Targeted opportunities to address the climate-trade dilemma in China

Zhu Liu[1,2,3], Steven J. Davis[4,5*], Kuishuang Feng[6,7*], Klaus Hubacek[6], Sai Liang[8] , Laura Diaz Anadon[1], Bin Chen[9], Jingru Liu[10] , Jinyue Yan[11] and Dabo Guan[12,13*]

[1] John F. Kennedy School of Government, Harvard University, Cambridge, Massachusetts 02138, United States

[2] Resnick Sustainability Institute, California Institute of Technology, Pasadena, California 91125, USA

[3] Cambridge Centre for Climate Change Mitigation Research, Department of Land Economy, University of Cambridge, 19 Silver Street, Cambridge CB3 9EP, UK.

[4] University of California, Irvine, Department of Earth System Science, Irvine, CA, 92697, USA

[5] Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang, 110016

[6] Department of Geographical Sciences, University of Maryland, College Park, MD 20742, USA

[7] Center for Environment Policy Research, Institute of Policy and Management, Chinese Academy of Sciences, Beijing 100190, China

[8] School of Natural Resources and Environment, University of Michigan, Ann Arbor, Michigan 48109-1041, United States

[9] State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China

[10] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, 100085, Beijing, China

[11] KTH-Royal Institute of Technology, SE-100 44 Stockholm, Sweden & Malardalen University, SE-721 23, Sweden

[12] Ministry of Education Key Laboratory for Earth System Modeling, Center for Earth System Science, Tsinghua University, Beijing, 100084, China

[13] Tydnall Centre for Climate Change Research, School of International Development, University of East Anglia, Norwich NR4 7TJ, UK

*Corresponding author: Steven J. Davis <sjdavis@uci.edu>, Kuishuang Feng <kfeng@umd.edu> or Dabo Guan <dabo.guan@uea.ac.uk>.

The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper.

[Introductory Paragraph]

International trade has become the fastest growing driver of global carbon emissions, with emerging countries are the major producer of the trade embodied emissions an. International trade with emerging countries poses a dilemma for climate and trade policy: To the extent emerging markets have comparative advantages in manufacturing, such trade is economically efficient and desirable. However, if carbon intensive manufacturing in emerging countries such as China entails drastically more CO_2 emissions than making the same product elsewhere, then trade increases global CO_2 emissions. Here we show that the emissions embodied in Chinese exports, which are larger than the annual emissions of Japan or Germany, are primarily contributed by China's coal-based energy mix and very high emissions intensity (emission per unit of economic value) in a few provinces and industry sectors. Exports from these province-sectors therefore represent targeted opportunities to address the climate-trade dilemma by improving production technologies and decarbonizing the underlying energy systems or reducing trade volumes. [*157 words*].

Despite international efforts to reduce CO_2 emissions[1,2], global emissions have increased by an average of 3.1% per year since 2000[3,4]. Economic growth has been identified as the main driver of the sharp increase of CO_2 emissions in the 2000s, and in particular the rapid industrialization of China[5], which is the world's largest carbon emitter since 2006[6]. However, China is also the world's largest net exporter of CO_2 emissions embodied in goods and services: In 2007, emissions in China were 7.3 Gt CO_2, (production-based emissions), of which 1.7 Gt (23%) were related to goods exported and ultimately consumed in other countries[7,8]. In contrast, only 0.2 Gt CO_2 emissions were embodied in products imported to China from other countries. As of 2008, Chinese trade accounts for a third of all emissions embodied in global trade, and these traded emissions have been growing faster than global emissions[9]. The magnitude and growth of emissions embodied in Chinese trade pose a dilemma for trade and climate policy: To the extent China and other emerging markets have comparative advantages in manufacturing, international trade is economically efficient and desirable[10]. However, if carbon intensive manufacturing in China entails drastically more carbon emissions than making the same production elsewhere, then trade increases global carbon emissions. Yet, although previous studies have quantified emissions embodied in China's trade[7,11-13], none have quantified the underlying factors driving these emissions, leaving open the question of how to mitigate such embodied emissions.

Here, we decompose the key factors contributing to the prodigious imbalance of emissions embodied in China's international trade (See Methods for details): (1) the large trade surplus between China and its trading partners, (2) the structure of the Chinese economy (i.e. specialization in energy-intensive production), (3) the energy mix of China's production (i.e. energy mainly supplied by fossil fuels) and (4) the emissions intensity of Chinese production (i.e. the emissions produced per unit of economic output)[10,11]. China is a country with substantial regional differences in technology, energy mix and economic development, as well as large volumes of interprovincial trade[8,14,15-17], our analysis assessed the magnitude and intensity of emissions from 46 industry sectors (Extended Data Table 1) traded among 30 Chinese provinces/cities and 129 other countries/regions .

Details of analytic approach are presented in *Methods*. We track emissions embodied in trade among 159 regions using a global multiregional input–output (MRIO) model of emissions and trade as of the year 2007. The trade and emissions data supporting the model are a combination of the Global Trade Analysis Project (GTAPv8) and province-level input-output tables of China that we constructed[8,15,18]. We analyze the driving factors of emissions embodied in international trade using an improved index decomposition approach (IDA)[15,19]. The results presented below and in the figures reflect only international trade. Our model links physical production of emissions with the consumption of final goods without regard for the location of intermediate consumption. For example, emissions related to components manufactured in Inner Mongolia that become part of a product assembled in Beijing and exported to another country are assigned to Inner Mongolia. If the same final product were exported to another Chinese province, the embodied emissions are consumed domestically and are therefore excluded from our analyses.

Magnitude and intensity of emissions embodied in Chinese exports

Figure 1 shows the top 5 countries and the top 5 Chinese provinces whose exports (first row), imports (second row) and net trade (third row) embody the greatest CO_2 emissions (first column), including the greatest emissions per unit of economic output (second column) and per capita (third column). China is the largest net exporter of embodied emissions, by a large margin (Fig. 1g) with 8 times more emissions embodied in its exports than its imports (Figs. 1a and 1d). In contrast, this ratio of emissions embodied in exports to imports is much less in other major exporting nations (e.g., 0.5 in the U.S., 0.5 in Japan, 1.3 in India, 1.2 in Canada, 0.5 in Germany and 1.5 in Australia).

All of the 30 Chinese provinces assessed are net exporters of embodied emissions, meaning that in all cases the emissions embodied in exports exceed the emissions embodied in imports. Figure 1 also highlights the significance of particular Chinese provinces; 7 of the top 10 net exporting regions are Chinese provinces—larger than many large nations (Fig. 1g). Furthermore, the ratio of emissions embodied in exports to imports in these Chinese provinces is immense: 11 of China's 30 provinces export more than 10 times as much emissions as they import, including Xinjiang, Shanxi, and Hebei, whose export-import ratios are the largest of any region in our model: 25, 19 and 16, respectively. Five provinces account for 46% of the 1,671 Mt CO_2 embodied in China's exports in 2007: Shandong (178 Mt CO_2), Jiangsu (173 Mt CO_2), Guangdong (161 Mt CO_2), Hebei (139 Mt CO_2) and Zhejiang (111 Mt CO_2) (Fig. 1a).

