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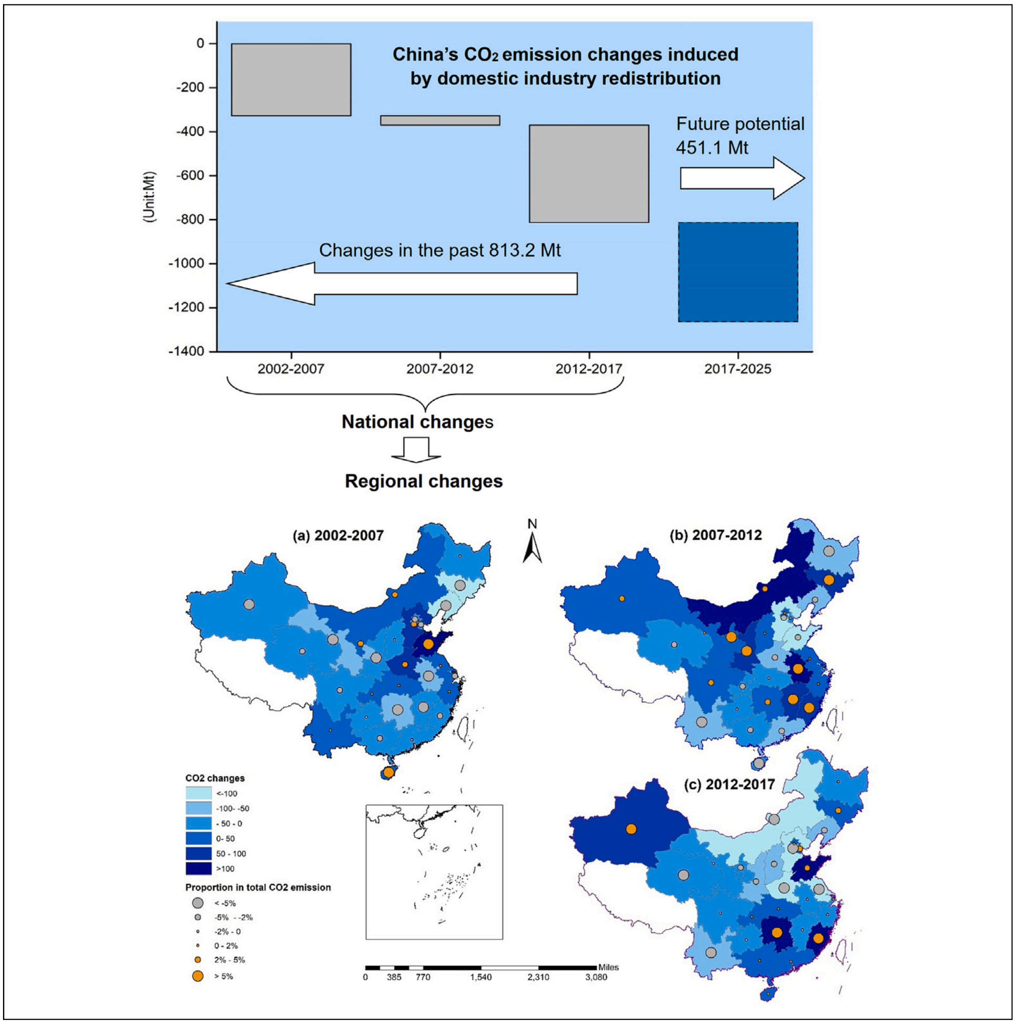

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Highlights

Quantify the impact of China’s domestic industry redistribution on carbon emissions

Propose a counterfactual approach in the multi-regional input-output framework

Domestic industry redistribution decreased China’s emissions during 2002–2017

Effective policies are critical to overpass the pollution haven effect

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China's domestic industry redistribution facilitates carbon emissions mitigation

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SUMMARY

Industry redistribution is a common economic phenomenon that involves a dynamic configuration of the production location across a region, country, or the world. However, measurements of the associated pollutant emission effects have not been well conducted at the domestically regional level. Here, we calculate the CO_2 emission changes induced by China's domestic inter-provincial industry redistribution during 2002–2017 using a counterfactual approach in the multi-regional input-output framework. We find that China's domestic industry redistribution decreased CO_2 emissions during 2002–2017 and has considerable potential to continuously mitigate CO_2 emissions in the future. We emphasize that the pollution haven effect may accompany the process of industry redistribution but can be weakened by effective policies, including stringent access thresholds in the regions undertaking industry relocation and regional industry structural upgrading. This paper provides policy recommendations for strengthening regional coordination to achieve China's transformation to carbon neutrality.

