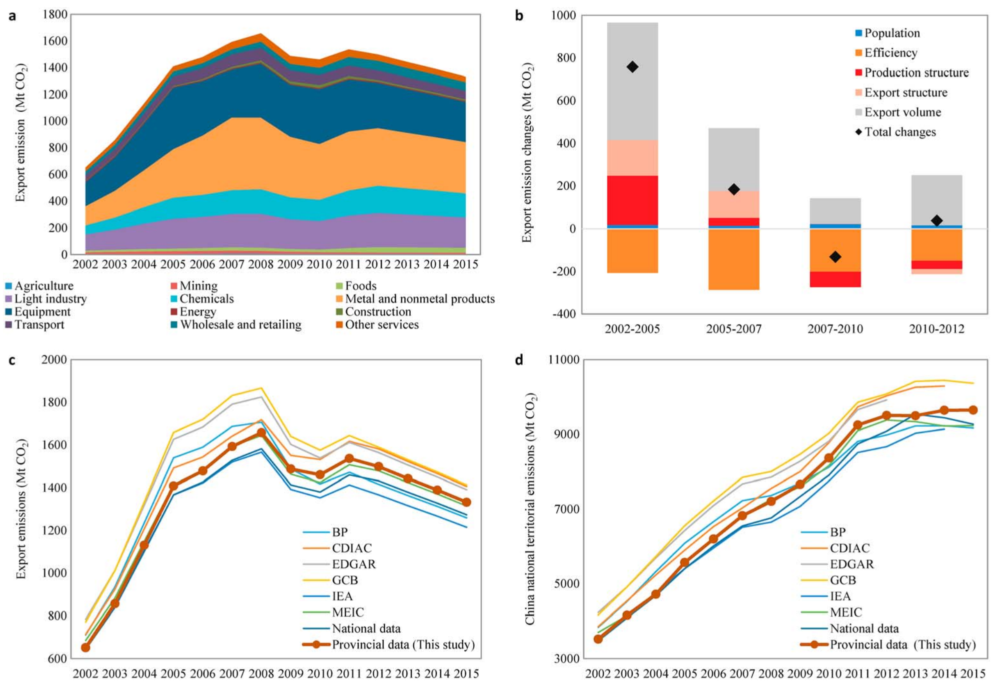

Figure 1. Chinese territorial-based CO_2 emissions and emissions embodied in its exports. (a) Chinese export-embodied emissions at sector level. See Table S4 for the breakdown by sector. (b) Effects of different factors on changes in Chinese export-embodied emissions. (c) Chinese export-embodied emissions on the basis of different data sources. (d) Chinese national territorial-based emissions based on different data sources. Data source: national and provincial data provided by National Bureau of Statistics (2015), Multiresolution Emission Inventory for China (MEIC, 2018), Emissions Database for Global Atmospheric Research (Janssens-Maenhout et al., 2017), Carbon Dioxide Information Analysis Centre (Boden et al., 2017), Global Carbon Budget (Le Quéré et al., 2016), International Energy Agency (IEA, 2017), and British Petroleum (BP, 2017).

Statistical Yearbook (National Bureau of Statistics, 2016a). The cement production data were obtained from the China Statistical Yearbook (National Bureau of Statistics, 2016b). The emission factors were obtained from Liu et al. (2015).

3. Results and Discussions

3.1. The Peak of Emissions Embodied in China's Exports

Emissions embodied in China's exports accounted for about 15–30% of national territorial-based emissions during 2002–2015. Additionally, notable variations in the absolute emissions embodied in Chinese exports were observed over this period, and emissions ranged from a low of 651 Mt in 2002 to a high of 1,657 Mt in 2008. While the decrease in export-embodied emissions after 2008 has been noted in previous studies (Mi, Meng, Guan, Shan, Liu, et al., 2017; Su & Thomson, 2016), our analysis of more recent data, up to 2015, permits the more confident conclusion that China's export CO_2 emissions peaked in 2008.

In the period from 2002 until the global financial crisis, emissions embodied in China's exports rapidly increased (Gregg et al., 2008). China's export-embodied emissions grew by 1,006 Mt in total from 2002 to 2008, which accounted for 32% of total emissions growth in China over that period (Figure 1a). From a sectoral perspective, most of China's exported emissions growth in this period was caused by secondary industry. For example, emissions embodied in the exports of metallurgy and chemical products increased dramatically, adding 188 and 102 Mt CO_2 respectively to exported emissions from 2002 to 2008. From a regional perspective, exported emissions in all provinces increased from 2002 to 2008, but the growth in exported emissions was faster in eastern coastal provinces than in western and central regions. The five provinces that exhibited the largest exported emissions growth from 2002 to 2008 (Jiangsu, Guangdong, Zhejiang, Shanghai, and Shandong) are all relatively prosperous and located in eastern coastal regions. Together, they contributed to 66% of the total growth in exported emissions during 2002–2008.