China's provinces are also the most carbon-intensive exporters in the world. The average emissions embodied per dollar of Chinese exports is 1,357 g CO_2/\$, which is about 6 times the average emissions embodied per dollar of China's international imports (230 g CO_2/\$). This is reflected in the very high emissions embodied per dollar of exports from individual provinces, which comprise all of the top 10 regions in this category (Fig. 1b). The provinces with the greatest emissions intensity of exports also tend to be less economically developed; provinces where GDP is less than \$4,000 per capita show the largest difference in the emission intensity of exports and imports (Extended Data Fig. 1). About 80% of China's export-related emissions are produced by these poorer regions where the emissions intensity of exports is more than 5 times the emissions intensity of imports. For example, in Guizhou, where per capita GDP was $900 in 2007, the emissions intensity of international exports was almost 31 times of the emissions intensity of imports (Extended Data Fig. 1). Similarly high ratios exist in the also poor provinces of Inner Mongolia, Yunnan and Gansu. In the more affluent coastal provinces, ratios of emissions intensity of exports to imports are much smaller: ratios in Beijing, Zhejiang and Shanghai are 2.8, 3.0 and 4.1, respectively. But even these ratios are still much higher than those of other large trading nations such as U.S. (0.8), Germany (0.4), Japan (0.2), Canada (1.1), the UK (0.3), and India (1.7).

Although it is the most populous country in the world, since 2013 China's per capita emissions are approaching the average level in Europe when one ignores the fact that a large fraction of emissions are destined to exports[20,21]. However, the per capita net export of embodied emissions from some Chinese provinces is also much larger than most developed countries, three Chinese provinces among the top 10 in the category of global 159 regions(Fig. 1i), and 15 of China's 30 provinces could listed as the world top 30 regions with the highest net trade emissions per-capita.

Figure 2 shows the destination of exports from the five provinces whose exports embody the greatest emissions (see also Fig. 1g). Just five provinces, Jiangsu, Shandong, Guangdong, Hebei and Zhejiang, represent 10.7%, 10.4%, 9.7%, 8.3% and 6.7% of all emissions embodied in China's exports, respectively (Fig. 2). As previous studies have shown[22,23], developed countries are the primary importers of Chinese embodied emissions, foremost among them the U.S. (395 Mt CO_2, 24% of China's exported emissions and 44% of the U.S.'s imported emissions, respectively), the EU (422 Mt CO_2, 25% and 42%, respectively) and Japan (149 Mt CO_2, 9% and 48%).

Driving factors of China's carbon intensive trade

Several factors can contribute to the observed differences in the magnitude and intensity of emissions embodied in exports and imports. First, in recent years China has become a "factory for the world," with high concentrations of global heavy industry and manufacturing. For example, China produces 60%, 51% and 65% (by mass) of the world's cement, steel and coke , respectively[24]. Such large imbalances in the volume of traded products may correspond to similarly large imbalances in the emissions embodied in traded products. Figure 3 compares the percentage of emissions related to consumed goods that are imported (y-axis) and the percentage of produced emissions that are embodied in exports for a number of industry sectors in China (Fig. 3a) and Europe (Fig. 3b). For example, 34% (26 Mt CO_2) of emissions produced by the

European metal production industry are embodied in products exported from Europe in 2007, but emissions embodied in all metal products consumed in Europe were 140 Mt CO_2, 64% of which (90 Mt CO_2) were imported from outside Europe (Fig. 3a; red circle labeled "Metal") . In comparison, the share of emissions produced by China's metal production sector that is exported is similar to Europe's (33%; Fig. 3b), but the share of emissions related to Chinese consumption of metals that is imported is much lower: 11% .

Overall, Figure 3 highlights that, across many industry sectors, the share of European consumption (import from other countries) is consistently greater that the share of produced emissions that are exported, and the opposite is true for China. These trade imbalances are evident for both industries (yellow circles) and secondary industries (red and purple circles).

A second factor influencing emissions embodied in trade is the trade structure. Figure 4 shows the industry categories that make up Chinese imports, exports and domestic consumption. Emissions embodied in heavy, energy-intensive products such as metal and non-metal products and equipment make up much larger shares of China's exports (37% and 22%, respectively) than its imports (19% and 16%, respectively; light green and dark blue bars in Fig. 4). Meanwhile, mining products is the category with the greatest proportion of emissions embodied in Chinese imports (23%). The dominance of these industries in Chinese trade implies that China is not just the world's workshop, but is engaged in the most emission-intensive stages of manufacturing: the smelting and processing of raw materials. This pattern is visible at the province level, as well; in Shandong, where emissions embodied in trade are largest, 8 Mt CO_2 are embodied in imports of mining products from other countries (42% of all emissions embodied in imports) and 60 Mt CO_2 are embodied in exported metal and non-metal products (34% of emissions embodied in the province's exports).

The third major factor is emissions intensity, or CO_2 emissions per dollar of output in each particular industry. Such emissions intensity reflects both energy intensity (energy consumed per dollar of output) and carbon intensity of energy (CO_2 per unit of energy consumed). The combination of a carbon-intensive power industry, relying primarily on coal, and of a relatively low value-added of industry thus translate into a high emissions intensity of Chinese production (Figs. 1b, 1h, and 2). In 2007, 75% of China's primary energy was supplied by coal, the highest level among major energy-consuming nations. As a result, the carbon intensity of energy consumption in general (for internal consumption and exports combined) in China is extremely high: Chinese exports entail 61 tCO_2/PJ on average, which is almost triple the carbon intensity of imports to China, 24 tCO_2/PJ. The energy intensity of China's exports is similarly high; in 2007, China consumed 22 MJ per dollar of output, on average, or more than twice the energy intensity of products imported to China (9 MJ/$). This high energy intensity is underpinned by low value-added and less advanced technology of China's production, as previously suggested by other studies[22,25] covering the 2002-2010 time period.

Extended Data Figure 2 further indicated that the industry sectors with the greatest emissions intensity in each of the six Chinese top carbon export provinces (see also Fig. 1b). Although there is some variation among the emissions intensity of sectors in these six provinces, the manufacture of heavy industrial materials for export (e.g., mining products, chemical products, metal/non-metal products, and energy) is many times higher than the emissions intensity of similar products that are imported and consumed in China (Extended Data Figure 1, 2 and 3).

Figure 5 shows the contribution of the different factors to the net emissions embodied in trade of each Chinese province. Four factors are decomposed: (1) differences in the total economic value of exports and imports (trade volume, black bars), where greater trade volumes correspond to greater embodied emissions; (2) differences in sectors responsible for exports and imports (economic structure, orange bars), where greater shares of energy and emission intensive heavy industry and manufacturing, for example, correspond to greater embodied emissions; (3) differences in the carbon-intensity of energy used to produce exports and imports, where a greater share of low-carbon energy sources such as renewables and nuclear correspond to less embodied emissions; and (4) differences in the sectoral energy intensity of exports and imports, where greater shares of low-energy, high value-added products correspond to less embodied emissions (shown combined with (3) as emissions intensity, purple bars).

On average, the high energy intensity of sectors and the coal-dominated energy mix accounted for 43.3% and 43.0% of the net emissions embodied in exports, respectively (Fig. 5). In comparison, the structural preference for manufacturing and heavy industry accounted for only 8% of the net emissions embodied in exports, and less than 6% of the net exports are related to the larger volume of exports than imports. Emissions intensity (contributed by both energy intensity and carbon intensity of sectoral energy use) is the most important factor underlying the large net exports of embodied emissions, accounting 86% of the emissions embodied in exports, or 1,438 Mt CO_2 of emissions. All 30 regions are net exporters of emissions, but only 11 of the 30 would remain net exporters of emissions if differences in emissions intensity were eliminated. The emission intensive manufacturing reflects China's current development status with features discussed above.

Discussion

We show that the very large quantities of emissions embodied exported from China on net are likely due primarily to Chinese reliance on coal energy and the very high energy intensity of the exporting industries, which are in turn geographically concentrated in a small number of less-developed provinces.