INTRODUCTION

The COVID-19-related supply disruptions thrust industry redistribution—the dynamic configuration of the production location—to both the front pages of the mass media and the top of policymakers' agendas. Industry redistribution is a long-lasting phenomenon that builds on production costs, industrial policies, environmental regulations, etc. During the process, the inextricable parts of industrial production, e.g., energy consumption and the accompanying CO_2 emissions, are redeployed in new locations with varied technology conditions, environmental capacities, governance levels, and so on. Consequently, industry redistribution leads to the redistribution of CO_2 emissions and thus impacts the aggregated amount of CO_2 emissions.[1,2] Many countries in the world have experienced or are experiencing industry redistribution, which triggers distributional changes in regional CO_2 emissions. Understanding the CO_2 emission effects of industry redistribution is crucial for forming effective emission control strategies regionally and globally.

As the world's largest carbon emitter, China plays an important role in global CO_2 emissions mitigation.[3] China has made a pledge to peak its CO_2 emissions before 2030 and reach carbon neutrality before 2060, which brings challenges to its regional development patterns.[4,5] In recent years, the trend of reverse globalization is emerging under the cumulative impacts of COVID-19 and prevailing trade protectionism. To cope with the uncertainties of international economic transformation, China has established a new development strategy of "dual circulation" with domestic large circulation as the main body and domestic-international dual circulations mutually promoting each other, which gives full play to China's domestic industry transformation.[6] China's domestic industry redistribution (DIR) is anticipated to play a significant role in China's future development, and its effects on China's CO_2 emission mitigation deserve particular attention.

China has experienced profound transitions in domestic industry distribution in the past decades. Chinese economy is characterized by significant spatial disparities. For instance, Eastern China has large economic superiorities over Central and Western China due to its prestigious geographical location, favorable economic conditions, pioneering supporting policies, etc. To narrow the disparities among regions, China implemented a series of regional development strategies around the early 2000s (e.g., "*The Western Development Strategy*" in 1999, "*The Northeast Revitalization Strategy*" in 2003, and "*The Rise of Central China Strategy*" in 2006) to stimulate the economic development in Central and Western China through

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industry transfer. Meanwhile, more stringent environmental regulations and the rising costs of labor and land in the developed eastern regions also had driven the energy-intensive industries to transfer to Central and Western China where environmental regulations are relatively more lenient.[7] Along with the opportunities for economic growth in the less-developed regions, CO_2 emissions were also spatially redistributed in the process.

There have been debates over the effects of industry redistribution on CO_2 emissions. One of the most popular hypotheses is the "pollution haven hypothesis", which suggests that developed countries/regions tend to relocate "dirty" industries to less-developed ones with less stringent environmental regulations to reduce production costs, consequently compromising the environment of those regions.[8–10] Although there have been some studies on the pollution haven hypothesis, a consensus has not yet been reached. Some studies supported the existence of pollution haven effects,[11–14] while other studies found no robust evidence supporting the hypothesis.[15–18] The widely applied methodologies in those studies include econometric models[19–21] and input-output analysis.[22–25] However, most previous studies focused on the impacts of cross-national industry redistribution.[26–30] A limited number of studies realized the significance of DIR inside a country, but the investigations were confined to a fragmented period and the effects of industry redistribution were not separated from other influencing factors relevant to CO_2 emissions.[31,32] China is a large country consisting of heterogeneous regions involved in complex and massive domestic cross-region economic activities that are expected to be further strengthened in the trend of "reverse globalization" or "regionalization" in the future.[33] Therefore, it is essential to investigate the spatial and temporal dynamic trends of the carbon effects of China's DIR. Considering regional industry redistribution is a chronic and continuous process, relatively long-term analysis is conducive to a comprehensive and objective understanding of the carbon effects of industry redistribution, which can provide implications for other countries experiencing DIR to avoid carbon leakage.

