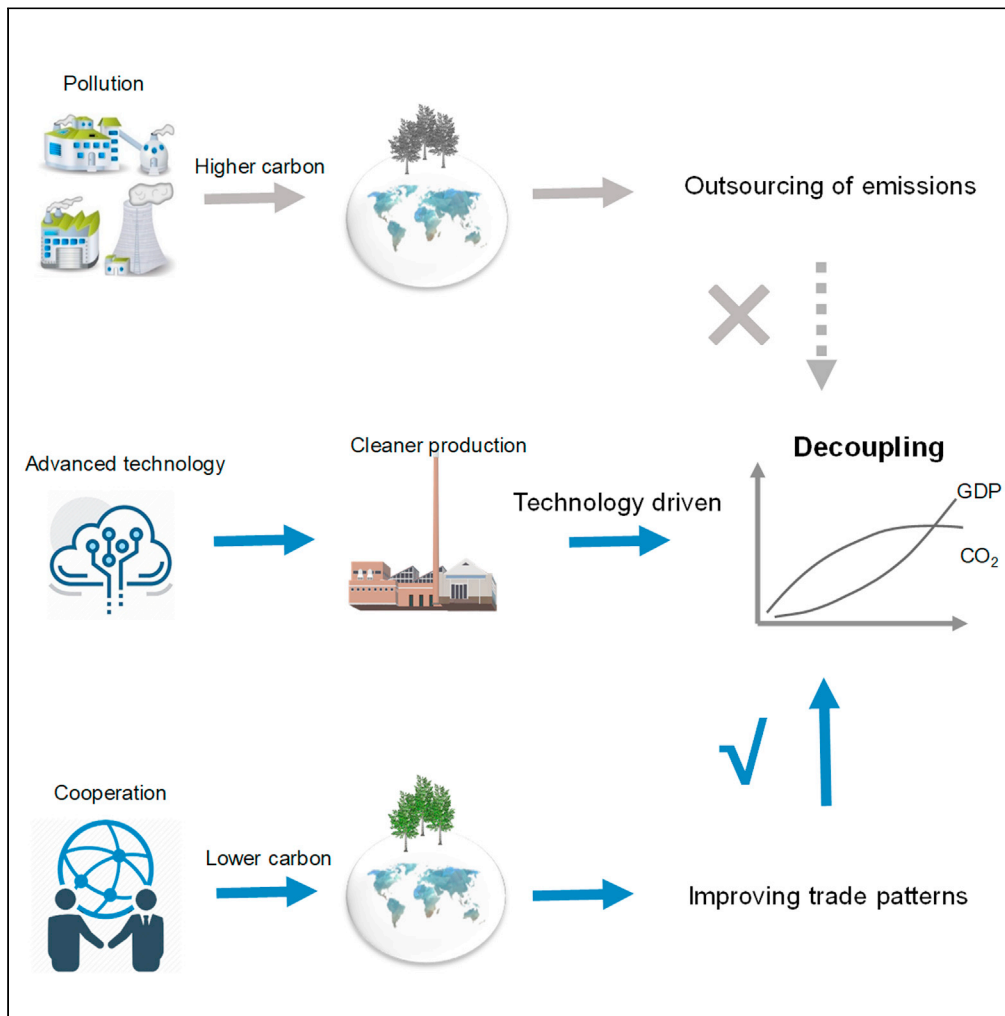


Article

Decoupling without outsourcing? How China's consumption-based CO₂ emissions have plateaued



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Highlights

China's consumption-based CO₂ emissions have plateaued during the "new normal" period

Technology-adjusted consumption emissions show relative decoupling is technology driven

The slowdown in import emissions growth is related to restructuring of import patterns

Improvements in trade patterns have occurred, rather than pure outsourcing of emissions

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Article

Decoupling without outsourcing? How China's consumption-based CO₂ emissions have plateaued

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SUMMARY

The shift of China's economy since 2013, dubbed the “new normal”, has caused its production and consumption emissions to plateau, with the country seeming to embody the tantalizing promise of decoupling its economic growth from carbon emissions. By using multi-region input-output analysis, we find that China's relative decoupling in the new normal is technology driven, evidenced by the narrowing gap between its technology-adjusted and non-adjusted consumption emissions. By applying structural decomposition analysis, we further explore the driving forces behind the slowdown in China's imported emissions growth, finding that it is attributable to restructuring of import patterns resulting from changes in the structures of domestic demand. These changes could have been caused by China moving along the global value chain and rebalancing its industrial linkages toward trade in carbon-efficient goods to avoid transferring emissions-intensive production to other regions, indicating a shift to less emissions-intensive trade rather than pure outsourcing.

INTRODUCTION

Since the turn of the 21st century, China has been central to both the expansion of world trade and the rapid rise in global greenhouse gas (GHG) emissions. China's ascendancy in international trade followed its accession to the World Trade Organization in 2001, with over 10% of global merchandise exports coming from China by the end of that decade (Wang et al., 2017). At around the same time, China's emissions of GHGs began to accelerate rapidly, with the country overtaking the United States as the largest annual emitter in 2006 and its energy-related emissions tripling between 2000 and 2013.

China's contribution to these two global phenomena can best be interpreted in the light of two distinctive periods in the country's economic development: the rapid industrial growth phase (roughly 2000–2013) and the “new normal” phase (roughly 2014 onwards). In the rapid industrial growth phase, China's GDP grew at double-digit rates, largely due to exceptionally high levels of investment in urban infrastructure and in the associated production of materials and energy, which in turn drove the dramatic increase in GHGs (Davis and Socolow, 2014; Zhang et al., 2017b). Over the rapid industrial growth phase, and especially in the years before the global financial crisis, a significant amount of China's carbon- and energy-intensive materials were produced for export, accounting for 32% in total emissions growth (Mi et al., 2018). This pattern fueled concerns that some countries, such as the US, were outsourcing emissions to countries such as China (Baumert et al., 2019), and prompted claims of unfairness in the global climate regime (Peters and Hertwich, 2008). In international climate policy, countries' obligations to mitigate their GHG emissions are predicated on a system of production-based accounting (PBA), meaning that the GHGs emitted in the course of producing goods for export are attributed to the exporting country not the importing country. However, under a consumption-based accounting (CBA) system, the opposite would hold (Kagawa et al., 2015; Wei et al., 2021).

As foreign demand for Chinese exports crashed following the global financial crisis, the Chinese Government replaced much of that demand using domestic stimulus. However, as the stimulus began to wane in the early 2010s, underlying changes in the structure of China's economy began to emerge, including a shift away from unsustainable, heavy industry-driven growth (Green and Stern, 2015; Grubb et al., 2015; Zheng et al., 2019a). China's economy began to enter into a “new normal” phase—a more sustainable economic trajectory and inclusive development model marked by a higher consumption share of expenditure, an industrial reorientation toward services and high value-added manufacturing, and greater attention to

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environmental protection and reduced GHG emissions. Put simply, this phase is represented by a slower rate of higher quality growth (Green and Stern, 2015, 2017; Zhang et al., 2017c). This phase of structural change is important to study from a climate perspective, as it has profound implications for China's carbon dioxide (CO₂) emissions.