Our analysis is based on aggregated sectors (e.g., "electronic equipment and machinery") rather than the specific products (e.g., iPhones), such that we may underestimate the effect of economic structure on net trade of emissions if differences in production are too specialized to be reflected by the 46 sectors in our model (Extended Data Table 1). The comprehensive data necessary to support product-level analysis are not yet available. However, we also used up-to-date and independent life cycle analysis datasets (PRé SimaPro LCA 7.3 dataset[26] for Europe and RCEES 2012 database[27] for China) to investigate the carbon emission per unit product of the production process for a sample of 15 industrial products made in Europe and China (Table 1). Doing so revealed that the emissions per unit mass of each product (kg CO_2/kg) for Chinese products was on average 4.4 times higher than the same products made in Europe, ranging from 1.4 times as high for copper production to 18.4 times as high for propylene production (Table 1). Product-level data are therefore entirely consistent with our more aggregate sector-level analysis showing that production in China is several times as carbon intensive as the same production in other countries, supporting our conclusion that the emissions intensity of Chinese production is the main factor driving the country's large net exports of embodied emissions. This suggests that, although international trade with China may be economically optimal given comparative advantages in labor costs, for instance, such trade is on average causing increase global CO2 emissions relative to production taking place in the countries which now import from China.

However, because Chinese emissions intensity is highest in a small number of provinces and sectors, targeted changes in primary energy generation and improvements in the technology used by these industrial sectors and provinces could drastically reduce the emissions embodied in Chinese exports and thereby global emissions. For example, if the emissions intensity of China's international exports were equal to the intensity of its imports, total emissions embodied in exports as of 2007 would be reduced by 86%, from 1,671 Mt CO_2 to 233 Mt CO_2. In this hypothetical, the avoided emissions are roughly equivalent to the total CO_2 emissions of Japan. Even without improving the energy intensity of its economy, decarbonizing China's energy supply to the global average of emissions per $GDP would reduce the emissions embodied in Chinese exports by 43% (619 MtCO_2). Similarly, Chinese targets to increase the share of energy produced from renewable sources to 20% of the total by 2020 could reduce exported emissions by 5%.

National economic policy underlines China's carbon-intensive exports. China has for many years prioritized economic growth over environmental management, maintaining 10% economic growth over the past decade, even as the world experienced a global economic crisis that slowed consumption in the major developed countries that consume most of China's exports. The Chinese government has sustained such a high level of economic growth in part by large capital investments in energy-intensive infrastructure and by favoring industry sectors with high emissions intensity[28], which has caused China's national carbon intensity to increase by 3% during 2002-2009[5,29].

There is a now large opportunity to improve the emissions intensity of the Chinese economy by focusing on a small number of provinces and sectors where more energy-efficiency technologies can be installed and by shifting the Chinese energy systems away from coal towards lower-carbon energy sources. Such improvements can be supported by both domestic and international efforts to deploy best-available technologies into critical and still underdeveloped Chinese provinces. Until the vast difference between the emissions intensity of Chinese exports and domestic production in developed countries is reduced, international trade with China conflicts with efforts to reduce global CO_2 emissions.

(2947 words)

References

1. UNFCCC. (Kyoto Protocol to the United Nations Framework Convention on Climate Change, 1997).
2. COP15. Copenhagen Accord. (2009).
3. Le Quéré, C. *et al.* The global carbon budget 1959-2011. *Earth System Science Data* **5**, 165-185, doi:10.5194/essd-5-165-2013 (2013).
4. Andres, R. J. *et al.* A synthesis of carbon dioxide emissions from fossil-fuel combustion. *Biogeosciences* **9**, 1845-1871 (2012).
5. Raupach, M. R. *et al.* Global and regional drivers of accelerating CO2 emissions. *Proceedings of the National Academy of Science* **104**, 10288-10293 (2007).
6. Liu, Z. *et al.* A low-carbon road map for China. *Nature* **500**, 143-145 (2013).
7. Weber, C. L., Peters, G. P., Guan, D. & Hubacek, K. The contribution of Chinese exports to climate change. *Energy Policy* **36**, 3572-3577 (2008).
8. Feng, K. *et al.* Outsourcing CO2 within China. *Proceedings of the National Academy of Sciences* (2013).
9. Le Quéré, C. *et al.* Global carbon budget 2014. *Earth Syst. Sci. Data* **7**, 47-85, doi:10.5194/essd-7-47-2015 (2015).
10. Jakob, M. & Marschinski, R. Interpreting trade-related CO2 emission transfers. *Nature Climate Change* **3**, 19-23 (2013).
11. Minx, J. *et al.* A "Carbonizing Dragon": China's Fast Growing CO2 Emissions Revisited. *Environmental Science & Technology* **45**, 9144-9153 (2011).
12. 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 CO2 emissions surge. *Geophysical Research Letters* **36**, L04709, doi:10.1029/2008GL036540 (2009).
13. Jiang, X. *et al.* Revealing the hidden health costs embodied in Chinese exports. *Environmental science & technology* **49**, 4381-4388 (2015).
14. Liu, Z. China's Carbon Emissions Report 2015. (2015).
15. Liu, Z., Geng, Y., Lindner, S. & Guan, D. Uncovering China's greenhouse gas emission from regional and sectoral perspectives. *Energy* **45**, 1059-1068 (2012).
16. Feng, K., Siu, Y. L., Guan, D. & Hubacek, K. Analyzing drivers of regional carbon dioxide emissions for China. *Journal of Industrial Ecology* **16**, 600-611 (2012).
17. Lindner, S., Liu, Z., Guan, D., Geng, Y. & Li, X. CO 2 emissions from China's power sector at the provincial level: Consumption versus production perspectives. *Renewable and Sustainable Energy Reviews* **19**, 164-172 (2013).
18. Liu, Z. *et al.* Embodied energy use in China's industrial sectors. *Energy Policy* **49**, 751-758 (2012).
19. Ang, B. W. The LMDI approach to decomposition analysis: a practical guide. *Energy policy* **33**, 867-871 (2005).
20. Friedlingstein, P. *et al.* Persistent growth of CO2 emissions and implications for reaching climate targets. *Nature Geosci* **7**, 709-715 (2014).
21. Liu, Z., Xi, F. & Guan, D. Climate negotiations: Tie carbon emissions to consumers. *Nature* **493**, 304-305 (2013).
22. Davis, S. J., Peters, G. P. & Caldeira, K. The supply chain of CO2 emissions. *Proceedings of the National Academy of Sciences* **108**, 18554-18559, doi:10.1073/pnas.1107409108 (2011).
23. Davis, S. J. & Caldeira, K. Consumption-based accounting of CO2 emissions. *Proceedings of the National Academy of Sciences* **107**, 5687-5692 (2010).
24. National Bureau of Statistics. *China Statistical Yearbook 2013*. (China Statistics Press, 2013).

25 Yang, Y. & Suh, S. Environmental Impacts of Products in China. *Environmental Science & Technology* **45**, 4102-4109, doi:10.1021/es103206g (2011).
26 Consultants, P. Introduction to LCA with SimaPro 7. *PRé Consultants* (2008).
27 Yang, D., Liu, J., Yang, J. & Ding, N. Life-cycle assessment of China's multi-crystalline silicon photovoltaic modules considering international trade. *Journal of Cleaner Production* **94**, 35-45, doi:10.1016/j.jclepro.2015.02.003 (2015).
28 Liu, Z. *et al.* Climate policy: Steps to China's carbon peak. *Nature* **522**, 279-281 (2015).
29 Guan, D. *et al.* Determinants of stagnating carbon intensity in China. *Nature Climate Change* **4**, 1017-1023 (2014).