The environmental effects of China's DIR have attracted increasing attention in recent years. Quite a few studies have measured China's regional carbon transfer as the gap between the provincial production-based and consumption-based carbon emission.[34–38] However, when it comes to the relationship between China's DIR and regional carbon transfer, there is no unambiguous conclusions. Some works find the direction of China's DIR and carbon transfer is inconsistent.[39] The main reason behind is that there exist other factors affecting carbon transfer such as changes in carbon emission intensity, environmental regulation, and urbanization.[40,41] In consequence, the measured carbon transfer is not exactly the changes in carbon emissions driven by DIR.

In this work, we eliminate the interference of other factors influencing CO_2 emissions using a counterfactual approach in the multi-regional input-output framework. We adopt the quantifiable definition of industry redistribution as changing the sourcing regions of intermediate and final products.[42] We investigate the changes in CO_2 emissions induced by China's DIR over 15 years (2002–2017). In this period, China experienced intensive domestic industry relocation under a series of influential regional economic development policies. We also predict China's CO_2 emission reduction potential by the end of "the 14^{th} Five-Year Plan" by updating Chinese provincial multi-regional input-output tables to the year 2025 and applying the counterfactual approach to the updated table. The results show that China's CO_2 emissions decreased by 813.2 million tons (Mt) due to DIR during 2002–2017 and have a potential reduction of 451.1 Mt during 2017–2025. The results confirm the positive contribution of China's DIR in CO_2 emission mitigation during 2002–2017 and the considerable reduction potential in the future. We argue that the carbon impacts of DIR are a dynamic process with a "turning point" and the pollution haven effect is an interim phase of this process. We emphasize that the pollution haven effect can be weakened or avoided by implementing effective policies, including stringent access thresholds in regions undertaking industry transfers and regional industry structural upgrading.

RESULTS

Aggregated CO_2 emission changes induced by China's DIR (2002–2017)

In the multi-regional input-output framework, the carbon emission can be calculated as the product of a list of factors including the emission per unit of output, production technique, domestic final demands, exports, the source region of products, the substitution effects among regions, etc. In this work, we define industry redistribution as the changes in the source regions of products. We then calculate the changes

Figure 1. Aggregated CO_2 emission changes induced by domestic industry redistribution

in carbon emissions driven by DIR by letting the source region be flexible and keeping all the other factors constant.

Figure 1 presents China's aggregated CO_2 emission changes induced by DIR. It shows that China's DIR decreased its CO_2 emissions by a considerable amount of 813.2 Mt during 2002–2017. China's CO_2 emissions would have increased 14.2% more than the actual situation if there had been no DIR in this period. It suggests that China's industries have been generally redistributing in a cleaner direction. Moreover, the impacts of DIR on CO_2 emission changes varied in different periods. During 2012–2017, DIR decreased CO_2 emissions by the largest amount of 443.3 Mt, which was over half of the total decrease in the entire study period, followed by a decrease of 327.4 Mt during 2002–2007. The decrease in CO_2 emissions during 2007–2012 was 42.5 Mt, the least amount in the three periods.

It is worth noting that the three study periods correspond to three phases of the evolutionary history of China's DIR: the "agglomeration to the East" phase of 2002–2007, the "transfer to the Central & West" phase of 2007–2012, and the "integral optimization" phase of 2012–2017. We demonstrate the diverse features of the CO_2 emission changes in the three phases at the four-zone level (Figure 2) and province level (Figure 3). The divisions of the four zones in China are provided in Table S1.

