Outsourcing CO_2 within China

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Recent studies have shown that the high standard of living enjoyed by people in the richest countries often comes at the expense of CO_2 emissions produced with technologies of low efficiency in less affluent, developing countries. Less apparent is that this relationship between developed and developing can exist within a single country's borders, with rich regions consuming and exporting high-value goods and services that depend upon production of low-cost and emission-intensive goods and services from poorer regions in the same country. As the world's largest emitter of CO_2, China is a prominent and important example, struggling to balance rapid economic growth and environmental sustainability across provinces that are in very different stages of development. In this study, we track CO_2 emissions embodied in products traded among Chinese provinces and internationally. We find that 57% of China's emissions are related to goods that are consumed outside of the province where they are produced. For instance, up to 80% of the emissions related to goods consumed in the highly developed coastal provinces are imported from less developed provinces in central and western China where many low–value-added but high–carbon-intensive goods are produced. Without policy attention to this sort of interprovincial carbon leakage, the less developed provinces will struggle to meet their emissions intensity targets, whereas the more developed provinces might achieve their own targets by further outsourcing. Consumption-based accounting of emissions can thus inform effective and equitable climate policy within China.

embodied emissions in trade | regional disparity | multiregional input–output analysis

As the world's largest CO_2 emitter, China faces the challenge of reducing the carbon intensity of its economy while also fostering economic growth in provinces where development is lagging. Although China is often seen as a homogeneous entity, it is a vast country with substantial regional variation in physical geography, economic development, infrastructure, population density, demographics, and lifestyles (1). In particular, there are pronounced differences in economic structure, available technology, and levels of consumption and pollution between the well-developed coastal provinces and the less developed central and western provinces (2).

In the 2009 Copenhagen Climate Change Conference of the United Nations Framework Convention on Climate Change, China committed to reducing the carbon intensity of its economy [i.e., CO_2 emissions per unit of gross domestic product (GDP)] by 40–45% from 2005 levels and to generating 15% of its primary energy from nonfossil sources by 2020 (3). In the meantime, China's 12th 5-year plan sets a target to reduce the carbon intensity of its economy by 17% from 2010 levels by 2015 (4), with regional efforts ranging from a 10% reduction of carbon intensity in the less developed west and 19% reduction in east coast provinces. Thus, the regions that produce the most emissions and use the least advanced technologies have less stringent intensity targets than the more affluent and technologically advanced regions (5), where the costs of marginal emissions abatement are much higher. In further recognition of such regional inequities, pilot projects are being implemented to test the feasibility and efficacy of interprovincial emissions trading (6–9). Additionally, progress against emissions targets could be evaluated not only by "production-based" inventories of where emissions occur, but also by "consumption-based" inventories that allocate emissions to the province where products are ultimately consumed (10). Such consumption-based accounting of CO_2 emissions may better reflect the ability to pay costs of emissions mitigation (11).

Details of our analytic approach are presented in *Materials and Methods*. In summary, we track emissions embodied in trade both within China and internationally using a global multiregional input–output (MRIO) model of 129 regions (including 107 individual countries) and 57 industry sectors, in which China is further disaggregated into 30 subregions (26 provinces and 4 cities). Although a number of recent studies have used a similar MRIO approach to assess the emissions embodied in international trade (12–14), studies of emissions embodied in trade within individual countries remain rare due to a lack of data. Here, we use the latest available data to construct input–output tables of interprovincial trade and nest these tables within a global MRIO database. From this framework, we calculate CO_2 emissions associated with consumption in each of the 30 Chinese subregions as well as emissions embodied in products traded between these subregions and the rest of the world (i.e., 128 regions).

Results

In 2007, 57% of China's emissions from the burning of fossil fuels, or 4 gigatonnes (Gt) of CO_2, were emitted during production of goods and services that were ultimately consumed in different provinces in China or abroad. To facilitate reporting and discussion of our results, we group 30 Chinese provinces and cities into eight geographical regions (for details of this grouping, see Fig. 2). Fig. 1, *Upper Left*, shows the largest gross fluxes of embodied emissions among the eight regions, with regions shaded according to net emissions embodied in trade (i.e., the difference between production and consumption emissions) in each region. Beijing–Tianjin, the Central Coast, and the South Coast are the most affluent regions in China, with large imports of emissions embodied in goods from poorer central and western provinces. More than 75% of emissions associated with products consumed in Beijing–Tianjin occur in other regions. Similarly, the Central Coast and South Coast regions outsource about 50% of their consumption emissions.