Methods (online only)

Production-based accounting of emissions. Emissions resulting from combustion of fossil fuels or cement production within a territory, or production-based emissions, are the primary basis for national emission inventories[30,31]. For example, the methodology prescribed in IPCC guidelines for greenhouse gas (GHG) emission inventories calculates production-based emissions based on activity data in the region (i.e. the amount of energy consumption) and the associated emission factors (i.e. GHG emissions per unit energy consumption), the emission factors are based on in situ measurements in which the value is lower than IPCC suggested[30] .

$$\text{Emission} = \sum\sum\sum(Activity\ data_{i,j,k} \times Emission\ factor_{i,j,k} \quad (1)$$

Notes: i: fuel types, j: sectors, k: technology type.

Emission factors can be further disaggregated into net heating value of certain fuel "*V*", carbon content "*F*" and oxidization rate "*O*".

$$\text{Emission} = \sum\sum\sum(Activity\ data_{i,j,k} \times V_{i,j,k} \times F_{i,j,k} \times O_{i,j,k} \quad (2)$$

Detailed calculation process can be seen in literature[30].

Consumption-based accounting of emissions. An alternative to production-based accounting of CO_2 emissions is to compile inventories according to where related goods and services are ultimately consumed. Such a consumption-based method accounts for inter-regional exchange of energy supply, goods and materials by adding emissions embodied in imports to the production-based total and subtracting emissions embodied in exports.

The emissions embodied in a region's imports and exports can be calculated using environmentally-extended input-output analysis (EIO). Environmentally-extended multi-regional input-output (MRIO) analysis has been widely developed for calculating the embodied carbon emission[8,11,23], virtual water[32,33], material use[34], biodiversity loss[35], and land use[36,37] associated with international trade.

In MRIO framework, different regions are connected through inter-regional trade, Z^{rs}. The technical coefficient sub-matrix A^{rs} consists of "$[a_{ij}^{rs}]$" is derived from $a_{ij}^{rs} = z_{ij}^{rs}/x_j^s$, where z_{ij}^{rs} is the inter-sector monetary flow from sector *i* in region *r* to sector *j* in region *s*; x_j^s is the total output of sector *j* in region *s*. The final demand matrix is Y consist of "$[y_i^{rs}]$", where y_i^{rs} is the region's final demand for goods of sector *i* from region *r*. Therefore, MRIO analysis can be shown as:

$$\begin{bmatrix} x^1 \\ x^2 \\ x^3 \\ \vdots \\ x^n \end{bmatrix} = \begin{bmatrix} A^{11} & A^{12} & \cdots & A^{1n} \\ A^{21} & A^{22} & \cdots & A^{2n} \\ A^{31} & A^{31} & \cdots & A^{3n} \\ \vdots & \vdots & \ddots & \vdots \\ A^{n1} & A^{n2} & \cdots & A^{nn} \end{bmatrix} \begin{bmatrix} x^1 \\ x^2 \\ x^3 \\ \vdots \\ x^n \end{bmatrix} + \begin{bmatrix} \sum_s y^{1s} \\ \sum_s y^{2s} \\ \sum_s y^{3s} \\ \vdots \\ \sum_s y^{ns} \end{bmatrix} \quad (3)$$

Using familiar matrix notation and dropping the subscripts, Equation 3 can be written as: x = Ax + y or x = $(I - A)^{-1}y$, where $(I - A)^{-1}$ is the Leontief inverse matrix that captures both direct and indirect inputs required to satisfy one unit of final demand in monetary value; I is the identity matrix. To calculate the consumption-based CO_2 emissions, we then extend the MRIO table with sector-specific CO_2 emissions: E = $k (I - A)^{-1}y$, where E is the total CO_2 emissions embodied in goods and services used for final demand and k is a vector of CO_2 emissions per unit of economic output for all economic sectors in all regions.

Index decomposition analysis of emissions embodied in trade. The index decomposition of trade embodied CO_2 emissions is presented by equation:

$$E = \sum_i E_i = \sum_i Q \frac{Q_i}{Q} \frac{V_i}{Q_i} \frac{E_i}{V_i} = \sum_i Q S_i I_i F_i \quad (4)$$

where E describes CO_2 emissions embodied in imports or exports, Q is the GDP value of imports or exports, S_i refers to the share of the GDP value for sector i, I_i to energy intensity of sector i and F_i refers to the emission per unit of energy consumption of of sector i *(i* for 46 sectors). Thus, the factors contributing to a net trade in embodied emissions can be expressed based on the logarithmic mean divisia index (LMDI) approach (additive form) [19]as:

$$\Delta E = E^{export} - E^{import} = \Delta E_{act} + \Delta E_{str} + \Delta E_{int} + \Delta E_{mix} \quad (5)$$

Where ΔE is the difference between the CO_2 emissions embodied in exports (E^{export}) and the CO_2 emissions embodied in imports (E^{import}); ΔE_{act}, ΔE_{str}, ΔE_{int} and ΔE_{str} refer to economic scale effect, economic structure effect, sector intensity effect and energy mix effect, respectively. Where ΔE_{act}, ΔE_{str} , ΔE_{int} and ΔE_{str} are expressed as:

$$\Delta E_{act} = \sum_i w_i \ln\left(\frac{Q_i^t}{Q_i^0}\right) \quad (6)$$

$$\Delta E_{str} = \sum_i w_i \ln\left(\frac{S_i^t}{S_i^0}\right) \quad (7)$$

$$\Delta E_{int} = \sum_i w_i \ln\left(\frac{I_i^t}{I_i^0}\right) \quad (8)$$

$$\Delta E_{mix} = \sum_i w_i \ln\left(\frac{F_i^t}{F_i^0}\right) \quad (9)$$

$$w_i = \frac{E_i^t - E_i^0}{\ln E_i^t - \ln E_i^0} \quad (10)$$

Q^t , S^t , I^i *and* F^0 is the GDP, GDP share, energy intensity and the emission coefficient of export, respectively. Q^0 , S^0, I^0 *and* F^0 is GDP, GDP share, energy intensity and the emission coefficient of imports, respectively.

Estimates of sectoral level imported and exported CO_2 emissions

In a region IO model, a regional economy is considered as its system boundary, thus exports are treated as final products in a region's economy. Let G_i^r be the total CO_2 emissions in economic sector *i* and region *r*, thus $\sum_i G_i^r$ represents the production-based emissions in region *r*. In each region *r*, there are intermediate consumption, denoted Z_{ij}^r, which represents the domestic purchases of sector *i* by sector *j* in region *r* and final consumption, denoted y_i^r, represents the domestic purchases of sector *i* by final consumers in region *r* which includes households, government, capital investments. In the single region IO model, exports, e_i^{rs} , from region *r* to region *s* are also treated as final consumption. By summing intermediate and final consumption, we can obtain the total output in each region:

$$x^r = Z^{rr} + y^{rr} + \sum_s e^{rs} \quad \text{(S1)}$$

By assuming fixed production ratios, we obtain the technical coefficients, A_{ij}^{rr}, the ratio of input to output, by diving Z_{ij}^{rr} by x_j^r:

$$A_{ij}^{rr} = Z_{ij}^{rr} / x_j^r \quad \text{(S2)}$$

Thus, Equation (S1) can be re-written as:

$$x^r = (I - A^{rr})^{-1} * (y^{rr} + \sum_s e^{rs}) \quad \text{(S3)}$$

Where $(I - A^{rr})^{-1}$ is Leontief inverse matrix for region *r*.

CO_2 emissions are estimated based on the direct emission intensity, k^r in each sector in region *r*.

$$k_i^r = G_i^r / x_i^r \quad \text{(S4)}$$

Therefore, the total embodied emissions (direct and indirect) in exports from region *r* to region *s* can be calculated by:

$$Exp^r = k^r (I - A^{rr})^{-1} \hat{e}^{rs} \quad \text{(S5)}$$

where Exp^r is a vector of embodied CO_2 emissions in sectoral exports of region *r* to region *s*; k^r is a row vector of sectoral emissions intensities in region *r*; $\hat{e}^{rs}$ is a matrix with sectoral export from region *r* to region *s* on diagonal.