During 2002–2007, the CO_2 emissions in Eastern China increased by 144.4 Mt due to DIR. In particular, the eastern provinces, such as Shandong and Hebei, had large increases in CO_2 emissions. In contrast, DIR resulted in a CO_2 emission decrease in the other three zones, namely Central China, Western China, and Northeastern China (Figures 2, 2B, 3, and 3A). During this period, geographical location advantages and preferential policies accelerated industry agglomeration in Eastern China, while industrial development in Central and Western China fell behind. Moreover, the economic development in Northeastern China—the traditional industrial base—was stuck in recession, making its status in the national industry system degraded seriously. Therefore, the industry redistribution characterized as "agglomeration to the East" led to an increase in CO_2 emissions in Eastern China and a decrease in the other regions.

The situation was significantly different in the "transfer to the Central & West" phase of 2007–2012. DIR made the CO_2 emissions in Eastern China decrease by 247.3 Mt, 1.4% of its total CO_2 emissions, whereas it made the CO_2 emissions in Central and Western China increase by 165.8 Mt and 141.2 Mt, respectively. Some eastern provinces, such as Hebei and Shandong, which used to have high increases in emissions during the "agglomeration to the East" phase, experienced significant decreases in CO_2 emissions (Figures 2, 2C, and 3–3B). To some extent, the results confirm the existence of the "pollution haven hypothesis" during the period. Under policies targeting at narrowing regional disparities, such as *"The Great Western Development Strategy"* and *"The Rise of Central China Strategy"*, Eastern China started massive industry transfers to Central and Western China, where many carbon-intensive industries were relocated during the process. Compared with Eastern China, Central and Western China were less economically developed and thus generally prioritized local economic growth over environmental protection when considering the trade-off.[43,44] As a result, the stringency of formal environmental regulation was relatively more lenient in Central and Western China.[45,46] Therefore, during this period, Central and Western China achieved economic growth by accepting the transferred industries from Eastern China at the cost of an increase in CO_2 emissions.