China has committed to peaking its CO₂ emissions by 2030 (Liu, 2015) and further pledged to achieve carbon neutrality before 2060. However, in light of these structural economic shifts, later analysis would reveal that China's emissions had already begun to plateau by approximately 2012–2013 (Green and Stern, 2015, 2017; Guan et al., 2018). This unexpected shift brought the elusive goal of peaking and even neutralizing China's—and the world's—CO₂ emissions suddenly within sight, along with the tantalizing promise of a decoupling of economic growth from GHG emissions (Deutch, 2017). However, as the structure of China's economy changes toward domestic-led consumption growth and its domestically produced emissions level off, there is a risk that China could itself end up outsourcing emissions to other countries. Therefore, is the promise of China's "decoupling" real or merely a "delusion" (Jiborn et al., 2018)?

By investigating trends in China's consumption emissions and drivers of emissions embodied in imports in the new normal period, this paper systematically answers this question. Specifically, we measure trends in China's emissions over the period from 2002 to 2018 using technology-adjusted CBA (TCBA) in addition to PBA and CBA (Kander et al., 2015; Peters et al., 2011). We do so by linking multi-region input-output (MRIO) tables from the Global Trade and Analysis Project (GTAP) database to China's single-region input-output (SRIO) tables. Furthermore, from the perspective of the global value chain (GVC), we apply structural decomposition analysis (SDA) to analyze the drivers of changes in China's imported emissions, allowing us to investigate more deeply what is contributing to the slowdown in the key component of China's consumption emissions in the new normal.

The reason for including TCBA is that some conclusions, which appear misleading when viewed from the perspective of only PBA or CBA, can be corrected (Jiborn et al., 2018). TCBA applies a similar formula to CBA with a twist: export-related emissions are subtracted based on the average carbon intensity for the relevant sector on the world market, rather than the domestic average. The reasoning is this: if carbon footprints are to reflect the effects of a country's exports on global emissions, we must consider not only how a certain exported commodity was actually produced but also what alternative production it replaces (Kander et al., 2015). Thus, where a country or region (e.g. the EU) has a level of TCBA emissions lower than its PBA emissions, which are in turn lower than its CBA emissions, this suggests the interpretation that some of the difference between its CBA and PBA emissions is due to its relative carbon efficiency compared with its trading partners, rather than the difference being entirely a matter of outsourcing (Kander et al., 2015).

While various studies have examined the trends and drivers of China's production emissions in the new normal (Zheng et al., 2020b) and while others have examined its consumption emissions before this period (Jiborn et al., 2020), limited existing research examines both production and consumption emissions at the national level in the new normal period. With respect to production emissions in the new normal, China's production-based CO₂ emissions were estimated and decomposed by emission factors for energy consumption (Yang et al., 2020), showing that production emission reductions are structural and likely to be sustained (Guan et al., 2018), while the effect of changing trade patterns on China's production emissions and its exported emissions was explored in multi-national studies (Meng et al., 2018; Mi et al., 2017; Wang and Zhou, 2020). Existing research on China's consumption emissions pertains to the period before the new normal (Liu et al., 2019) and focuses on different spatial units at a subnational scale (Liu et al., 2016; Mi et al., 2019). This makes it difficult to understand the characteristics of, and mechanisms underlying, changes in China's national consumption and production emissions in the crucial "new normal" period. This study fills these research gaps by expanding the dataset on production and consumption emissions to 2018, clarifying the role of technology-driven decoupling without outsourcing. Moreover, referring to the scientific accounting of emissions embodied in trade (Zhang et al., 2017a), this study explores the drivers of changes in cross-border carbon flows from the consumption-based perspective adjusted by technology, providing a clearer picture of the world's largest emitter's changing role in the international trade of carbon-intensive products.

RESULTS

China's plateaued consumption-based and production-based CO₂ emissions

We first estimated China's CO₂ emission inventories between 2002 and 2018 and found that China's CO₂ emissions dramatically increased from 2002 but gradually plateaued after 2012. During the rapid industrial

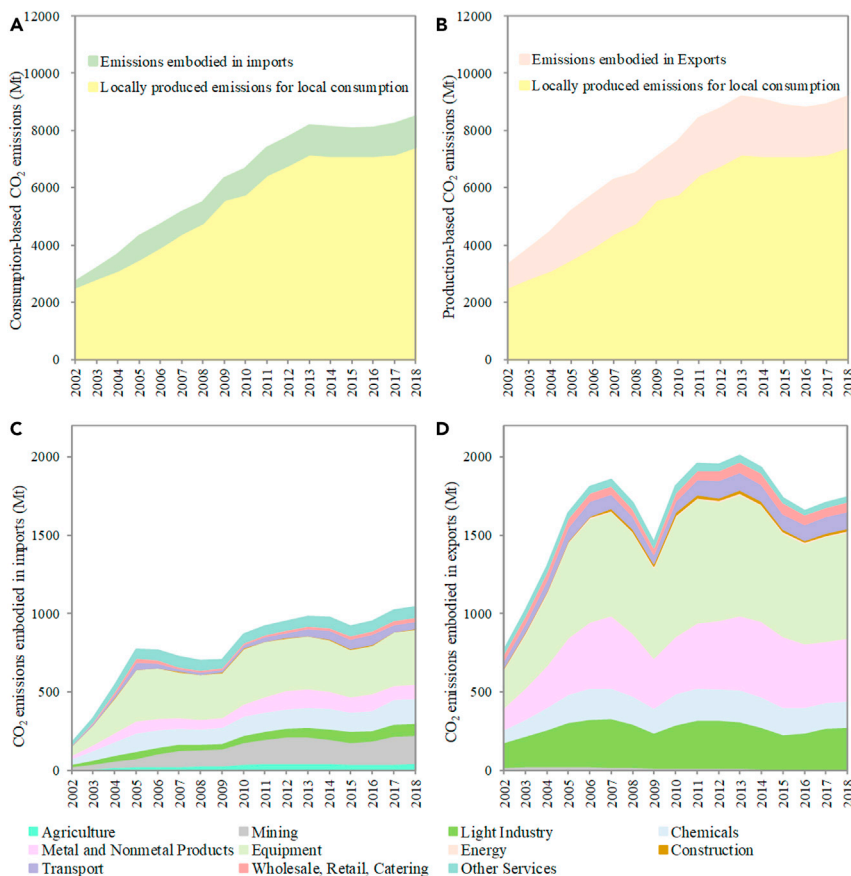


Figure 1. Trends in China's CO₂ emissions in megatons (Mt) from 2002 to 2018

(A) Consumption CO₂ emissions (emissions from local production and embodied in imports).
 (B) Production CO₂ emissions (locally produced emissions embodied in local consumption and embodied in exports).
 (C and D) CO₂ emissions at the sectoral level embodied in imports (C) and exports (D).

growth phase, CO₂ emissions almost tripled, from 3.5 gigatons (Gt) in 2002 to 9.5 Gt in 2013 (Guan et al., 2018). Emissions plateaued since 2013, consistent with the economic transitions in industry and energy systems associated with the new normal (Zheng et al., 2020a). The trend of our estimation is broadly consistent with that of public data from other researchers and institutions (Pan et al., 2018), despite differences in the estimated emissions from various data sources (BP, 2021; Crippa et al., 2020; GCP, 2020; Gilfillan and Marland, 2021; IEA, 2021) caused by the lack of officially published annual emissions data in China (Shan et al., 2018) (Figure S1A). At the sectoral level, "energy" and "metal and nonmetal products" dominated contributions to emissions from 2002 to 2018 (Figure S1B). Based on the estimated CO₂ emission inventories by emission factors for energy use, China's consumption (Figure 1A) and production (Figure 1B) emissions were then calculated, both of which shifted from the rapid increase in the industrial growth phase to a decelerating growth trend in the new normal (since 2013), with the annual growth rate dramatically falling from 11.1% to 1.5% (consumption) and from 10.3% to 0.8% (production), respectively. One of the important causes is that the emissions produced in China for goods and services consumed domestically—the common component accounting for large proportions of both consumption and production emissions—stabilized after 2012, at a little above 7 Gt.