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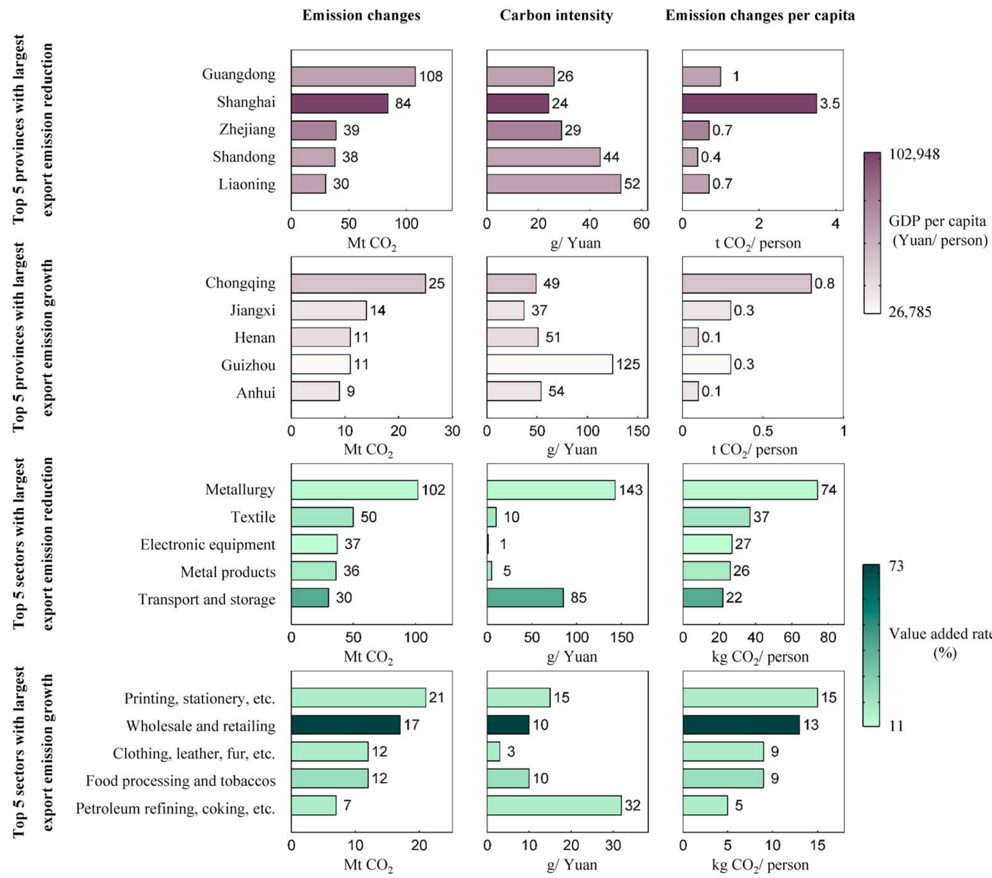

Figure 2. The top five provinces for (first row) export-embodied emission reduction and (second row) growth and the top five sectors for (third row) export-embodied emission reduction and (fourth row) growth from 2008 to 2015. The bar colors correspond to regional per capita gross domestic product in the first and second rows and the value added rate in the third and fourth rows. The value added rate is the value added per unit of total output.

Emissions embodied in China's exports trended downward during 2008–2015. In the immediate aftermath of the global financial crisis, the decrease in the overseas demand for Chinese exports was the primary cause of the decline. The value of Chinese exports declined by 7% from 2008 to 2009, which resulted in a 10% decrease in China's export-embodied emissions. Then, China's export-embodied emissions increased by 5% from 2010 to 2011, and this increase was mainly due to the government stimulus measures focused on the economy and exports, as well as a recovery in overseas demand for Chinese exports. These trends led some observers at the time to assume that China's export-embodied emissions would return to the sort of strong growth exhibited before the financial crisis (Su & Thomson, 2016; Tang et al., 2016).