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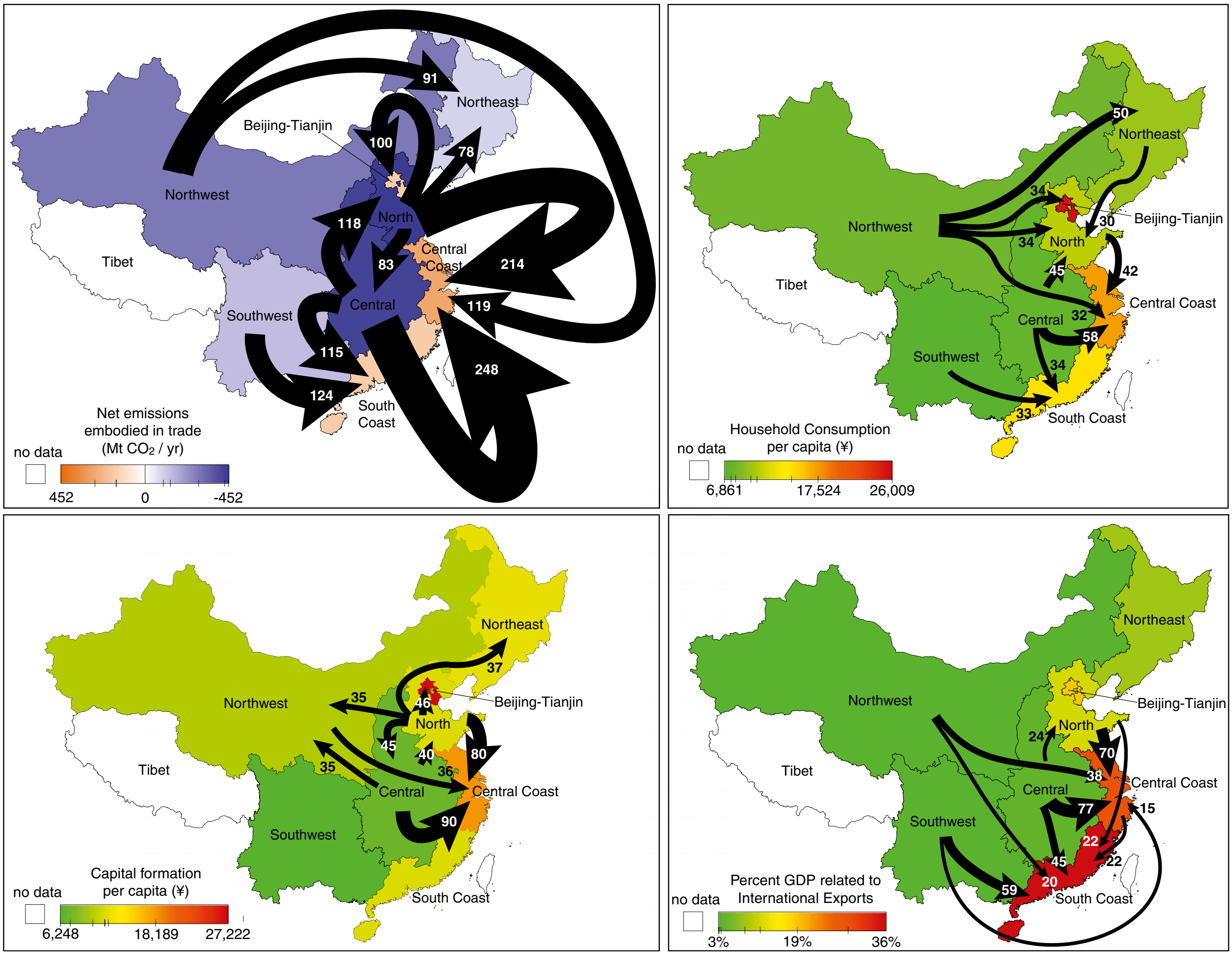