While the broad trends were similar, the absolute production emissions were much higher than the consumption emissions. This gap is explained by the discrepancy in emissions embodied in imports (Figure 1C) and emissions embodied in exports (Figure 1D). Specifically, the annual emissions exported by China are around twice the value of its imported emissions. There were two visible declines in trends of both emissions embodied in imports and emissions embodied in exports. The first is possibly attributable to shocks associated with the global financial crisis (Mi et al., 2017), while the second concerns adjustments in China's

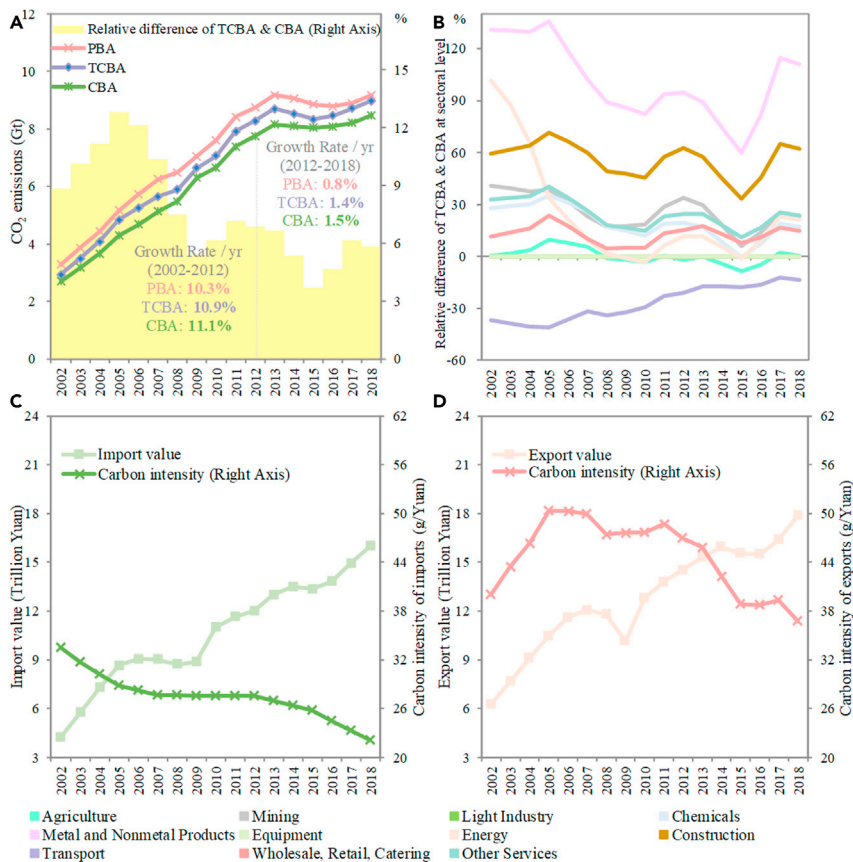


Figure 2. Changes in CO_2 emissions embodied in trade from 2002 to 2018

- (A) Comparison of PBA, CBA, and TCBA and the relative difference (calculated by the difference of emissions between TCBA and CBA divided by CBA).
- (B) Relative difference of TCBA and CBA at sectoral level.
- (C) Import value and carbon intensity of imports.
- (D) Export value and carbon intensity of exports.

“supply side” policies (Zheng et al., 2019b). The sectoral structures of emissions embodied in imports and exports were similar.

That said, the gap between consumption and production emissions has narrowed over time, from 22% in 2002 to around 10% between 2012 and 2018, because the decline in exported emissions occurred at a faster rate (i.e. -1.9% per year) than the rate of the increase in imported emissions (i.e. 1.5% per year) over this period of 2012–2018 (Boitier, 2012). Compared with the significant increase in carbon emissions embodied in imports (782 Mt) and exports (1193 Mt) over the course of the rapid industrial growth phase (Figure S2A), after entering the new normal the emissions embodied in imports increased slightly by 92 Mt, while emissions embodied in exports dramatically decreased by 210 Mt (Figure S2B). The narrowing of the gap resulted from changes in traded emissions, which raises questions about the role of outsourcing (Baumert et al., 2019).

Technology-driven decoupling evident from TCBA

Our estimates of the decoupling factor (OECD, 2002) show that China has experienced relative decoupling (i.e. the economy growing faster than emissions) since 2015, with the decoupling factor reaching 0.1 in 2018. China’s emissions, currently and historically, exhibit a pattern of relationships typical of a major insourcing country (i.e. $PBA > TCBA > CBA$) (Figure 2A). This is mainly because on average around a quarter of its total emissions—as estimated by this research (24%) and previous studies (Weber et al., 2008; Yunfeng and Laike, 2010)—are generated in the course of producing products for export, while it is also a

representative emerging economy with a higher carbon intensity of production than the global average (Baumert et al., 2019). China's CO₂ emissions calculated by PBA, CBA, and TCBA all have plateaued since 2013, with its TCBA as well as CBA below PBA throughout the period. Particularly, its PBA has grown slower than TCBA as well as CBA, indicating that China is insourcing emissions to a lesser extent, which is relevant for the assessment of evidence of decoupling. The extent to which this decoupling has been achieved by technology improvement can be observed from the relative gap between TCBA and CBA (calculated by the difference between them divided by the cumulative CBA). Consider the EU as an example. In contrast to emission-outsourcing countries represented by the US (Baumert et al., 2019), emissions calculated for the EU using TCBA are far below CBA because it uses advanced, relatively energy efficient technology that is above the world average level, resulting in its carbon intensity being below the world average (Kander et al., 2015). This TCBA-CBA gap in China has been decreasing from 8% (2002–2012) to 5% (2013–2018), indicating that its technology has been improving during the new normal period—narrowing the gap between its national carbon intensity and the world average level—rather than it purely outsourcing emissions to its trading partners (Jakob and Marschinski, 2013; Jakob et al., 2014; Kander et al., 2015).

Accordingly, China can maintain this benign trend of TCBA continuing to decrease at a relatively high rate compared with PBA and CBA, until it falls below both of them. In its Nationally Determined Contributions to the Paris Agreement, China proposed targets to peak its CO₂ emissions and reduce its carbon intensity simultaneously. China is focusing on both absolute emission cuts and carbon efficiency improvement to achieve decoupling without outsourcing by setting specific targets and introducing target-related policies (Shi and Xu, 2018; Zheng et al., 2019a, 2019b). The reduction in China's national carbon intensity in the new normal has been composed of adjustments in the energy mix and improvements in technology that improve the emission efficiency of output. The former is likely to be attributable to a combination of direct environmental regulations on emissions and pollutants (Shi and Xu, 2018), such as policies targeting coal-fired power plants (Tang et al., 2019), while the latter might be associated with indirect economic structural changes, including regional cooperation, industrial transition, and consumption stimulus (Zheng et al., 2019a, 2019b).