However, with the benefit of data from 2012 to 2015 generated from our analysis, it can be seen that China's export-embodied emissions declined by an average of 3.5% annually from 2011 to 2015. Thus, it appears that the effects of the crisis and subsequent stimulus package on exported emissions were more akin to cyclical "noise" around an underlying structural trend of declining exported emissions since 2008. Overall, China's exported emissions declined by 20% from 2008 to 2015, notwithstanding the temporary growth in emissions from 2010 to 2011.

Closer analysis of the results from 2008 to 2015 reveals some further interesting trends at the sectoral and regional levels. From a sectoral perspective, China's export-embodied emissions declined due to the reduction in the export-embodied emissions of highly carbon-intensive but low value-added sectors (Table S5). Between 2002 and 2008, exported emissions in the metallurgy sector increased by 188 Mt—the largest emissions increase among the 30 economic sectors. Between 2008 and 2015, however, the metallurgy sector experienced the largest exported emissions reduction (i.e., 102 Mt; Figure 2, row 3, left). Metallurgy is a typical highly carbon-intensive but low value-added sector. Notably, the carbon intensity of the metallurgy industry (i.e., emissions per unit of output) was 143 g/Yuan in 2015, which was three times the national average level (49 g/Yuan), but its value added rate (i.e., value added per unit of output) was only 13% in 2015, which was substantially lower than the national average level (33%). The textile industry is another highly carbon-intensive but low value-added sector that exhibited a dramatic decline of 42% in exported emissions from 2008 to 2015, even though China increased the export tax rebate on textile products to encourage their production and export. By contrast, exported emissions in some low carbon-intensive but high value-added sectors increased over this period. For example, the exported emissions of the wholesale and retailing sector increased by 17 Mt from 2008 to 2015 (Figure 2, row 4, left). The carbon intensity of wholesale and retailing, however, only was 10 g/Yuan in 2015, which was much lower than the national average level (49 g/Yuan), and its value added rate was 73%, which was the highest of the 30 sectors analyzed. These changes are consistent with the wider structural changes occurring in China's economy in the new normal period.

From a regional perspective, the decline in China's export-embodied emissions over this period was due to the reduction in exported emissions from eastern coastal regions (Table S6). Before the 2008 financial crisis, eastern coastal provinces accounted for the majority of China's exported emission growth. Subsequently, however, exported emissions declined in most eastern coastal provinces. For example, exported emissions in four eastern coastal provinces (Guangdong, Shanghai, Zhejiang, and Shandong) declined by 270 Mt from 2008 to 2015 (Figure 2, row 1, left), which accounted for 83% of the total reduction in exported emissions. Exported emissions in many western and central regions, however, grew over this period. The five provinces with the largest exported emissions growth in this period are all located in China's western and central regions (Figure 2, row 2, left). Overall, the declines in CO_2 emissions in the eastern regions (404 Mt from 2008 to 2015) were much larger than the increases in the central and western regions (79 Mt), resulting in a large net decrease in export-embodied CO_2 emissions over the study period.

3.2. Determinants of Changes in China's Export-Embodied Emissions

From 2002 to 2007, CO_2 emissions embodied in China's exports increased from 651 to 1,592 Mt, or by 145%. Efficiency was the only factor to offset export-embodied emissions before 2007 (Figure 1b). The efficiency improvement offset 494 Mt of CO_2 emissions, if other factors were kept constant. This offset was driven by carbon intensity reductions in some key sectors, including the energy sector, whose carbon intensity declined by 47% from 2002 to 2007. The other factors all drove emissions growth over this period. The export volume alone caused an 844-Mt increase in CO_2 emissions. This increase was associated with China's export value, which increased by 22% from 2002 to 2007. Changes in China's export structure and production structure created 291 and 267-Mt increases in CO_2 emissions, respectively, between 2002 and 2007. In addition, population growth induced an increase of approximately 33 Mt of CO_2 emissions during the same period.

From 2007 to 2010, CO_2 emissions embodied in China's exports declined from 1,592 to 1,460 Mt, or by 8%. Growth in export volume remained the strongest determinant of growth in China's export-embodied emissions, although the global financial crisis reduced the contribution of export volume to growth in export-embodied emissions considerably. Notably, China's export value increased by 5% from 2007 to 2010, although it declined from 2008 to 2009, mainly due to the financial crisis (Lardy & Subramanian, 2011). Efficiency improvement was the strongest factor that reduced China's export-embodied emissions, offsetting 202 Mt of CO_2 emissions from 2007 to 2010, if other factors were kept constant. China's energy efficiency policies had a great impact on the energy efficiency of Chinese production. In the 11th Five-Year Plan (2006–2010), for example, China set a target to reduce energy intensity (i.e., energy consumption per unit of gross domestic product) by 20% over 5 years and introduced numerous energy conservation policies. Changes in China's production structure put further downward pressure on export-oriented emissions after 2007–a reversal of the effect of production structure changes prior to that point. Specifically, changes in production structure offset 72 Mt of CO_2 emissions from 2007 to 2010 (Figure 1b). Therefore, production structure changes and efficiency gains are the key reasons for the peak in China's export-embodied emissions.