Fig. 1. *Upper Left* shows largest interprovincial fluxes (gross) of emissions embodied in trade (megatonnes of CO_2 per year) among net exporting regions (blue) and net importing regions (red). *Upper Right* shows the largest interprovincial fluxes of emissions embodied in products consumed by households, with regions shaded according to value of household consumption per capita (from high in red to low in green). *Lower left* shows the largest interprovincial fluxes of emissions embodied in products consumed by capital formation, with regions shaded according to the value of capital formation per capita (from high in red to low in green). *Lower Right* shows the largest interprovincial fluxes of emissions embodied in products destined for international export, with regions shaded according to the share of GDP related to international exports (from high in red to low in green). Note: carbon fluxes caused by government expenditure are not shown separately in this figure but are included in the total emissions embodied in trade (*Upper Left*).

The other maps in Fig. 1 highlight emissions embodied in products traded within China that are triggered by different categories of GDP: household consumption (*Upper Right*), capital formation (*Lower Left*), and international exports (*Lower Right*). People living in Beijing–Tianjin, Central Coast, and South Coast provinces have much higher per capita household consumption than do people living in other provinces. For example, household consumption per capita in Beijing–Tianjin in 2007 was more than three times the consumption in the Southwest region. However, our analysis shows that higher levels of household consumption in more developed coastal regions are being supported by production and associated emissions occurring in less developed neighboring regions (Fig. 1, *Upper Right*). In the case of Beijing–Tianjin, household consumption causes emissions in the Northwest (34 Mt) and North (29 Mt) regions. Similarly, substantial emissions related to household consumption in the Central Coast region are outsourced to the Central (58 Mt), North (42 Mt), and Northwest (32 Mt) regions, and household consumption in South Coast is supported by emissions in the Central (34 Mt) and Southwest (33 Mt) regions. Interestingly, emissions in the North region support household consumption in more affluent coastal regions, but at the same time, household consumption emissions in the North region are in turn outsourced to the Central (45 Mt) and Northwest (34 Mt) regions.

In keeping with its rapid growth but in contrast to most countries, capital formation (i.e., new infrastructure and other capital investments) in China represents a larger share of GDP (42% in 2007) than household consumption (36% in 2007). In addition, in less-developed western provinces such as Guangxi, Qinghai, Ningxia, and Inner Mongolia, capital formation in recent years has represented an even greater proportion of provincial GDP, for example, more than 70% in 2010. Because such capital formation often entails energy-intensive materials like cement and steel, it is also responsible for a large proportion of China's emissions: 37% in 2007. The largest transfers of embodied emissions caused by capital formation were to the Central Coast from the Central (90 Mt), North (80 Mt), and Northwest regions (36 Mt); and capital formation in Beijing–Tianjin was supported by substantial emissions produced in the North (46 Mt) (Fig. 1, *Lower Left*). Partly in contrast to the dominant pattern of emissions embodied in interprovincial trade for household consumption, the emissions related to capital formation reflect the large-scale expansion of infrastructure that is underway in relatively poor regions such as Southwest and Northwest, such that less developed provinces are in some cases outsourcing emissions to the more affluent regions of eastern China. For example, in 2007 emissions in the North region supported capital formation in the Northwest (35 Mt) and Central (45 Mt) regions.

Previous studies have emphasized international exports as a primary driver of Chinese CO_2 emissions (15–18). According to China's statistical yearbook, 74% of China's exports in 2007 originated in provinces of the Central Coast and South Coast regions (19). However, here we find that 40% of the emissions related to exports from these coastal regions actually occurred in other regions of China (Fig. 1, *Lower Right*). In particular, international exports from the Central Coast region were supported by substantial emissions in the Central (77 Mt), North (70 Mt), and Northwest (38 Mt) regions. Similarly, international exports from the South Coast were supported by large amounts of emissions in Southwest (59 Mt), Central (45 Mt), and Northwest (20 Mt) regions.