At the sectoral level (Figure 2B), the relative difference between TCBA and CBA in the “energy” sector (including electricity, gas, and water) declined significantly from 102% in 2002 to 21% in 2018, as a result of worldwide increases in clean energy production and lower-carbon production processes in general. Simultaneously, the technology used in the “transport” sector is relatively advanced in China compared with the average global technology used in transport, resulting in a similar (negative) value of the difference, changing from –37% in 2002 to –14% in 2018. With independent research and design, the considerable demand in China for transport was facilitated through the development of logistic networks and transport infrastructure and services (i.e. water transport, air transport, and other transport including road, rail, pipelines, auxiliary transport activities, and travel agencies), especially high-speed rail (Ke et al., 2017). In the new normal phase, the largest declines in the difference between TCBA and CBA occurred in the “mining” and “light industry” sectors, both of which were around 10%.

When comparing PBA, TCBA, and CBA, the difference between PBA and TCBA, measured by technology-adjusted exports minus imports, is related to trade patterns showing the state of balance of payments. By contrast, the difference between TCBA and CBA, calculated by exports minus technology-adjusted exports (i.e. export carbon intensities adjusted by the world average), is associated with the production technology of countries from which China imports (Kander et al., 2015). We further explore those trade- and technology-related differences in imports (Figure 2C) and exports (Figure 2D). At the beginning of the study period, export volumes were approximately 47% larger than import volumes, but by 2018, the gap had narrowed to 12%. In addition to the trade volume, China's move up the GVC plays an important role, with increasing weights of value added in high-tech manufacturing industries (Table S1) (Koopman et al., 2014; Los et al., 2016). With respect to carbon intensity, the world average level (22–34 gCO₂/yuan) is lower than that of China (37–50 gCO₂/yuan), while the latter (28%) declined relatively faster than the former (24%) in the new normal period, supporting the narrowing gap between China's TCBA and CBA. Overall, the carbon intensity of China's two-way trade, both imported and exported, is trending downward, especially in the new normal period, which is conducive to slowing the increase in China's emissions. In addition to technology, emissions embodied in imports, as a key component under TCBA, can be further reduced by adjusting and restructuring trade. China could realistically manage a deceleration in the growth of the emissions embodied in its imports, with a simultaneous gain in technological efficiency.

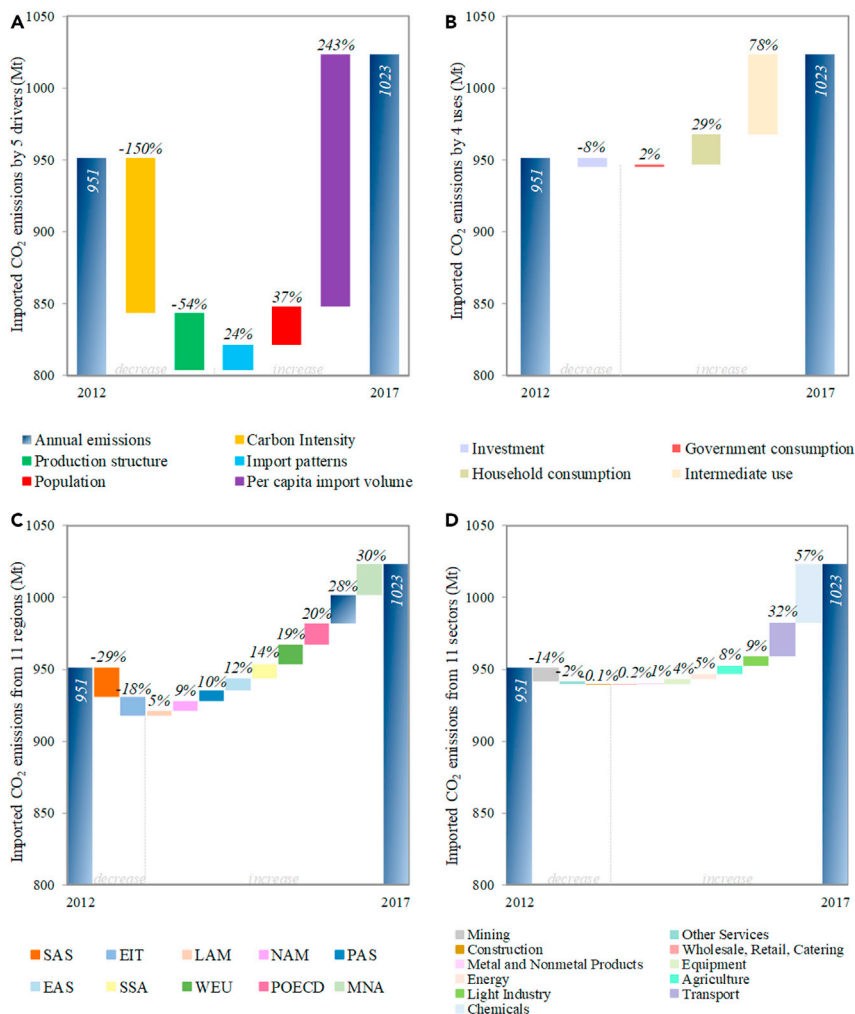


Figure 3. Changes in CO₂ emissions embodied in imports (CBA) from 2012 to 2017

(A) Changes in imported emissions caused by five driving factors.

(B) Changes in imported emissions embodied in four domestic Chinese uses.

(C) Changes in imported emissions from 11 source regions, including SAS (South Asia, mainly India), EIT (Economies in Transition, including Eastern Europe and the Former Soviet Union), LAM (Latin America and the Caribbean), NAM (North America, including the USA and Canada), PAS (South-East Asia and the Pacific), EAS (East Asia, excluding China), SSA (Sub-Saharan Africa), WEU (Western Europe), POECD (Pacific OECD-1990 Countries, including Japan, Australia, and New Zealand), and MNA (the Middle East and North Africa) (for definitions of world regions see [Data S1](#)).

(D) Changes in imported emissions from 11 source sectors. The percentages in subfigures are relative change rates, calculated by taking the overall change (i.e. 72 Mt of 2012–2017) as 100% (see [Data S2](#) for the absolute change rates, calculated by taking the base year of 2012 as the denominator with the overall change as 7.6%).

Below, we explore in greater detail the factors behind the slowdown in the growth of imported CO₂ emissions to build a clearer picture of what is driving the plateau in China’s consumption emissions in the new normal period.

Driving forces of the decelerating growth of CO₂ emissions embodied in imports

In the new normal period, from 2012 to 2017, the emissions embodied in China’s imports slightly increased by 7.6% or 72 Mt. We explore the causes of this slowdown in growth, by MRIO, using four distinct analytical perspectives—driving factors (defined below), use structures (defined below), source regions, and source sectors.