In turn, the total embodied emissions in imports from region s to region r can be estimated by:

$$Imp^r = k^s (I - A^{ss})^{-1} \hat{e}^{sr} \quad \text{(S6)}$$

where Imp^r is a vector of embodied CO_2 emissions in sectoral imports of region *s* to region *r*; k^s is a row vector of sectoral emissions intensities in region *s*; $\hat{e}^{sr}$ is a matrix with sectoral import from region *s* to region *r* on diagonal.

Emissions and trade data. In this study we estimate emissions from fossil fuel energy combustion and cement production, which together account for about 90% of GHG emissions produced in China. Our calculations include 20 different types of fuel and 46 energy consumption sectors. Further details of data sources and processing methods are available in Liu et al. (2015)[30], Liu et al. (2012)[15] and Guan et al. (2012)[38].

Our multi-regional input-output (MRIO) relies on data from the Global Trade Analysis Project (GTAP)[39], which includes 129 regions (mostly countries, but some aggregated regions). Although GTAP data covers 57 industry sectors, we aggregate to 30 sectors in order to match input-output tables of interprovincial trade compiled by Liu *et al.* at the Chinese Academy of Sciences[40]. In turn, we use Liu *et al.*'s tables to disaggregate the Chinese region in GTAP into 30 sub-regions (26 provinces and 4 cities). Thus, we have a global MRIO comprised of the latest available economic data that allows us to assess consumption-based CO_2 emissions in each Chinese sub-region as well as emissions embodied in trade among these sub-regions and all 129 other GTAP regions around the world. Technical details of how the Chinese IO tables are nested with the GTAP MRIO are available in Feng *et al.* (2013)[8].

References:

30 Liu, Z. *et al.* Reduced carbon emission estimates from fossil fuel combustion and cement production in China *Nature*, doi:DOI 10.1038/nature14677 (2015).

31 IPCC. *Guidelines for National Greenhouse Gas Inventories*. Vol. 4 (IPCC WGI Technical Support Unit, 2006).

32 Feng, K., Hubacek, K., Pfister, S., Yu, Y. & Sun, L. Virtual Scarce Water in China. *Environmental Science & Technology* **48**, 7704-7713 (2014).

33 Lenzen, M. *et al.* International trade of scarce water. *Ecological Economics* **94**, 78-85 (2013).

34 Wiedmann, T. O. *et al.* The material footprint of nations. *Proceedings of the National Academy of Sciences*, doi:doi: 10.1073/pnas.1220362110 (2013).

35 Lenzen, M. *et al.* International trade drives biodiversity threats in developing nations. *Nature* **486**, 110-112 (2012).

36 Yu, Y., Feng, K. & Hubacek, K. Tele-connecting local consumption to global land use. *Global Environmental Change* **23**, 1178-1186 (2013).

37 Weinzettel, J., Hertwich, E. G., Peters, G. P., Steen-Olsen, K. & Galli, A. Affluence drives the global displacement of land use. *Global Environmental Change* **23**, 433-438 (2013).

38 Guan, D., Liu, Z., Geng, Y., Lindner, S. & Hubacek, K. The gigatonne gap in China's carbon dioxide inventories. *Nature Climate Change* **2**, 672-675 (2012).

39 Narayanan, B. G., Aguiar, A. & Walmsley, T. L. *Global Trade, Assistance, and Production: The GTAP 8 Data Base*. (Purdue University, 2012).

40 Liu, W. Theories and Practice of Constructing China's Interregional Input-Output Tables between 30 Provinces in 2007. (Beijing, 2012).

Author Contributions: Z.L., K.F. and S.J.D. designed the research. : Z.L., K.F. and S.J.D. conceived the paper. K. F. and J. L. provided the data. Z.L., S.J.D., K. F. and K.H. performed the analysis. S.J.D. drew the figures. All authors contributed to writing the paper.

Acknowledgements

Z.L. acknowledges the Giorgio Ruffolo fellowship and the support from Italy's Ministry for Environment, Land and Sea. S.J.D acknowledges support from the Institute of Applied Ecology, Chinese Academy of Sciences Fellowships for Young International Distinguished Scientists. S.L. thanks the support of the Dow Sustainability Fellows Program.

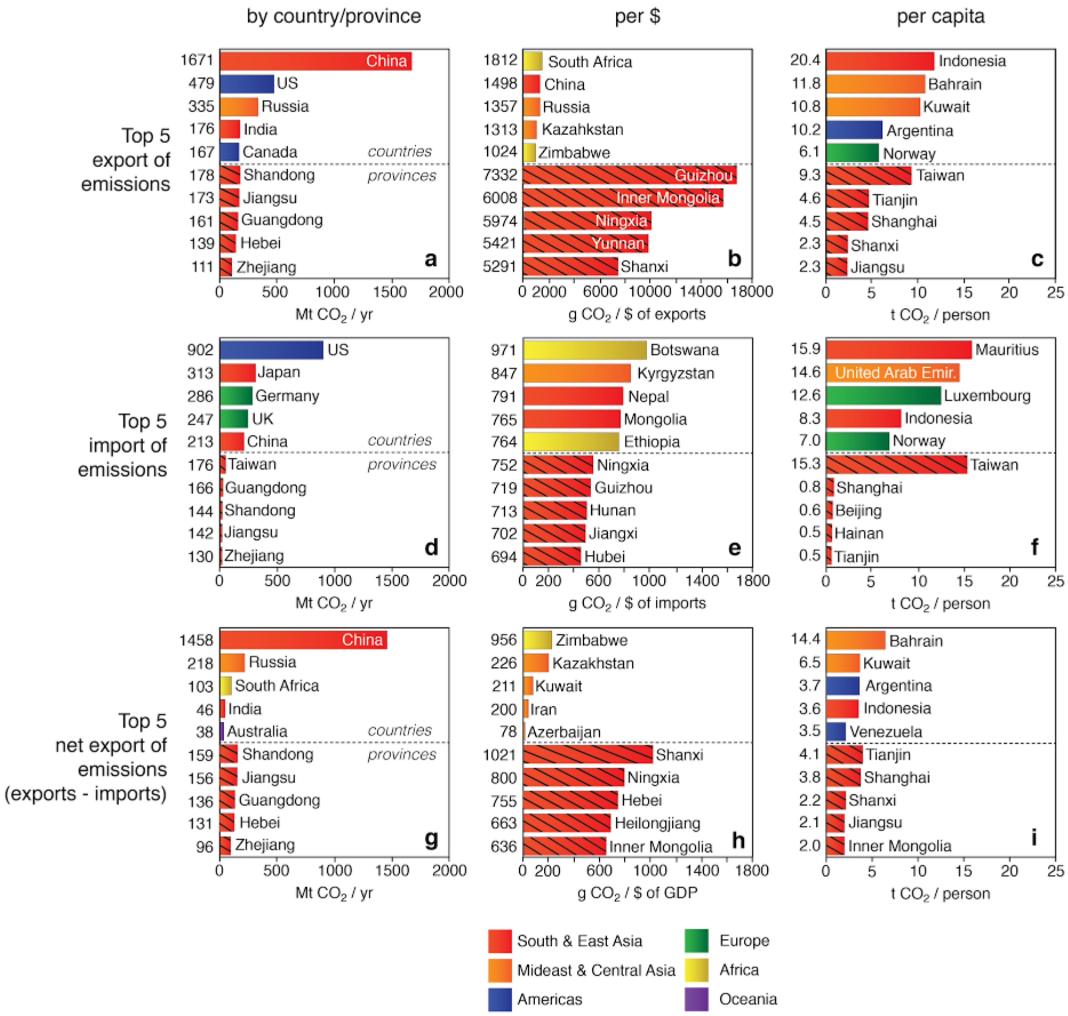


Figure 1 | Emissions embodied in trade. Top ten regions (including top five countries and top five Chinese cities/provinces) by emissions embodied in exports (**a-c**), imports (**d-f**) and net trade (**g-i**), shown in absolute numbers (**a, d, g**), per dollar of output (**b, e, h**) and per capita (**c, f, i**). Data is in year 2007.