Fig. 2 shows the balance of emissions embodied in China's interprovincial and international trade. In provinces in which net export of emissions is large (e.g., Hebei, Henan, Inner Mongolia, and Shanxi), a substantial portion (in those cases, 81–94%) of the emissions embodied in exports were for intermediate (i.e., unfinished) goods traded to other provinces in China. In contrast, 38–54% of the emissions imported to Hebei, Henan, Inner Mongolia, and Shanxi were embodied in finished goods. In Inner Mongolia, exported emissions are also driven by the dominance of energy-intensive heavy industry (more than 70% of that province's gross industrial output in 2007) and coal use (92% of its fuel mix). Meanwhile, Guangdong, Zhejiang, Shanghai, Tianjin, and Beijing are net importers of embodied emissions, with a relatively high proportion of imported emissions embodied in finished goods: from 12% in Zhejiang up to 62% in Tianjin. This shows that the poorer regions export a larger share of low–value-added and import a larger share of high-value products.

Not surprisingly, in each province the emissions embodied in international exports exceeded emissions embodied in imports from other countries in 2007 (Fig. 2). In coastal provinces such as Shandong, Jiangsu, Guangdong, Zhejiang, Shanghai, and Fujian, a considerable fraction of emissions produced support international exports, ranging from 35% to 51% in 2007, whereas for central and western provinces (e.g., Anhui, Hunan, Hubei, Yunnan, Xinjiang), this share is generally less than 25%. However, as discussed above, substantial emissions in these interior provinces are embodied in intermediate goods exported to coastal provinces, where they become part of finished goods for international export.

Fig. 3, row 1, *Left*, shows the largest net domestic importers of embodied emissions produced elsewhere in China, dominated by affluent cities and provinces along the coast such as Zhejiang, Shanghai, Beijing, Guangdong, and Tianjin. The main net domestic exporters of these emissions include mostly less developed provinces in the Central and Northwest regions of China such as Inner Mongolia, Shanxi, and Henan, as well as a few provinces in the North and Northeast regions such as Hebei, Shangdong, and Liaoning. Normalizing net domestic imports of emissions per unit of GDP (Fig. 3, row 1, *Center*) and per capita (Fig. 3, row 1, *Right*) further emphasizes the disproportionate outsourcing of emissions from rich coastal cities such as Shanghai, Beijing, and Tianjin. In the case of net domestic exports of emissions per unit GDP (Fig. 3, row 2, *Center*), we find that the carbon intensity of net domestic exports is greatest in Inner Mongolia (247 g of CO_2 embodied in net exports per ¥GDP), Shanxi (164 g per ¥GDP), and Hebei (144 g per ¥GDP) due to the prevalence of heavy industry and/or energy products (i.e., coal and electricity) exported from these provinces.

Overall consumption-based emissions are greatest in large and rich coastal provinces such as Shangdong, Jiangsu, Guandong, Zhejiang, Hebei, Liaoning, and Shanghai, as well as populous provinces such as Henan and Sichuan (Fig. 3, row 3, *Left*). However, the provinces with the lowest consumption-based emissions include the least developed provinces in the Central, Northwest, and Southwest regions as well as cities or provinces with relatively small populations (e.g., Tianjin) (Fig. 3, row 4, *Left*). However, the consumption-based carbon intensity (emissions per unit GDP) is