The largest contributing driving factor has been the improvement in the carbon intensity of production in the countries from which China imports, contributing a massive –150% ([Figure 3A](#)). The contribution of

improved carbon intensity in the countries from which China imports indicates that, globally, advanced technologies have played an extremely important role in attenuating China's consumption emission growth. This trend has held true for each year of measurement between 2007 and 2017 (Figure S3A). In addition, changes in the production structure, as reflected by complex associations among sectors in the global IO tables, made a –54% contribution. These two factors, related to global technologies, are determined by other countries and sectors. In contrast, the other three driving factors, affected by the importing nation (i.e. China), are putting upward pressure on China's imported emissions. Among them, the emission growth contributed by import patterns (24%), composed of the use structures, was only one tenth of the growth caused by per capita import volume (243%), indicating that imported emission growth can be decelerated by adjusting use structures in case of moderate increases in import volume.

Now consider the role of changes in use structures (i.e. the distribution of products across semi-manufactured products and goods consumed in final demand). Emissions embodied in investment fell by 8% between 2012 and 2017, while emissions embodied in consumption grew by 29% (Figure 3B)—the former decrease and the latter increase were desired and encouraged, according to their distributions in sectors with higher emissions and cleaner production, respectively. After the weakening of government stimulus in the post-crisis era after 2010, market forces and government policy conspired to shift the Chinese economy toward domestic consumption-led growth (Zheng et al., 2019b). Driven by policies to reduce China's trade dependence and increase domestic demand, changes in the rate of growth in—and the composition of—the final uses in the new normal period led to changes in consumption of imports and changes in emissions embodied in imports (Mi et al., 2019). In addition, with regard to intermediate use, there was a significant decline in the relative proportion of contributions to the imported emission growth, from 93% in the last financial crisis phase of 2007–2012 to 78% in the new normal phase of 2012–2017; its absolute contribution reduced more dramatically from 29% (2007–2012) to 6% (2012–2017). From the perspective of GVC, some semi-produced and produced exports made in China are from its intermediate use of imports in complex global value chains, where goods are imported, refined with value added, and then re-exported. China is moving up the value chain, showing a proportional increase in domestic value added from 91% in 2011 to 94% in 2014 (Table S1), with a simultaneous gain in emission efficiency.

Specifically, unlike the decrease in import volumes caused by the financial crisis shock, policy-driven structural transition has played an important role in the new normal period. China has implemented “supply side reforms”—such as forcing the closure of redundant industrial capacity and encouraging firm mergers, especially in the coal industry (Ministry of Commerce, 2017a). Thus, the energy supply gap has been supplemented by imports of gas (which produces less emissions than coal when burned) (Ministry of Commerce, 2017b), reducing intermediate-use imported emissions in the “energy” sector by 24% from 2012 to 2017. In addition to quantity tools, price tools in the form of changes to import tariffs have been used to upgrade the industrial structure from heavy industry to high-tech manufacturing. For example, similar to policies of infant industry protection, value added is shifted to the “equipment” sector by adding equipment in the early stages of development into the support list of tariff-exempt key components and raw materials that are really necessary to be imported; while policy supports for mature and stable domestic equipment, which is capable of competing against established international industry competitors, were canceled (Ministry of Finance, 2018). Thus, for the “equipment” sector from 2012 to 2017, imported emissions in final use for investment decreased by 12%, whereas they increased by 4% in intermediate use. Furthermore, policies can be more specifically adjusted and implemented through bi- and multi-lateral agreements focusing on different source regions and specific source sectors.

With respect to source regions, the decelerating pressure on China's growing imported emissions is mainly attributable to import origins shifting from the middle to the ends along the value chain. Both South Asia (–29%) and Economies in Transition (–18%), located in the midstream of the value chain, contributed to the downward force in China's imported emissions (Figure 3C), with the largest decreases (in the “metal and nonmetal products” sector) showing –14% and –5% for these regions, respectively (Table S2). Imported emissions in the “mining” sector from South Asia also dramatically decreased at the same level of –14%, perhaps resulting from the import substitution in this sector from Sub-Saharan Africa (located relatively downstream in the value chain), with an emission increase of 14% (Table S2). In addition to the emission increase contributed by Sub-Saharan Africa (14%), the Middle East and North Africa (30%) dominated the increase in imported emissions, mainly caused by relatively high-emission intensity “chemicals” imports. However, imports not only moved down along the chain but also up to the other end, centralizing

in sectors related to equipment manufacturing and tertiary industry from Western Europe (19%). Meanwhile, the “chemicals” sector imported clean products from Western Europe with an emission increase of 4% (Table S2), indicating that trade sectors made efforts to “green” products by carefully selecting import sources rather than simply transferring manufacturing emissions to countries downstream in the value chain (Ministry of Commerce, 2012). The overall distribution of source regions showed that developed countries contributed slightly more than developing countries, i.e., North-South trade emissions were higher than those embodied in South-South trade (Figure S3B). However, contributions diverged in different phases—the opening up of China’s international trade (2002–2007), the Chinese economic stimulus period (2007–2012), and the new normal (2012–2017)—driven by each Five-Year Plan (FYP) policy.

From the perspective of source sectors, emission changes from those source sectors were closely related to industry-improving and consumption-led policies aimed at China’s moving up the value chain from low-end processing to high-tech manufacturing. As a result of these efforts, taking the expansion of free trade zones, for instance, the development of tertiary industry, including e-services, information sectors, etc., has been supported, leading to a sharp decline in the demand for imports (Ministry of Commerce, 2017c). Previously foreign-imported services were replaced by domestically provided services, leading to a dramatic decline (–2%) of imported emissions sourced from the “other services” sector globally (Figure 3D). This emission reduction was mainly attributable to China rebalancing its industrial linkages, where those formerly imported services inputs into China’s “mining” (–9%) and “chemicals” (–6%) sectors and low value-added industries (Table S3) were replaced by domestically provided services in those sectors. In addition, it is found that the global “chemicals” (57%), “transport” (32%), and “light industry” (9%) sectors, as source sectors, increased China’s imported emissions in its “equipment” sector and “household consumption” use. This is mainly attributed to policies encouraging finished goods for the equipment industry and final consumption while canceling incentives for importing some intermediate semi-manufactured products (The State Council, 2014). For example, the “mining” sector was the global source sector with the largest contribution to China’s imported emissions reduction (–14%); its semi-manufactured products led to an emission reduction of –11% in China’s “metal and nonmetal products” sector, while its finished goods showed an emission growth of 1% in China’s “household consumption” use.

DISCUSSION

The promise of green growth in a globalized world entails an absolute decoupling of economic growth from the emission of GHGs that cause climate change. Few countries will have a greater effect on the achievement of this global goal than China. Since the turn of the new millennium, China has played an increasingly important role in both global trade and global GHG emissions, taking the increase in trade-embodied non-CO₂ GHGs before 2014, for example (Fernández-Amador et al., 2020; Han et al., 2019; Teng et al., 2019; Wang et al., 2019). Accordingly, this study has sought to analyze China’s technology-adjusted CO₂ consumption emissions, with particular attention given to the emissions embodied in its imports during a period—the “new normal”—in which the country has begun to shift away from energy-intensive heavy industrial production and toward a more consumption-based economy.

During this period, the narrowing gap between technology-adjusted and non-adjusted consumption emissions indicates that China’s relative decoupling is partly explained by the improvement of its technology, registering a decline in emission intensity compared to the world average level. This development can be attributed to national efficiency gains from technology improvements or to institutional initiatives to restructure industries and consumption patterns. However, the transition was not achieved at the expense of global resources and the environment. For example, the no longer produced but still needed imports were supplemented through trade without outsourcing all of the emissions. How did this happen? The key forces decelerating the growth in imported emissions were the following: the change in trade patterns toward low-emission-intensive driving factors, use structures, source regions, and source sectors.