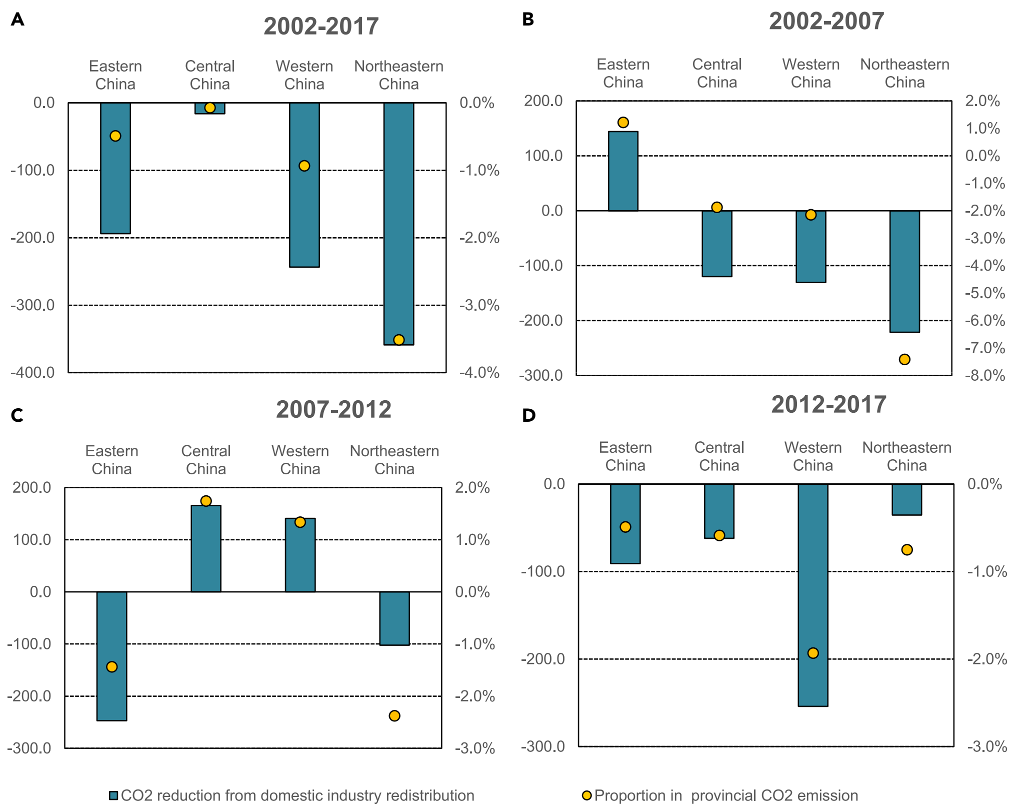

Figure 2. Regional changes in CO_2 emissions induced by China's domestic industry redistribution (by zone) (Unit: Mt)

During 2012–2017, the changes in CO_2 emissions induced by DIR in all four zones showed a consistent declining trend. Particularly, Western China had the largest decline of 254 Mt, accounting for approximately 2% of its regional total amount of CO_2 emissions. Many central and western provinces, such as Inner Mongolia, Henan, Shanxi, and Shaanxi, showed significant decreases during this period (Figures 2, 2D, and 3–3C). China formulated increasingly stringent and specific mitigation policies throughout the country during this period. The "12th Five-Year Plan" proposed a 17% reduction in CO_2 emissions per unit of gross domestic product (GDP) from 2011 to 2015.[47] The *"Plans for Greenhouse Gas Emissions Control in the 12th Five-Year Plan"* issued in 2012 explicitly proposed CO_2 mitigation methods for strictly curbing energy-intensive industries by raising the entry threshold and eliminating the outdated production capacity.[48] These tightening regulations accelerated the shrinkage of the carbon-intensive sectors in all the regions, which led to the overall decline in CO_2 emissions induced by DIR in this period.

Sectoral CO_2 emission changes induced by China's DIR (2002–2017)

During 2002–2017, sector 13-NMP (nonmetal mineral products) had the largest CO_2 emission decrease of 366.5 Mt induced by DIR, accounting for 45.1% of the total CO_2 emission changes induced by DIR of all sectors. This is followed by sector 22-EHP (Electricity and heating power production and supply) and sector 2-CMP (Coal mining, washing, and processing), with decreases in CO_2 emissions amounting to 152.8 Mt and 149.5 Mt, respectively (Figure 4).

During 2002–2017, the CO_2 emission decrease induced by DIR can be mostly attributed to the carbon-intensive sectors. The carbon-intensive sectors include 2-CMP, 11-PCN (petroleum processing, coking, and nuclear fuel processing), 12-CHM (chemicals), 13-NMP, 14-MSP (metals smelting and pressing), 22-EHP, and 26-TWP (transport, warehousing, and post), which are determined based on the CO_2 emission coefficient (Table S2). From 2002 to 2017, DIR made the CO_2 emissions of the carbon-intensive sectors decrease by 872.9 Mt, even exceeding the total CO_2 decrease induced by DIR in all sectors. The significant CO_2 emission reduction in the