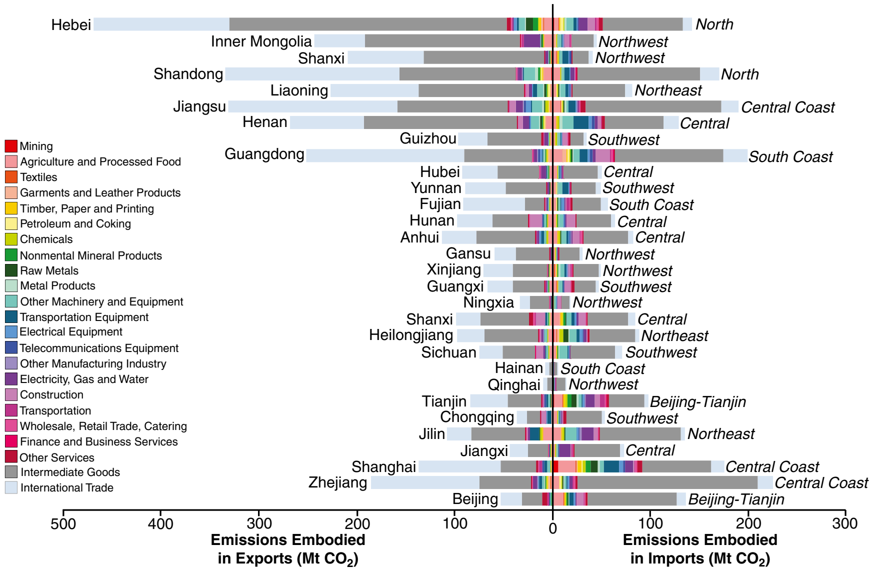

Fig. 2. Emissions embodied in interprovincial and international trade for 30 provinces. Colors represent trade in domestic finished goods by industry sector. Traded domestic intermediate goods (dark gray) are those used by industries in the importing provinces to meet consumer demand for domestic goods. Internationally traded goods (light gray) are those goods purchased from or sold to international markets. Italicized labels at the right of each bar indicate to which of the eight aggregated regions the province or city has been assigned.