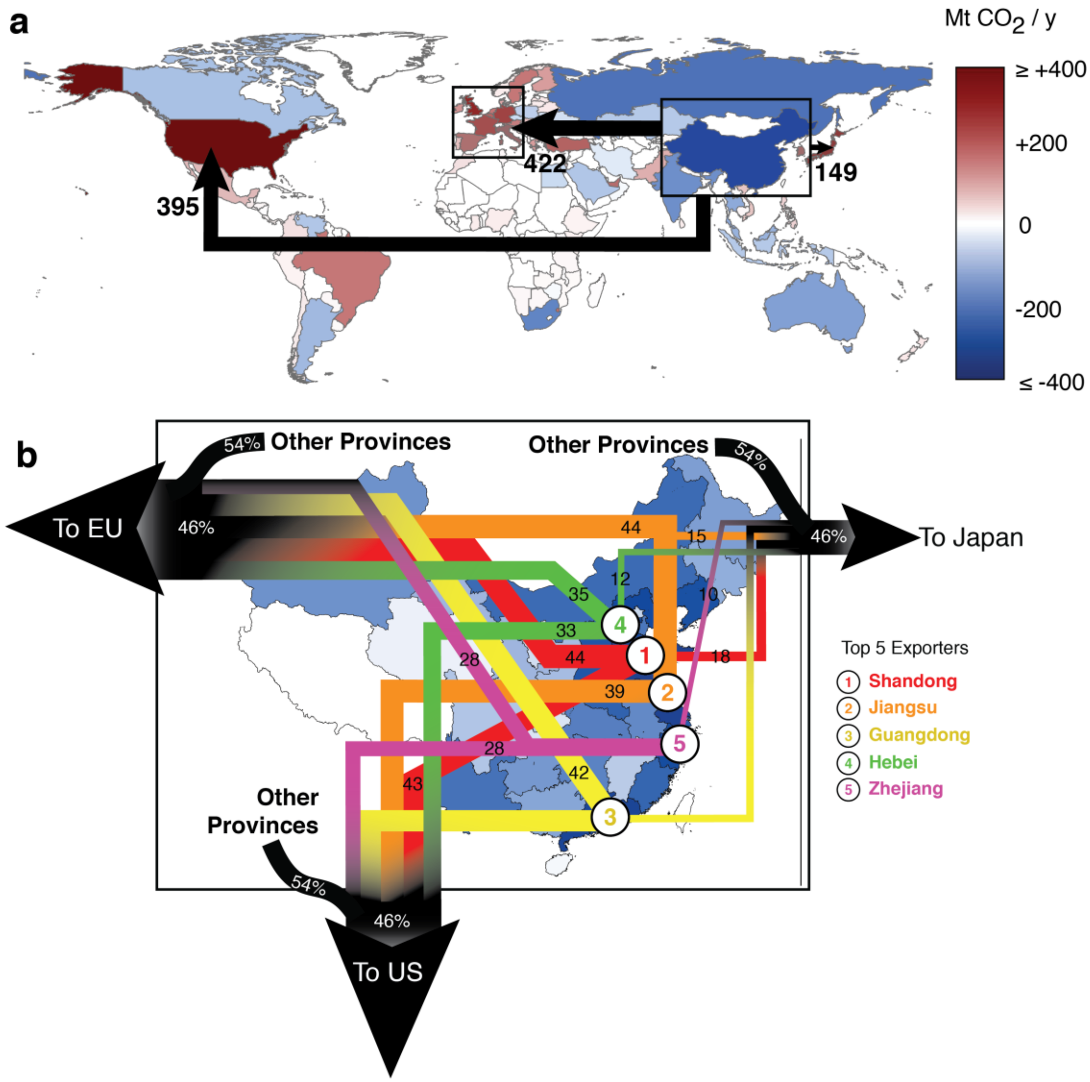


Figure 2 | Top exporting provinces. The emissions embodied in goods exported from China to the US, EU and Japan represented 58% of all emissions embodied in trade in 2007 (**a**). Five Chinese provinces account for 46% of these exports (**b**).

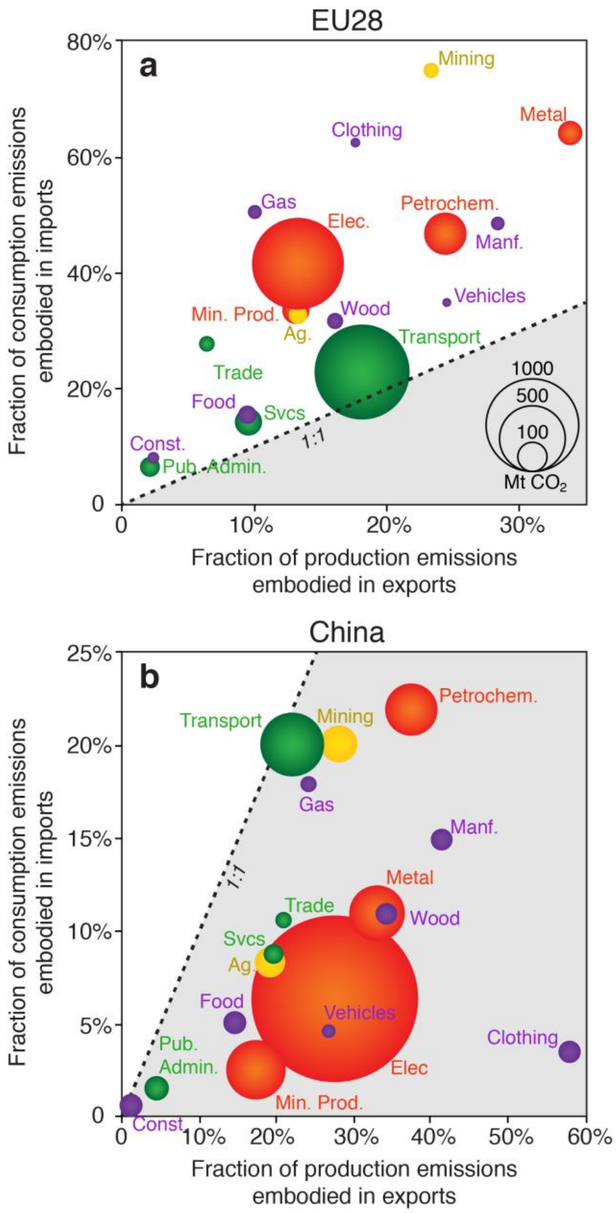


Figure 3 | Differences in share of embodied emissions traded by industry categories. Circles indicate the share of consumed emissions that are imported (y-axis) and the share of produced emissions that are exported (x-axis) for a range of industry categories in Europe (**a**) and China (**b**). The size of each circle denotes the sector's total production emissions, providing an indicator of the relative importance of different sectors. The colours of the circles indicate whether the industries are primary (yellow), secondary and energy-intensive (red), secondary and non-energy intensive (purple) or tertiary (green). It should be noted that while the marker area scale is common across both charts (to aid comparison); the x- and y-axis scales differ. A line representing equal import and export share is shown in each chart. Data is in year 2007.