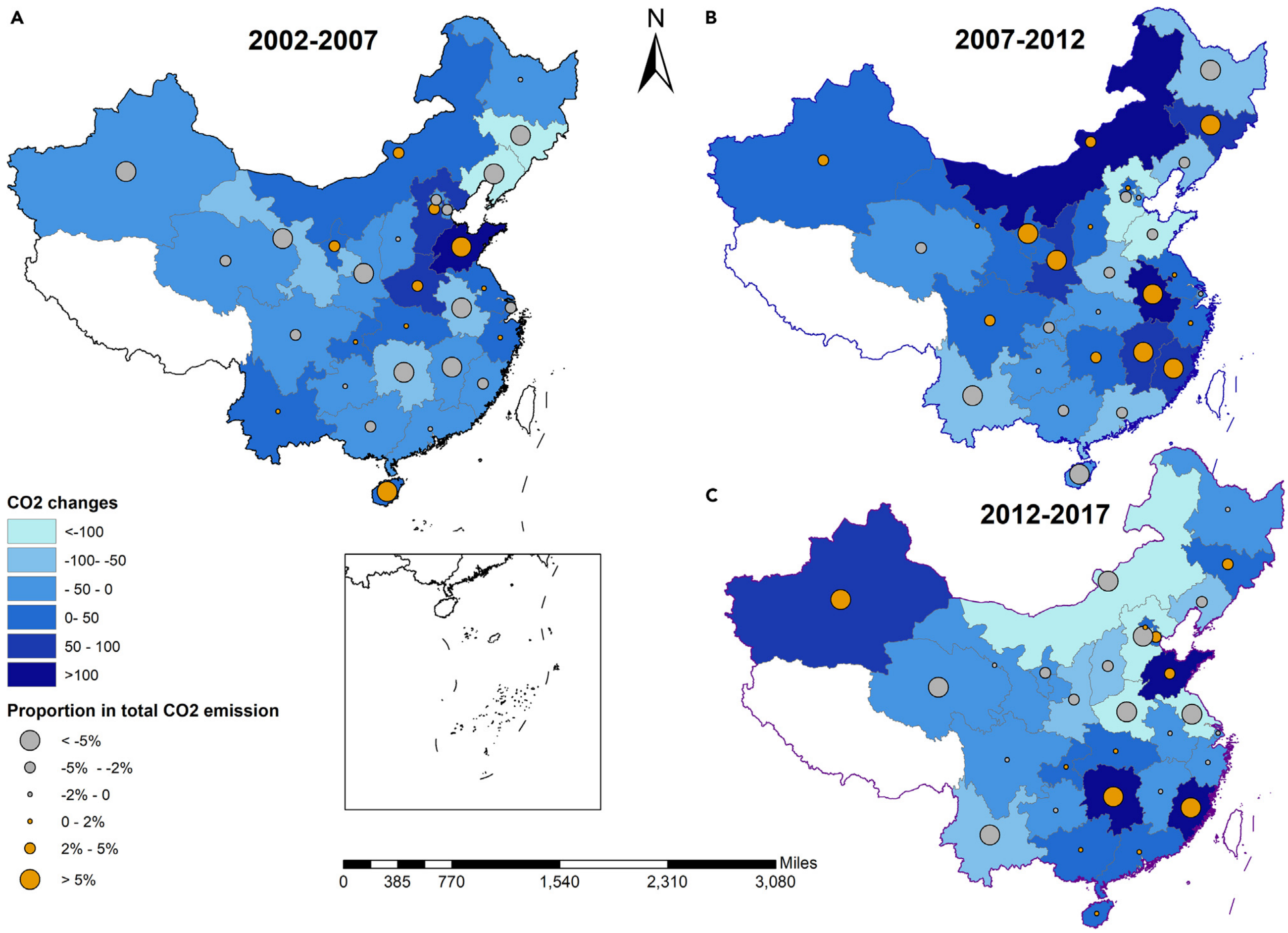

Figure 3. Regional changes in CO_2 emissions induced by China's domestic industry redistribution (by province (Unit: Mt)

carbon-intensive sectors is closely related to China's policies to constrain the development of carbon-intensive sectors. Since 2007, China has issued the "*Comprehensive Work Plan on Energy Conservation and Emission Reduction*", making an all-around plan for the major sectors of energy consumption. In the plan, the adjustment of the industrial structure was put in the key place. It exercises strict control over industries with high energy consumption, high carbon emission, and backward productivity, which expedited the transformation of traditional industries with advanced and applicable technology.