Those key forces with both types of consumption-based emissions are closely related to the imported and re-exported demand changes in the complex value chains at the regional or sectoral levels (Kander et al., 2015). Therefore, regional and sectoral analyses by global value chains were applied to further explore the underlying mechanisms. Results from the new normal phase indicate that the relative decoupling of economic growth from environmental degradation can still be achieved by a rapidly industrializing country, which further suggests the promise that absolute decoupling—the core promise of sustainable development—is not an illusion. In addition to whether renewable energy can be developed on a large scale in

China, whether China's consumption emissions will decline in the future will depend on whether the above-mentioned sources of downward pressure can be amplified, while key sources of consumption emissions growth—such as imports per capita—can be moderated.

To achieve sustainable absolute decoupling requires analyzing an entire demand profile from a consumption-based perspective: the production structure, via changes in the distribution of local and traded goods across intermediate use and final demand, can be linked with import-consumption adjustments and export-production decisions. This indicates that globally traded emissions can be restructured to enable relatively carbon-efficient global production patterns, thus contributing to reducing total global emissions. A country can substitute a locally produced carbon-intensive good with a less carbon-intensive import produced by advanced technology, while surplus factors of production, such as capital and labor, can be allocated to industries in which the country is comparatively carbon efficient (Daggash and Mac Dowell, 2019; Langevin et al., 2019). Policies to green the current economic recovery can provide a bridge to a future with net-zero emissions (Evans and Gabbatiss, 2020). Countries can seek to optimize carbon efficiency in their trade by exploiting “comparative advantages” in carbon efficiency to achieve a rebalancing of the global economy and emissions over time. For example, China coordinates the development of trade and the environment by issuing guidelines for high-quality trade development with strict carbon- or energy-intensity control over the relevant exports, contributing toward its goal to become carbon neutral before 2060 (The State Council, 2019). Simultaneously, from the perspective of comparative advantage, mutual benefits can be achieved in trade by considering both economic benefits and environmental costs. In addition to cooperation, other countries can follow the example of China to focus on technology-driven decoupling by carbon-efficient trade patterns without purely outsourcing emissions. The evidence we have assembled from the world's largest industrialized nation during a crucial period of economic change suggests the plausibility of such shifts. Whether they can occur in sufficient time to avert catastrophic climate change remains to be seen, particularly in light of the upward pressure on numerous pollutants caused by rising affluence (Parrique et al., 2019; Wiedmann et al., 2020). However, for carbon emissions, our analysis at least indicates that, in the context of sustainable development, economic growth and environmental governance may not necessarily entail a trade-off; rather, they can entail simultaneous gains, or even mutual benefits, if the pathways to their realization are appropriately designed and managed.

Limitations of the study

In IO analysis, there are several linear and static assumptions, including same needed quantity of inputs per unit of output and fixed input structure. Uncertainty in the results may arise because of the homogeneous product assumption within an industry. Thus, IO performs well in exploring previous mechanisms rather than future extrapolation (Leontief, 1936). However, the cross-sectional industrial linkages and its time-series structural changes are non-linear, as the IO process is derived from statistical data and based on the empirical principle. Therefore, the estimates can be constrained, and the results can be accepted (Mi et al., 2019).

Data limitations are that the latest available data for global IO tables was the GTAP data for the year 2014 released in version 10 of the GTAP database, which can be updated to make projections more reliable in further studies.

STAR★ METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- RESOURCE AVAILABILITY
 - Lead contact
 - Materials availability
 - Data and code availability
- METHOD DETAILS
 - Input data
 - CO₂ emission inventories
 - Linking the GTAP database to China's SRIO
 - Environmentally extended input-output analysis
 - Emissions embodied in trade

- Consumption-based CO₂ emission accounting (CBA)
- Technology-adjusted CBA (TCBA)
- Decoupling factor
- Structural decomposition analysis (SDA)

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at <https://doi.org/10.1016/j.isci.2021.103130>.

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AUTHOR CONTRIBUTIONS

Z.M. designed the study. J.Z. performed the analysis. Z.M., J.Z., and F.G. prepared the manuscript. J.M. and K.F. provided data. All authors (Z.M., J.Z., F.G., D.G., J.M., K.F., X.L., and S.W.) participated in interpreting the data and contributed to writing the manuscript. J.Z., D.G., and S.W. coordinated and supervised the project.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★ METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
China's national population annual data	National Bureau of Statistics of China (NBSC)	http://data.stats.gov.cn/english/
China's national trade volume annual data	General Administration of Customs of China (GACC)	http://www.customs.gov.cn/
China's IO tables	National Statistics Yearbook	http://data.stats.gov.cn/english/
China's estimated CO ₂ emissions	China Emission Accounts and Datasets (CEADs)	http://www.ceads.net/
GTAP database	Global Trade and Analysis Project (GTAP)	http://www.gtap.agecon.purdue.edu/
Price deflator data	United Nations Statistical Division (UNSD)	http://unstats.un.org/unsd/snaama/Introduction.asp
Software and algorithms		
Matlab	MathWorks	https://www.mathworks.com

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the Lead Contact, Jiali Zheng (zhengjiali@amss.ac.cn).

Materials availability

This is a reagent-free study.

Data and code availability

Data: This paper analyses existing, publicly available data. These accession numbers for the datasets are listed in the [key resources table](#). All data reported in this paper will be shared by the lead contact upon request.

Code: This paper does not report original code, which is available for academic purposes from the lead contact upon reasonable request.

Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

METHOD DETAILS

Input data

Five sets of data are used in this study: (1) China's national annual data, including population and trade volume; (2) China's IO tables; (3) China's estimated CO₂ emissions; (4) the GTAP database; and (5) the corresponding price deflator data.

First, China's national population data can be obtained from the National Statistics Yearbook, published by the National Bureau of Statistics of China (NBSC) (NBSC, 2019). The annual trade data for both imports and exports can be derived from the General Administration of Customs of China (GACC) (GACC, 2019).

Second, China's IO tables can be freely obtained from the official website of the National Statistics Yearbook (NBSC, 2019); however, tables for 2002, 2005, 2007, 2010, 2012, 2015 and 2017 are available based on the national surveys every five years.

The CO₂ emission inventories in China are constructed as mentioned above, without official release of China's emissions data. By using fossil fuel consumption, cement production and emission factors, inventory data are developed by and can be sourced from the China Emission Accounts and Datasets (CEADs), a free emission data sharing platform (CEADs, 2019). The energy consumption data can be derived from the published Energy Statistical Yearbooks by the NBSC, and emission factors are estimated by previous studies (Liu et al., 2015).

According to version 10 of the GTAP database, the global MRIO tables and CO₂ emissions are provided for 89 countries or regions in 2001 and 141 countries or regions in 2004, 2007, 2011 and 2014, with details of intermediate use among 57 sectors and final use including investment, household and government consumption (GTAP, 2019).

All the tables are deflated to 2017 prices. With respect to China, the pricing data for the IO tables are from the NBSC, while the pricing data for imports and exports are from the GACC. With respect to the GTAP database and China's IO tables, the double deflation method is applied (UNSD, 1999). The price deflator data for the global MRIO tables are from the National Account Main Aggregates Database (UNSD, 2018).