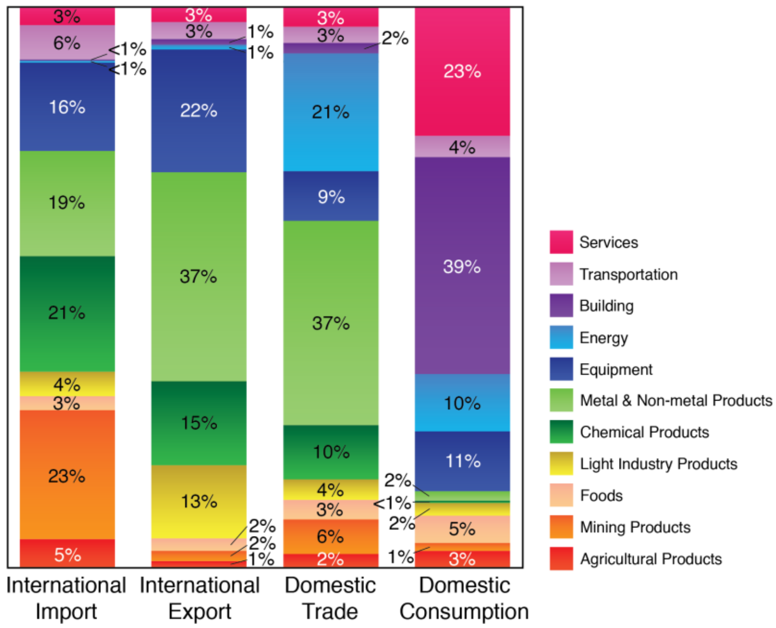


Figure 4 | Sectoral share of China's embodied emissions. Data is in year 2007.

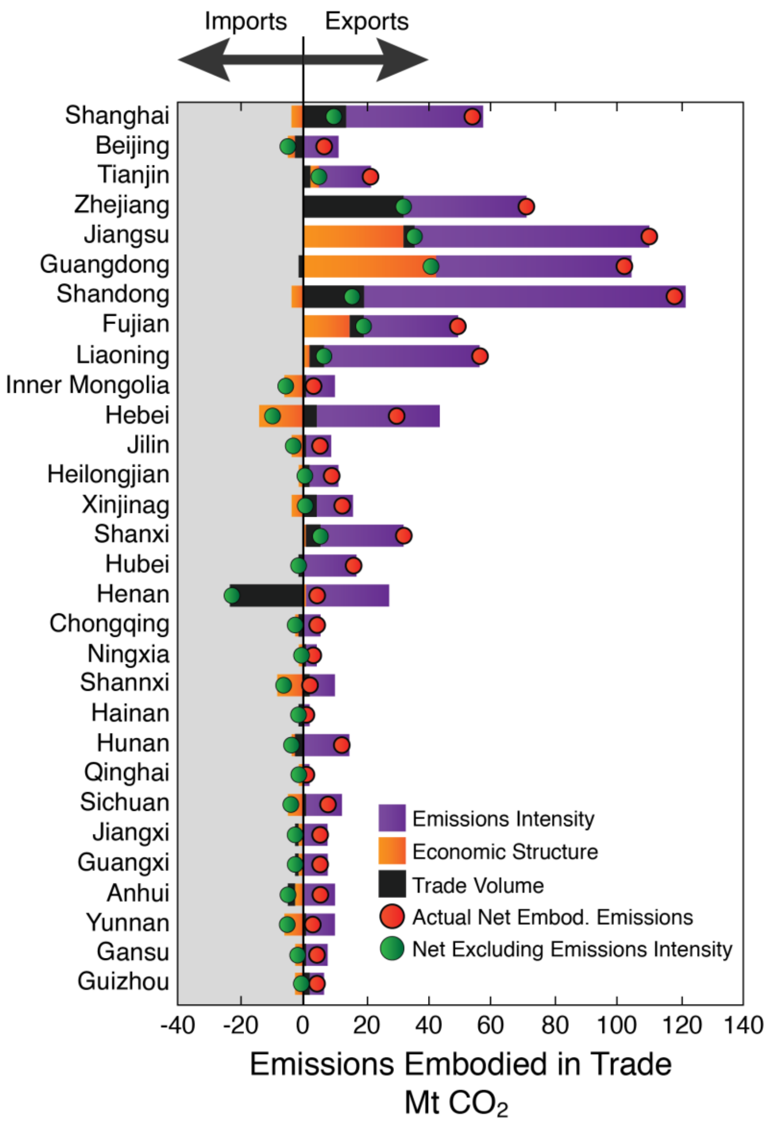
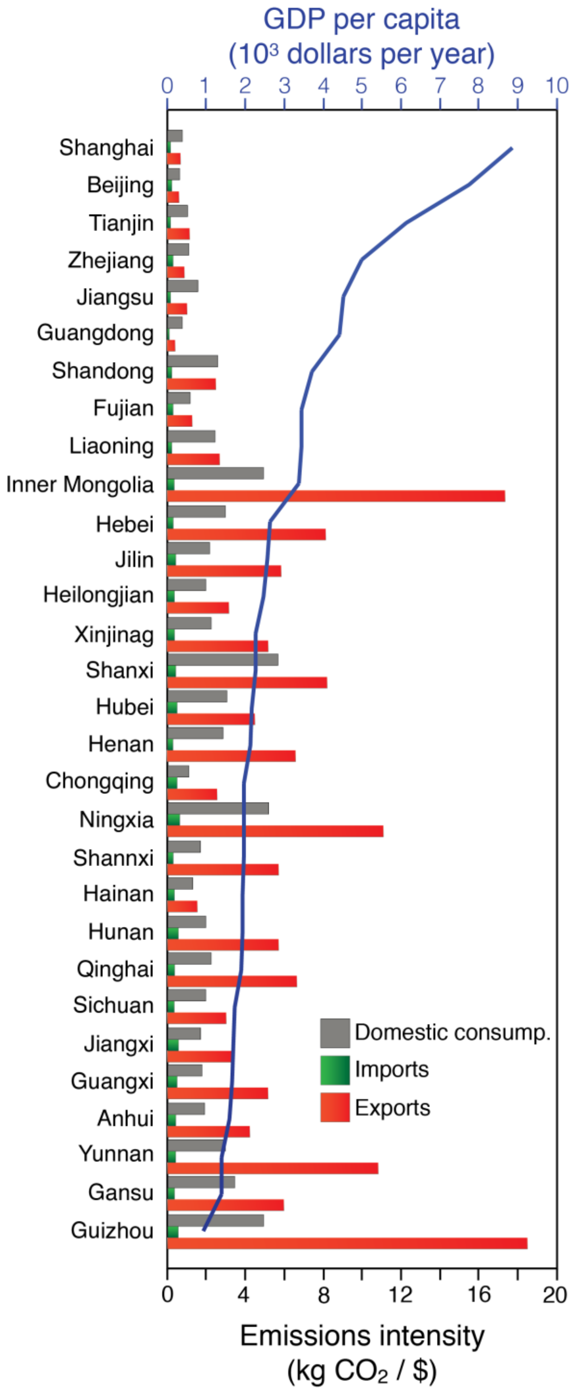