The regional CO_2 emission changes induced by DIR of the carbon-intensive sectors are shown in Figure 5. At the four-zone level, the changes in CO_2 induced by DIR of the carbon-intensive sectors showed a consistent declining trend. As a traditionally typical base of heavy industries, Northeastern China showed the largest CO_2 emission decrease induced by DIR in the carbon-intensive sectors. In particular, Liaoning showed the most significant decrease of 201.1 Mt. The carbon-intensive sectors in most central and western provinces indicated varying decreasing amounts in CO_2 emission changes induced by DIR. For provinces that are rich in mineral resources and relevant industries, such as Henan, Shanxi, and Yunnan, their carbon-intensive sectors showed significant decreases. Except for Xinjiang, most provinces showing an increasing trend of CO_2 emissions induced by DIR in carbon-intensive sectors were located in Central and Eastern China. The carbon-intensive sectors in Shandong and Fujian in Eastern China had the largest increases of 206.8 Mt and 151.7 Mt, respectively, and they were mostly attributed to the CO_2 emission increase in sector 22-EHP.

Note:13-NMP: Nonmetal mineral products; 22-EHP: Electricity and heating power production and supply; 2-CMP: Coal mining, washing, and processing; 14-MSP: Metals smelting and pressing; 26-TWP: Transport,

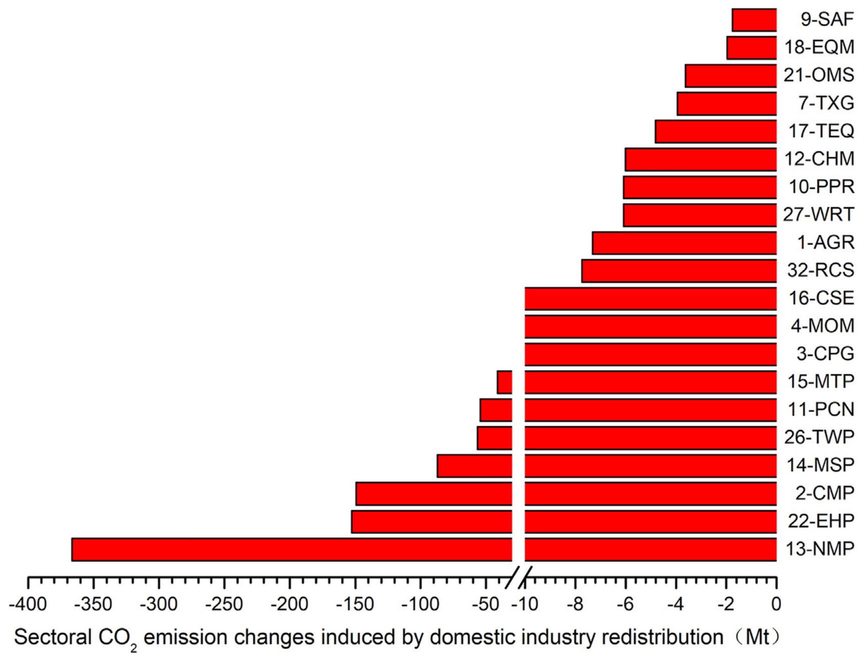

Figure 4. Sectoral CO_2 emission changes induced by domestic industry redistribution (2002–2017) (Unit: Mt)

warehousing, and post; 11-PCN: Petroleum processing, coking, and nuclear fuel processing; 15-MTP: Metal products; 3-CPG: Crude petroleum and natural gas products; 4-MOM: Metal ore mining; 16-CSE: Common equipment and special equipment; 32-RCS: Renting and commercial services; 1-AGR: Agriculture; 27-WRT: Wholesale and retail trade; 10-PPR: Paper and products, printing and record medium reproduction; 12-CHM: Chemicals; 17-TEQ: Transport equipment; 7-TXG: Textile goods; 21-OMS: Other manufacturing products, Scrap, and waste; 18-EQM: Electric equipment and machinery; 9-SAF: Sawmills and furniture.

Estimation of China's emission reduction potential induced by DIR (2017–2025)

Since China entered the "14^{th} Five-Year" period (2021–2025), the adjustment of regional industrial distribution has been regarded as a principal strategy to balance regional economic development and CO_2 emission mitigation. The national development plan enacted by the Chinese central government, *"The Outline of the 14^{th} Five-Year Plan (2021–2025) for National Economic and Social Development and Long-Range Objectives Through the Year 2035"*, proposed the requirement to improve the regional industrial layout. It is rational to anticipate that regional industrial distribution will continue to play a significant role in China's CO_2 emission mitigation. Therefore, the estimation of CO_2 reduction potential of DIR can be conducive to implications for achieving China's economic and CO_2 mitigation targets. To this end, we predict China's CO_2 emission reduction potential of DIR by the end of "the 14^{th} Five-Year Plan" by updating Chinese provincial multi-regional input-output tables to the year 2025 and applying the counterfactual approach to the updated table and the existing table of the year 2017.