At the sector level, the proportions of total inputs from highly carbon-intensive sectors in to other production sectors declined. For example, the proportion of inputs from electricity and hot water production, which had the highest carbon intensity (669 g/Yuan in 2010), reduced from 5.1% in 2007 to 4.9% in 2010 (Figure S1 in the supporting information). By contrast, the proportions of total inputs from some low carbon-intensive sectors increased, such as inputs from the "instrument and meter," electronic, and electrical equipment sectors.

For instance, the proportion of inputs from electronic equipment, which had the lowest carbon intensity of 1.4 g/Yuan in 2010, increased from 3.9% in 2007 to 4.0% in 2010.

From 2010 to 2012, the CO_2 emissions embodied in China's exports grew slightly, by 3%. As previously noted, China's export growth rate began to recover during this period, and the export value increased by 12% from 2010 to 2012. Export-embodied emissions only increased in 2010 and 2011 and decreased in 2012, but when measured over the 3-year period based on the availability of IOTs, the net growth masks the decline in 2012. As a result, the export volume induced 234 Mt of growth in China's export-embodied emissions over this period with other factors held constant. This growth was partially offset by changes in the export structure, which decreased China's export-embodied emissions in 2010–2012, in contrast to the previous period analyzed. Specifically, this shift decreased export-embodied emissions by 24 Mt. At the sector level, the contributions of some low carbon-intensive sectors to total Chinese exports increased. For example, the embodied carbon intensity (i.e., embodied CO_2 emissions per unit of exports) of electronic equipment was 92 g/Yuan in 2012, which was lower than the national average level (147 g/Yuan). Additionally, the associated proportion of total Chinese exports increased from 20% in 2010 to 22% in 2012 (Figure S2). In contrast, the contribution of the chemical industry, which had an embodied carbon intensity higher than the national average level, declined from 8.5% to 7.2% during the same period.

3.3. Uncertainty Analysis

There are uncertainties in the estimation of carbon emissions. The sources of these uncertainties are conflicting estimates of emission factors and energy consumption. First, emission factors play a critical role in the IPCC reference approach. The most widely used emission factors are default values recommended by the IPCC (IPCC, 2006). Liu et al. (2015), however, reevaluated carbon emissions for China and indicated that the IPCC default values overestimated China's CO_2 emissions. Therefore, we used the emission factors provided by Liu et al. (2015). Second, China publishes energy statistics for the country and its provinces. However, there are great gaps between the two available official energy data sets, which brings uncertainties for estimating carbon emissions. Guan et al. (2012), for example, showed that CO_2 emissions calculated based on the two data sets differed by 1.4 gigatonnes for 2010. The provincial data were used in this work.

We estimated and compared China's export-embodied emissions on the basis of eight different data sources (Figure 1c). These data sources have been widely used in researching China's carbon emissions (Jotzo et al., 2018; Liu et al., 2015; Shan et al., 2018). There are big gaps among different emission inventories (Figure 1d). However, the estimation from all these data sets indicated that China's export-embodied emissions peaked in 2008 (Figure 1c). The largest estimation on the peak value (from Global Carbon Budget) was 13% larger than that from provincial data, while the smallest estimation (from the International Energy Agency) was 5% smaller than that from provincial data.

4. Conclusions and Policy Implications

Emissions embodied in China's exports increased rapidly before the global financial crisis, which is one of the main reasons for the country becoming the world's largest carbon emitter. However, our analysis reveals a dramatic shift thereafter: China's export-embodied emissions peaked at 1,657 Mt in 2008. Our analysis suggests that the external reasons for the peak were the reduced growth in exports and a structural shift in the exports demanded by the overseas importers of Chinese goods and services. Additionally, the internal reasons include improvements in the intra-industry efficiency of Chinese production and a shift away from high-carbon, low value-added production sectors and toward low-carbon, high value-added sectors in the Chinese production mix. Although the financial crisis and the corresponding stimulus package from the Chinese government in response to the crisis clearly had significant short-term effects on Chinese exports and the CO_2 emissions embodied in them, our analysis shows that underlying structural trends partly accounted for the decrease in export-embodied emissions since 2008. This finding increases our confidence in the conclusion that 2008 was the emission peak.