Data S1 contains the definitions of the world's 11 regions. Data S2 provides the relative change rates and the absolute change rates of CO₂ emissions embodied in imports by four distinct analytical perspectives from 2012 to 2017. Data S3 shows the reconciliation of sectors from four different sources, including 45 sectors in emission inventories, 42 sectors in China's SRIO tables, 57 sectors in the GTAP MRIO tables and seven sectors in the sector classification of pricing data for global MRIO tables, all of which are unified into 11 sectors. As noted above, the data from the CO₂ emission inventories can be sourced and obtained from the CEADs (CEADs, 2019). Data S4 provides CO₂ emissions embodied in Chinese imports by different uses in 2002, 2005, 2007, 2010, 2012, 2015 and 2017. Data S5 provides CO₂ emissions embodied in Chinese imports sourced from different regions in 2002, 2005, 2007, 2010, 2012, 2015 and 2017. Data S6 provides CO₂ emissions embodied in Chinese imports sourced from different source sectors in 2002, 2005, 2007, 2010, 2012, 2015 and 2017. Data S7 provides the absolute change rates of CO₂ emissions embodied in imports from 2002–2007, 2007–2012 and 2012–2017.

CO₂ emission inventories

By using territorial CO₂ emission inventories from the Intergovernmental Panel on Climate Change (IPCC), China's CO₂ emission inventories are estimated by emissions from the consumption of both fossil fuels and non-fossil energy (Mi et al., 2019; Shan et al., 2016) as follows:

$$C = C_f + C_n \quad (\text{Equation 1})$$

where C represents China's total CO₂ emissions from a production perspective; C_f represents CO₂ emissions from fossil fuel combustion; and C_n represents CO₂ emissions from cement production.

The emissions caused by combusting fossil fuels, i.e. energy-related emissions, are measured by (IPCC, 2006; Liang et al., 2017):

$$C_f = D_f \times N \times H \times O \quad (\text{Equation 2})$$

where C_f represents the fossil fuel CO₂ emissions; D_f , defined as the unit fossil fuel consumption, is used to avoid missing values or double-counting (Peters et al., 2006); and the remaining terms represent emission factors for unit fossil fuel combustion— N is the net calorific value of released heat, H is the carbon content of released heat, and O is the oxidization rate in oxygenation.

The emissions caused by producing cement, i.e. process-related emissions, are measured by (IPCC, 2006):

$$C_n = D_n \times T \quad (\text{Equation 3})$$

where C_n represents the non-fossil fuel CO₂ emissions, which refer specifically to the emissions from cement production; D_n is the amount of cement production; and the emission factor for unit cement production is T , which is estimated to be 0.2906 tonne CO₂ per tonne of cement (Liu et al., 2015).

Linking the GTAP database to China's SRIO

Based on previous studies linking nationwide MRIO or SRIO models to global MRIO models, this study builds similar connections between China's SRIO and global MRIO from version 10 of the GTAP database

(Aguilar et al., 2019). China's SRIO tables are deflated to 2017 constant prices with the price index, while the double deflation method is applied to deflate the MRIO tables from the GTAP database to 2017 prices (UNSD, 1999).

The official release years of IO tables vary. According to other related research, the closest years of tables from different sources are commonly linked, including China 2007 with GTAP 2007 (Feng et al., 2013; Weitzel and Ma, 2014), China 1997 with Asia 2000 (Su and Ang, 2014), and China 2010 and 2012 with GTAP 2011 (Mi et al., 2017). Thus, linkages are as follows in this study: China 2002, 2005, 2007, 2010, 2012, 2015 and 2017 with GTAP 2001, 2004, 2007, 2011 and 2014, with all IO tables deflated to 2017 constant prices. By doing so, the accuracy of volume data at the national level and the clarity of structural data at the international level can be combined.

Similarly, the classifications of socioeconomic sectors published by official institutions and organizations are different, which requires reconciling sectors from different sources before linking. Version 10 of the GTAP database provides data on the import and export flows of 89 countries or regions in 2001 and 141 countries or regions in 2004, 2007, 2011 and 2014. Traded products can be divided into intermediate products circulating among 57 sectors and final products used in investment, household consumption and government consumption. China's IO tables at the national level can also be divided into intermediate uses by 42 sectors and final demand, including rural household consumption, urban household consumption, government consumption, fixed capital formation and changes in inventories. With respect to intermediate uses, 57 sectors in the GTAP database and 42 sectors in the Chinese SRIO tables are aggregated into 11 sectors (see Data S3 for the reconciliation of sectors). From the perspective of final use, five uses in the Chinese tables can be aggregated into the three uses in the GTAP, i.e. fixed capital formation and changes in inventories are combined to yield investment, rural and urban household consumption are combined to yield household consumption, and government consumption represents the third use.

By assuming the same proportions based on the generally-applied proportioning principle (Wiedmann et al., 2021), the distribution of imports across sectors in the Chinese SRIO tables is the same as that in all foreign countries from the GTAP database. Imports in China's SRIO tables are distributed by intermediate and final uses through proportions (see Data S4 for uses in detail), corresponding to uses provided by GTAP MRIO tables. China's imports in each sector are divided into all other regions of the world according to the trade structure obtained from the GTAP database. Thus, the CO₂ emissions embodied in imports are calculated through the global MRIO model.

Environmentally extended input-output analysis

By expanding the national input and output flows into fields related to the environment (Lenzen et al., 2012), carbon emissions can be systematically analyzed by the Leontief inverse matrix, reflecting direct and indirect economic relations among sectors (Leontief, 1936). The Leontief equation, as the fundamental equation in the quantified framework developed by Wassily Leontief, is expressed as follows:

$$X = LF = (I - A)^{-1}F \quad (\text{Equation 4})$$

where X is a column vector of the total output including the output of each sector; F is the vector of final demand comprising several uses; L is the Leontief inverse matrix mentioned above; and L is calculated by $(I-A)^{-1}$, where I is the identity matrix, and A is the technical coefficient matrix describing the inter-sectoral flows.

To expand the above approach to environmental accounting, emissions or energy are added to the equation as exogenous transactions among the sectoral networks. By multiplying the carbon intensity, the equation is still equal, and both sides represent the total emissions from households and industries, estimated as follows:

$$C = ELF = E(I - A)^{-1}F \quad (\text{Equation 5})$$

where C is the vector of total CO₂ emissions; and E is a diagonalized matrix by sections of the carbon intensity defined as the carbon emissions per unit of output (Peters, 2008).

Emissions embodied in trade

The national and regional CO₂ emissions embodied in trade can be estimated by the environmentally extended input-output analysis. Errors exist in the estimated emissions embodied in imports when assuming that imports are produced with Chinese technology (Meng et al., 2016), though used in previous studies (Guan et al., 2008). Therefore, carbon emissions embodied in imports are estimated with the assumption of technology differences in this study. The emissions embodied in imports are calculated by linking the GTAP MRIO database to China's SRIO tables, proportioned on the respective structures for the concordance of data at different levels (see Data S5 and S6 for regions and sectors in detail). Thus, the sectoral emissions embodied in China's imports are adjusted by global carbon intensity and production structure as follows (Mi et al., 2018):

$$C_{imp} = E_{imp} L_{imp} Imp = E_{imp} (I - A_{imp})^{-1} Imp \quad (\text{Equation 6})$$

where C_{imp} is the CO₂ emissions embodied in imports; E_{imp} is the vector of the adjusted carbon intensity of imports; L_{imp} is calculated by $(I - A_{imp})^{-1}$ as the Leontief inverse matrix; and Imp is the vector of imports, where the inter-sectoral flows from other regions describes the intermediate demand and products pouring into consumption as well as investments represent the final demand.