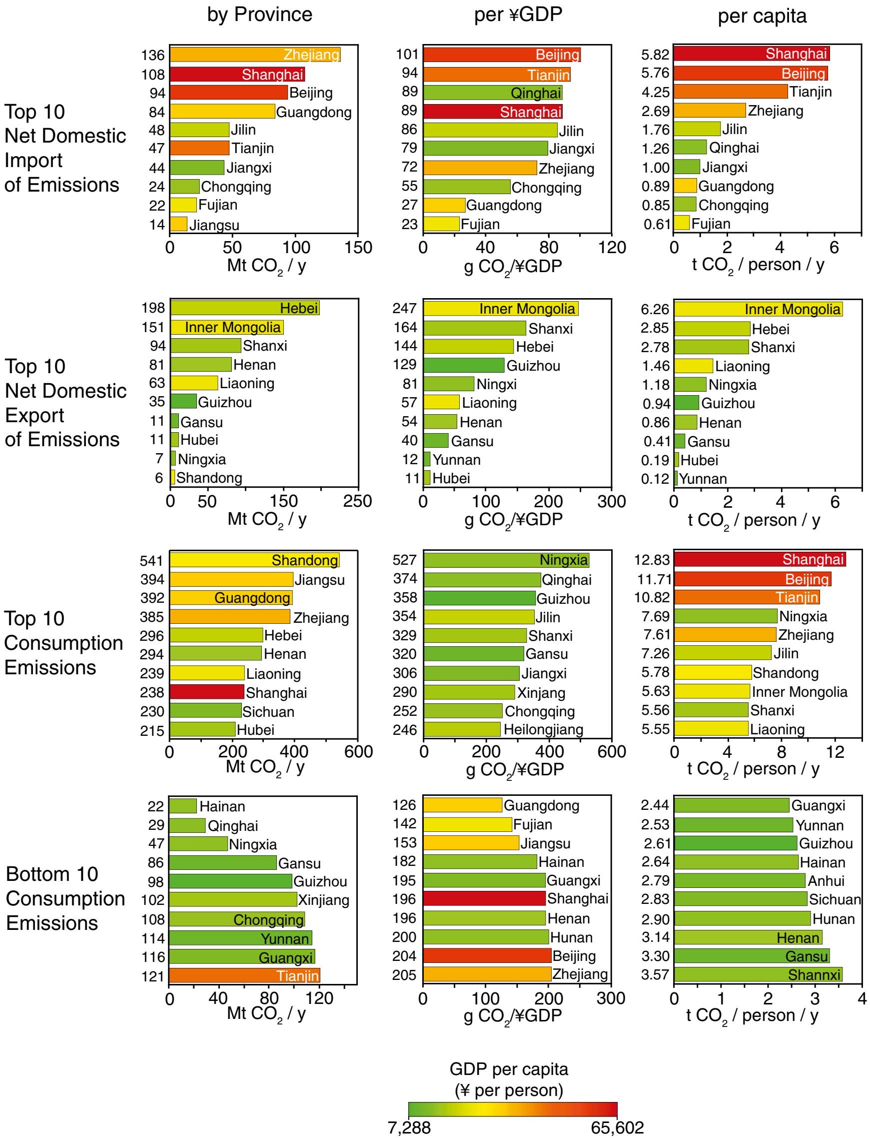

Fig. 3. The top 10 provinces by net domestic imports (row 1), net domestic exports (row 2), and consumption emissions (row 3), and the bottom 10 provinces by consumption emissions (row 4), all presented as regional totals (left column), per unit GDP (center column), and per capita (right column). The color of bars corresponds to provincial GDP per capita from the most affluent provinces in red to the least developed provinces in green (see scale).

greatest in provinces of the Central, Northwest, and Southwest regions where coal use and energy-intensive activities such as the production of capital infrastructure are dominant, and economies are growing rapidly (Fig. 3, row 3, *Center*). In contrast, the high GDP and more established economies in coastal provinces are among the least carbon intensive (Fig. 3, row 4, *Center*). For example, Ningxia, in the less developed Northwest region, has the highest consumption-based carbon intensity, 527 g of CO_2 per ¥GDP, which is more than four times the intensity of Guangdong, in the rich South Coast region, where carbon intensity reaches a low level of 126 g of CO_2 per ¥GDP. Similarly, per capita consumption-based carbon emissions in the most affluent cities of Shanghai, Beijing, and Tianjin (10.8–12.8 tons per person; Fig. 3, row 3, *Right*) are more than four times that of interior provinces such as Guangxi, Yunnan, and Guizhou (2.4–2.6 tons per person; Fig. 3, row 4, *Right*).

Discussion

Our results demonstrate the economic interdependence of Chinese provinces, while also highlighting the enormous differences in wealth, economic structure, and fuel mix that drive imbalances in interprovincial trade and the emissions embodied in trade. The highly developed areas of China, such as Beijing–Tianjin, Central Coast, and South Coast regions, import large quantities of low value-added, carbon-intensive goods from less developed Chinese provinces in the Central, Northwest, and Southwest regions. In this way, household consumption and capital formation in the developed regions, as well as international exports from these regions, are being supported by emissions occurring in the less developed regions of China (20). Indeed, the most affluent cities of Beijing, Shanghai, and Tianjin, and provinces such as Guangdong and Zhejiang, outsource more than 50% of the emissions related to the products they consume to provinces where technologies tend to be less efficient and more carbon intensive.

The carbon intensity of imports to the affluent coastal provinces is much greater than that of their exports—in some cases by a factor of 4, because many of these imports originate in western provinces where the technologies and economic structure are energy intensive and heavily dependent on coal. Provinces such as Inner Mongolia and Shanxi, which together produce more than 80% of coal burned in China and export 23% and 36% of the electricity they generate to other provinces, respectively, are locked into energy- and carbon-intensive heavy industries that account for more than 80% of their total industrial output.

At present, China's carbon policy seeks to address regional differences within China by setting higher targets for reducing emissions in Central Coast (reduction by 19%), Beijing–Tianjin (18–19%), South Coast (17.5–19.5%), except Hainan (11%), which is a tourist region, and North (18%); medium targets in Northeast (16–18%) and Central (17%); and lower targets in Northwest (10–16%) and Southwest (11–17.5%) by 2015 (4). However, provinces in the central and western parts of China will struggle to achieve even these more modest reduction targets if no funds are provided for updating their infrastructure and importing advanced technologies. Moreover, the more ambitious targets set for the coastal provinces may lead to additional outsourcing and carbon leakage if such provinces respond by importing even more products from less developed provinces where climate policy is less demanding.