The results of the regional, sectoral, and structural decomposition analyses performed in our study permit some conclusions about the future trajectory of China's export CO_2 emissions, of which we highlight three, before concluding with some remarks about the implications for Chinese and global climate change mitigation.

First, we expect the observed geographic shift in export-embodied CO_2 emissions from eastern coastal regions to western regions of China to continue but note that the export-oriented development of the latter need not necessarily be of the highly carbon-intensive variety. Export-embodied emissions in eastern coastal regions declined, while those from western and central regions increased between 2008 and 2015, reflecting both a relative shift in export volumes from east to west and the generally more emission-intensive production structure in western regions. China has implemented the Western Development Strategy since 2010. This policy promotes economic growth in western provinces and their inegration into global value chains, causing increased CO_2 emissions. In addition, the Silk Road Economic Belt and the 21st century Maritime Silk Road (the Belt and Road)—a development strategy and framework for economic cooperation between China and the rest of Eurasia—will likely reinforce this trend. In this process, some “carbon leakage” from eastern regions to central and western regions will likely occur. However, our study suggests that the most probable net effect would be a reduction in export-embodied CO_2 emissions. In addition, the factor endowments of western regions do not inexorably point to the replication of the eastern, coal-based, heavy-industry development path. For example, the superior renewable energy resources in western regions offer an opportunity to develop these regions using much lower-carbon electricity inputs than those utilized during the industrialization of the eastern provinces (Zhang & Kumar, 2011).

Second, we expect efficiency gains to continue to put downward pressure on export-embodied CO_2 emissions but to be overtaken in significance by desirable (from a CO_2 perspective) changes in China’s production structure. Efficiency gains have consistently decreased China’s export-embodied emissions, including in all periods analyzed in our study. In recent years (especially between 2010 and 2012), efficiency gains exerted less downward pressure on export-embodied emissions than in the 2002–2007 period, but this effect on emissions was reinforced by structural upgrading. China’s new development pattern emphasizes structural upgrading to promote a resource-saving and environmentally sustainable society. Structural changes consistent with this strategic emphasis have been observed in Chinese production structure in the years since the financial crisis. As China consolidates its new normal development phase, production structure changes will likely be the main drivers of future reductions in China’s export-embodied emissions.

Third, we expect China’s role in international trade to continue to evolve away from exporting highly emission-intensive, low value-added goods and toward low-carbon, high value-added goods and services. China’s export value has grown fast since its enty in the World Trade Organization in 2001. This fast growth relied largely on the exports of low value-added products. However, our study observed that the proportions of highly carbon-intensive but low value-added sectors in Chinese exports has declined in recent years. The emissions embodied in China’s exports of metallurgical products (such as steel) and textiles, two typical, highly carbon-intensive, low value-added sectors, declined by large margins (47% and 42%, respectively) from 2008 to 2015. Additionally, the share of domestic value added in Chinese exports has grown, indicating that China’s position in international value chains is moving upstream.

The peak in China’s export-embodied emissions is a significant milestone on the path to the peak in China’s overall emissions and those of the world as a whole. Although China’s Nationally Determined Contribution to the Paris Agreement on climate change includes a pledge to peak its CO_2 emissions by approximately 2030, China’s carbon emissions appear to have plateaued since 2013/2014 and may have even begun to decline. Exports contributed to a large share of China’s national CO_2 emissions, so the peak in China’s export-embodied emissions significantly contributed to the overall shift in China’s national emissions trajectory. From a global perspective, international trade has been one of the main drivers of global CO_2 emissions growth in recent decades, and Chinese exports played a major role in that growth. Therefore, the earlier-than-expected peak in China’s export-embodied emissions bodes well for the future peak in global emissions. This peak is necessary if the world is to restrain global warming to within 2 °C above preindustrial levels, let alone the 1.5 °C to which the Paris Agreement aspires.

However, the peak in China’s export-embodied emissions is no reason for complacency with respect to the emissions embodied in international trade. Various other countries whose economies are characterized by low wages, large labor forces, and relatively high carbon intensities of production are vying to replace

China as the "world's factory." (Meng et al., 2018) There is a risk that this shift in trade patterns could perpetuate the "leakage" of carbon from the developed world to developing exporter countries, as has been observed during economic globalization in recent decades. There is thus a strong case for effective climate policies in exporting countries, border carbon adjustment mechanisms in importing countries, and equitable cooperation between importers and exporters to phase down rapidly the harmful CO_2 emissions embodied in international trade.

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