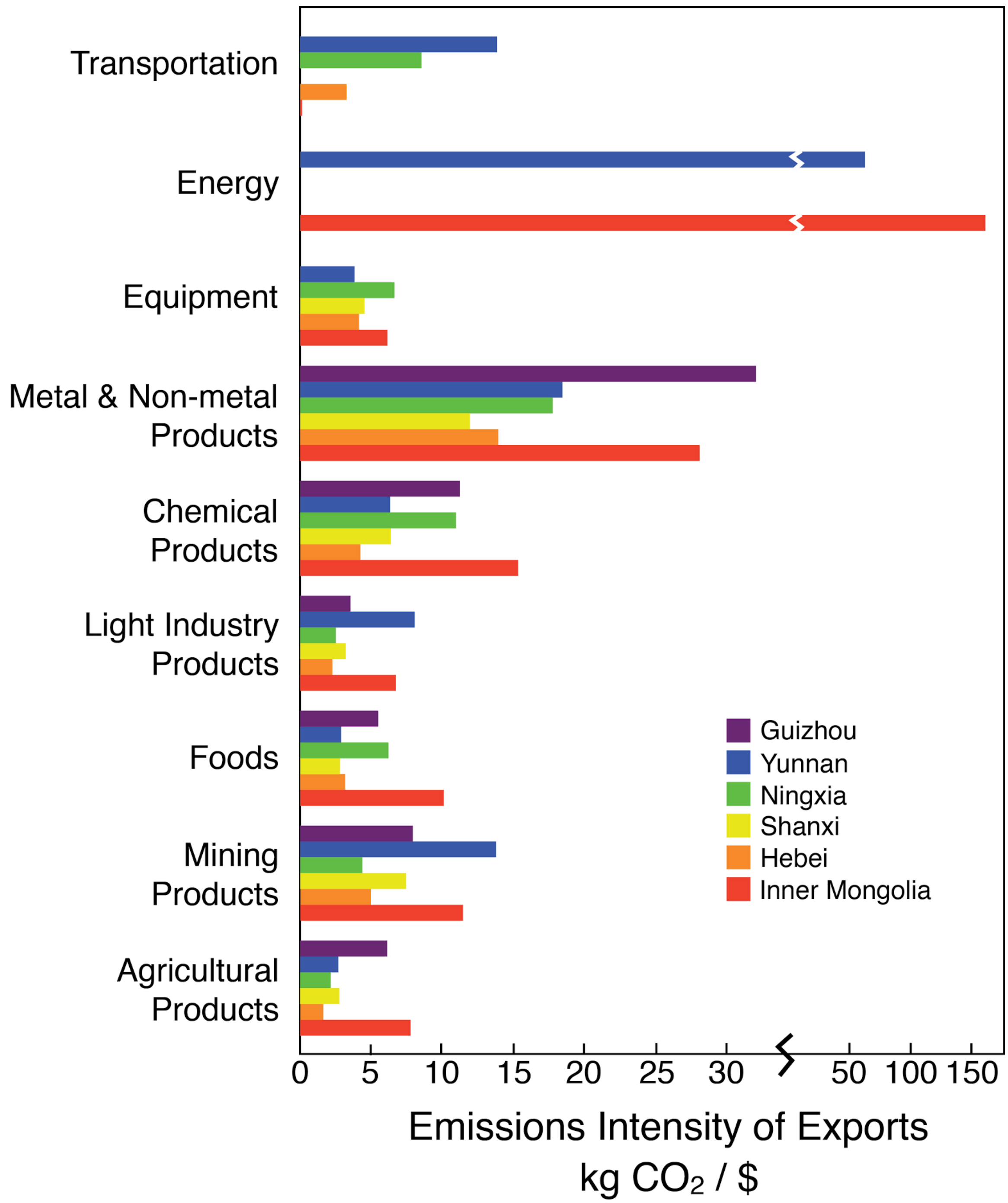
Figure 5 | Factors contributing to emissions embodied in provincial trade. Decomposition of factors underlying emissions embodied in trade for each of 30 Chinese cities/provinces. Net emissions embodied in trade (red circles) are equal to emissions embodied in exports minus emissions embodied in imports. Black bars show the effect of unbalanced trade volume; orange bars show the effect of differences in the industry sectors involved in trade (i.e. trade structure, for example, the proportation of heavy industries); and purple bars show the effect of differences in the emissions intensity of imported and exported goods. Green circles show what net emissions embodied in trade would be if there was no difference in the emissions intensity of imported and exported goods—i.e. if trade volume and economic structure were the only factors affecting embodied emissions. In reality, all 30 regions are net exporters of emissions, but only 11 of the 30 would remain net exporters of emissions if differences in emissions intensity were eliminated.

Table 1 Life cycle carbon emission intensity for 15 products from China and EU, unit: CO_2 kg/kg production.

	China-average	EU-average
Flat glass production	2.55	1.05
Crushed limestone	4.53	1.81
Propylene	21.2	1.15
ABS	11.6	3.63
Copper concentrate	0.436	0.357
Steel by electricity stove	5.23	3.62
Steel production	5.68	1.97
Cast iron production	5.45	1.31
Aluminum ingot production	68.4	10.4(USLCI)
Cast iron production	5.45	1.31
Pig iron production	3.23	1.34
Iron sinter production	1.89	0.331
Magnesium alloy production	34.3	11.5
Anode slime copper production	4.82	3.4
Water production	0.00196	0.0003



Extended Data Figure 1 | Emissions intensity of trade and GDP per capita of Chinese provinces in 2007. Kilograms of CO_2 per dollar of output in each of 30 Chinese cities/provinces for international export (red bars) and domestic consumption in China (gray bars), as well as the emissions intensity of goods imported to the city/province from outside China (green bars). The blue curve shows GDP per capita in each city/province according to the top axis.



Extended Data Figure 2, Sector-specific emissions intensity. In the six provinces with the highest emissions intensity, the energy sector dominates in Yunnan and Inner Mongolia, metal and non-metal products are intensive in all the provinces, especially Guizhou, and chemical products are also notably intensive. Where there are no bars, there are no exports from that sector-province.

Extended Data Table 1 Sector classification

Sector code	Original sectors	Aggregated sectors
1	Farming, Forestry, Animal Husbandry, Fishery and Water Conservancy	Agriculture products
2	Coal Mining and Dressing	Mining products
3	Petroleum and Natural Gas Extraction	
4	Ferrous Metals Mining and Dressing	
5	Nonferrous Metals Mining and Dressing	
6	Nonmetal Minerals Mining and Dressing	
7	Other Minerals Mining and Dressing	
8	Food Processing	Foods
9	Food Production	
10	Beverage Production	
11	Logging and Transport of Wood and Bamboo	Light industry products
12	Tobacco Processing	
13	Textile Industry	
14	Garments and Other Fiber Products	
15	Leather, Furs, Down and Related Products	
16	Timber Processing, Bamboo, Cane, Palm Fiber & Straw Products	
17	Furniture Manufacturing	
18	Papermaking and Paper Products	
19	Printing and Record Medium Reproduction	
20	Cultural, Educational and Sports Articles	
21	Petroleum Processing and Coking	Chemical products
22	Raw Chemical Materials and Chemical Products	
23	Medical and Pharmaceutical Products	
24	Chemical Fiber	
25	Rubber Products	
26	Plastic Products	
27	Nonmetal Mineral Products	No metal and Metal products
28	Smelting and Pressing of Ferrous Metals	
29	Smelting and Pressing of Nonferrous Metals	
30	Metal Products	
31	Ordinary Machinery	
32	Equipment for Special Purposes	Equipment
33	Transportation Equipment	
34	Electric Equipment and Machinery	
35	Electronic and Telecommunications Equipment	
36	Instruments, Meters, Cultural and Office Machinery	
37	Other Manufacturing Industry	
38	Production and Supply of Electric Power, Steam and Hot Water	Energy
39	Production and Supply of Gas	
40	Production and Supply of Tap Water	
41	Construction	Building
42	Transportation, Storage, Post and Telecommunication Services	Transportation
43	Wholesale, Retail Trade and Catering Services	Services
44	Others	

45	Urban Household Consumption	Household Consumption
46	Rural Household Consumption	