However, the marginal cost of emissions reductions are substantially lower in interior provinces such as Ningxia, Shanxi, and Inner Mongolia, where produced emissions, energy intensity, and coal use are all high relative to the cities and provinces along the central coast. The emissions trading scheme being tested now (6) may help achieve least cost emissions reductions through technology transfer and capital investment from the coast to the interior. However, this study provides another justification for such a scheme: the economic prosperity of coastal provinces is being supported by the industry and carbon emissions produced in the central and western provinces. For instance, if a uniform price were imposed on carbon within China, larger emissions reductions would occur in western provinces where marginal costs are lower, and the cost of these reductions would be shared by affluent consumers in coastal China who would pay more for the goods and services imported from the interior. In contrast, more lenient intensity targets in the western provinces will necessitate more expensive emissions reductions in coastal provinces, and will encourage additional outsourcing to the western provinces. Consumption-based accounting can thus inform effective and equitable policies to reduce Chinese CO_2 emissions.

Materials and Methods

In this study, we include 26 provinces and 4 cities (in total, 30 regions) except Tibet and Taiwan. The results are based on 30 regions, but for easier understanding the results and discussions are organized in 8 Chinese regions: Northeast (Heilongjiang, Jilin, Liaoning), Beijing–Tianjin (Beijing, Tianjin), North (Hebei, Shandong), Central (Henan, Shanxi, Anhui, Hunan, Hubei, Jiangxi), Central Coast (Shanghai, Zhejiang, Jiangsu), South Coast (Guangdong, Fujian, Hainan), Northwest (Inner Mongolia, Shannxi, Gansu, Ningxia, Qinghai, Xinjiang), and Southwest (Sichuan, Chongqing, Yunnan, Guizhou, Guangxi).

The 2007 input–output tables (IOTs) for each of China's 30 provinces except Tibet are compiled and published by the National Statistics Bureau (21). The official IOTs have 42 sectors and the final demand category in the tables consists of rural and urban household consumption, government expenditure, capital formation, and exports. The IOTs also report the total value, by sector, that is shipped out of each province and the total value, also by sector, that enters into each destination province. This set of sector-level domestic trade flow data provides the basis for constructing the interregional trade flow matrix with both sector and province dimensions. In terms of the core methodology for the construction, we adopt the best-known gravity model of Leontief and Strout (22) and augment it in line with LeSage and Pace (23) and Sargento (2009) (24) to accommodate the spatial dependences of the dependent variable. Because the calibration of the augmented gravity model for each sector needs a known trade matrix of dominant/representative commodities in the sector (e.g., grain and cotton in the agricultural sector) and because such detailed data are not available for some small sectors, we aggregate the provincial tables into 30 sectors to accommodate this data constraint.

In the standard Leontief–Strout gravity model, the sector-specific interregional trade flows are specified as a function of total regional outflows, total regional inflows, and the cost of transferring the commodities from one region to another. This cost is typically proxied by a distance function. In the augmented gravity model, the equation also includes three variables reflecting the spatial dependences of the dependent variable: The origin-based one is defined as the spatially weighted average of flows from the neighbors of each region of origin to each destination region; the destination-based one is the spatially weighted average of flows to the neighbors of each destination regions, which are from the same region of origin; the mixed origin-destination–based one is defined as the spatially weighted average of flows from the neighbors of each region of origin to the neighbors of each destination region. The mathematical simplicity and intuitive nature of the gravity model and more importantly the reasonability of its empirical results grant it popularity and success in calibrating trade flows (25, 26). The comparative assessment of Sargento (24, 27) on alternative models further indicates that the gravity model is well suited to explain trade flow behavior. A technical specification of our augmented gravity model is presented in *SI Text 1*.