For years without officially published IO tables, it is assumed that changes in the production structure associated with the IO tables are linear between the closest years on either side. Thus, the CO₂ emissions embodied in China's imports can be estimated by the linear-predicted IO production structure and timely data of emissions and imports for each year as follows (Mi et al., 2018):

$$C_{imp} = \begin{cases} E_t (I - A_t)^{-1} Imp_t & \text{if } t = 2002, 2005, 2007, 2010, 2012, 2015, 2017 \\ \frac{2}{3} E_t (I - A_{t-1})^{-1} Imp_t + \frac{1}{3} E_t (I - A_{t+2})^{-1} Imp_t & \text{if } t = 2003, 2008, 2013 \\ \frac{1}{3} E_t (I - A_{t-2})^{-1} Imp_t + \frac{2}{3} E_t (I - A_{t+1})^{-1} Imp_t & \text{if } t = 2004, 2009, 2014 \\ \frac{1}{2} E_t (I - A_{t-1})^{-1} Imp_t + \frac{1}{2} E_t (I - A_{t+1})^{-1} Imp_t & \text{if } t = 2006, 2011, 2016 \\ E_t (I - A_{2017})^{-1} Imp_t & \text{if } t = 2018 \end{cases} \quad (\text{Equation 7})$$

where E_t is the vector of the carbon intensity in year t ; $(I - A_t)^{-1}$ is the Leontief inverse matrix in year t ; and Imp_t is the vector of imports in year t . The data for year 2018 is predicted in different forms of functions. We use linear and quadratic functions for the fitting of estimated outputs X and emissions C in GTAP MRIO tables, respectively, and then calculate the carbon intensity by using emissions and outputs.

Consumption-based CO₂ emission accounting (CBA)

PBA and CBA are the two main approaches for calculating carbon emissions (Shigeto et al., 2012). PBA, as the most widely used approach, is composed of the CO₂ emissions from domestic production and exports (Peters, 2008). CBA is composed of the production emissions embodied in final goods consumed in the same country plus the emissions embodied in imports (Wiedmann, 2009). The above relationship of "locally produced emissions for local consumption = consumption-based emissions - emissions embodied in imports = production-based emissions - emissions embodied in exports" can be represented by the following mathematical expression:

$$C_{CBA} = C_{local} + C_{imp} = C_{PBA} - C_{exp} + C_{imp} = C - C_{exp} + C_{imp} \quad (\text{Equation 8})$$

where C_{CBA} is the vector of consumption-based CO₂ emissions; C_{local} is the vector of locally produced emissions for local consumption; C_{imp} is the CO₂ emissions embodied in imports as introduced above; C_{PBA} is the vector of production-based CO₂ emissions; and C_{exp} is the CO₂ emissions embodied in exports.

Technology-adjusted CBA (TCBA)

TCBA, introduced as the current state-of-the-art, is applied to analyze whether outsourcing exists (Kander et al., 2015). Outsourcing of emissions usually exists when PBA is lower than CBA. However, when PBA is higher than TCBA, it indicates that the aforementioned displacement is partly caused by differences in carbon efficiency among trade partners, instead of outsourcing. The carbon intensity in TCBA should be adjusted by weighted average carbon intensity at the global level as the emission multiplier for each sector.

This world weighted average carbon intensity multiplier, exported for foreign final demand, is calculated as:

$$\bar{C}_{exp} = \bar{E}_{exp} L Exp = \bar{E}_{exp} (I - A)^{-1} Exp \quad (\text{Equation 9})$$

where \bar{C}_{exp} is the vector of technology-adjusted CO₂ emissions embodied in exports; \bar{E}_{exp} is a diagonalized matrix by sections of the world weighted average carbon intensity defined as the global carbon emissions per unit of output worldwide (Peters, 2008); and Exp is the vector of exports.

By using world weighted average carbon intensity, TCBA can be calculated by the following mathematical expression:

$$C_{TCBA} = C_{local} + C_{exp} - \bar{C}_{exp} + C_{imp} = C - \bar{C}_{exp} + C_{imp} \quad (\text{Equation 10})$$

where C_{TCBA} is the vector of technology-adjusted consumption-based CO₂ emissions; C_{local} , C_{exp} , C_{imp} and C are the vectors of embodied CO₂ emissions as calculated from the local, export, import and production-based perspective as introduced above, respectively; and \bar{C}_{exp} is the vector of technology-adjusted CO₂ emissions embodied in exports.

Decoupling factor

The term decoupling indicator is used to track the relationship between environmental pressures and economic driving forces. By using the ratio of the value of the decoupling indicator and the end and start of a given time period, a decoupling factor, generated by OECD, is defined as:

$$\text{decoupling factor} = 1 - \frac{C^t/Y^t}{C^0/Y^0} \quad (\text{Equation 11})$$

where C represents CO₂ emissions; Y represents economic growth; and the superscript t and 0 denote the end and start of the period, respectively. Decoupling occurs when the value of the decoupling factor is between 0 and 1, while the value is negative in coupling. Absolute decoupling occurs when $Y^t > Y^0$ and $C^t \leq C^0$. Relative decoupling occurs when $Y^t > Y^0$, $C^t > C^0$ and $Y^t/Y^0 > C^t/C^0$, where both the economy and emissions grow but the economy has a faster growth rate (OECD, 2002).

Structural decomposition analysis (SDA)

This study uses SDA to decompose changes in China's CO₂ emissions embodied in imports between year t and year $t-1$ into five driving factors, including population, carbon intensity, production structure, import patterns and per capita import volume, as follows:

$$\Delta C_{imp} = \Delta P E_{imp} L_{imp} Imp_p Imp_v + P \Delta E_{imp} L_{imp} Imp_p Imp_v + P E_{imp} \Delta L_{imp} Imp_p Imp_v + P E_{imp} L_{imp} \Delta Imp_p Imp_v + P E_{imp} L_{imp} Imp_p \Delta Imp_v \quad (\text{Equation 12})$$

where ΔC_{imp} is the change in CO₂ emissions embodied in imports; P (million) is China's population; E_{imp} (MtCO₂/million Yuan) is the carbon intensity measured by global carbon emissions and outputs, describing the efficiency in terms of emissions per output in monetary units; L_{imp} is the GTAP Leontief inverse matrix at a global level; Imp_p is the import patterns structured by intermediate use for 11 sectors and three components in final use including investment, household consumption and government consumption; and Imp_v (million Yuan/million) is the per capita import volume measured by China's imports per unit of population.

There are different criteria for weight selection in SDA based on the base and reporting periods, resulting in several methods that can be used to decompose driving factors. For example, consider the polar decomposition and midpoint weight decomposition. The former is easier to execute, while the latter is more neutral. Based on the various characteristics and applications of these weighting methods (Su and Ang, 2012), the average of all possible first-order decompositions is applied in this study. Hence, weights are calculated by $5! = 120$ for five drivers (Dietzenbacher and Los, 1998; Hoekstra and Van Den Bergh, 2002).