We run regressions of the augmented gravity model based on the known trade matrix of dominant/representative commodities in 5 primary sectors, 16 manufacturing sectors, and 1 electricity sector. The regressions for agriculture, chemistry, and electronics are presented in *SI Text 1* as three illustrative examples. The regressions give us the estimated values of the model parameters. Substitution of the known values of the total regional outflows, total regional inflows, and distance function into the augmented gravity model with known parameters gives us the initial trade matrix for the 5 primary sectors (sectors 1–5), 16 manufacturing sectors (sectors 6–21), and 1 electricity sector (sector 22). For gas and water production (sector 23), construction (sector 24), and all service sectors (sectors 25–30), we do not have qualified sample data of dominant/representative commodities. To get the initial matrix for these sectors, a simple data pooling method of Hulu and Hewings (28) is adopted with an augmentation as follows. Sixty percent of the outflow of each province is distributed to other provinces in proportion to the inverse of distance, and the remaining 40% is distributed according to the ratio of a province's inflow to the sum of all provinces' inflows. The initial trade flow matrix produced above, which excludes intraregional flows, does not meet the "double sum constraints" in that the row and column totals match with the known values given in the 2007 IOTs. To assure agreement with the sum constraints, we apply the well-known iterative procedure of biproportional adjustment of the RAS technique. The RAS procedure tends to preserve as much as possible the structure of the initial matrix, with the minimum amount of necessary changes to restore the row and column sums to the known values (29, 30). To complete with the system boundary, we connect the Chinese MRIO 2007 to global trade database version 8 (based on 2007 trade data) published by Global Trade Analysis Project (GTAP) (31) (description of connecting to the GTAP database is included in *SI Text 2*).

China does not officially publish annual estimates of CO_2 emissions. We estimate CO_2 emissions of the 30 provinces based on China's provincial energy statistics. We adopt the Intergovernmental Panel on Climate Change reference approach (32) to calculate the CO_2 emissions from energy combustion as described by Peters et al. (17) and applied in previous work on China by three of the authors (2, 15, 16). We applied the method to calculate emissions for all provinces in 2007. The inventories include emissions from fuel combustion and cement production. Total energy consumption by production sectors and residents provide the basis for calculating the energy combustion CO_2 emissions (21). We construct the total energy consumption data for production purposes based on the final energy consumption (excluding transmission energy loss), plus energy used for transformation (primary energy used for power generation and heating) minus nonenergy use. The transmission energy loss refers to the total of the loss of energy during the course of energy transport, distribution, and storage, and the loss caused by any objective reason in a given period (26). The loss of various kinds of gas due to discharges and stocktaking is excluded (26). We understand there are two different official and publicly available energy data sources in China between provincial and national statistics and the discrepancy is up to 18% (33). We adopted the provincial energy statistics to compile the emission inventories for every Chinese province as it more closely represents energy consumption at the provincial level.

In a MRIO framework, different regions are connected through interregional trade. The technical coefficient submatrix $A^{rs}=(a_{ij}^{rs})$ is given by $a_{ij}^{rs}=z_{ij}^{rs}/x_j^s$, in which z_{ij}^{rs} is the intersector 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 $F=(f_i^{rs})$, where f_i^{rs} is the region's final demand for goods of sector i from region r. Let $x=(x_i^s)$. Using familiar matrix notation and dropping the subscripts, we have the following:

$$A=\begin{bmatrix} A^{11} & A^{12} & \cdots & A^{1n} \\ A^{21} & A^{22} & \cdots & A^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A^{n1} & A^{n2} & \cdots & A^{nn} \end{bmatrix};\quad F=\begin{bmatrix} f^{11} & f^{12} & \cdots & f^{1n} \\ f^{21} & f^{22} & \cdots & f^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ f^{n1} & f^{n2} & \cdots & f^{nn} \end{bmatrix};\quad x=\begin{bmatrix} x^{1} \\ x^{2} \\ \vdots \\ x^{n} \end{bmatrix}.$$

Consequently, the MRIO framework can be written as follows: $x = Ax + F$, and we have $x = (I - A)^{-1}F$, where $(I - A)^{-1}$ is the Leontief inverse matrix, which captures both direct and direct inputs to satisfy one unit of final demand in monetary value; I is the identity matrix. To calculate the embodied emissions in the goods and services, we extend the MRIO table with environmental extensions by using CO_2 emissions as environmental indicator: $CO_2 = k\,(I - A)^{-1}F$, where CO_2 is the total CO_2 emissions embodied in goods and services used for final demand; k is a vector of CO_2 emissions per unit of economic output for all economic sectors in all regions. The application detail of the MRIO framework to our research is presented in *SI Text 1*.

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