Our estimation results indicate that China's CO_2 emission changes induced by DIR have a declining potential of 451.1 Mt during 2017–2025, and the average annual decrease will be 56.4 Mt. According to the report released by the China Coal-Control Project, China should achieve an annual decrease in CO_2 emissions by nearly 400 Mt after 2020 under the 1.5°C warming-rise target.[49] Taking this as a mitigation benchmark, the CO_2 decrease induced by DIR will account for approximately 14.1% of the annual CO_2 mitigation goal, verifying the significance of DIR in China's CO_2 emission mitigation in the future.

At the four-zone level, Western China, Central China, and Eastern China all indicate CO_2 reduction potentials. In particular, Western China has the largest CO_2 reduction potential of 271.6 Mt, accounting for 60.2% of the national total during the period, followed by Central China (185.8 Mt) and Eastern China (166.7 Mt). It is interesting to note that Northeastern China will have an increase of 173 Mt during the period (Figure 6).

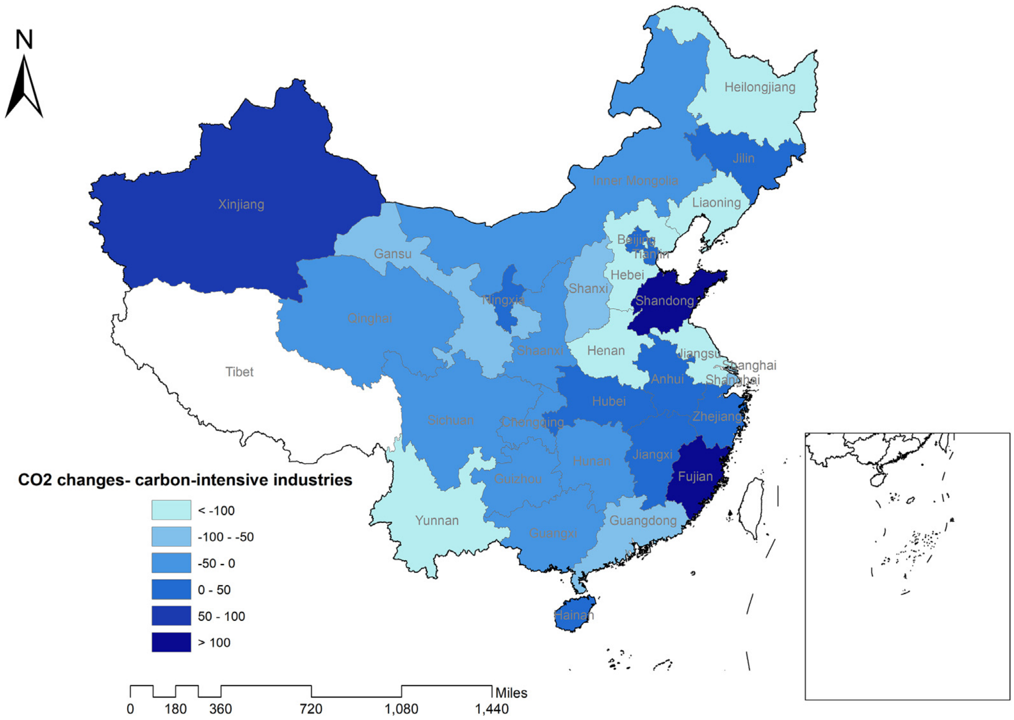

Figure 5. Regional contributions to CO_2 emission changes induced by domestic industry redistribution in the carbon-intensive industries (2002–2017) (Unit: Mt)

Northeastern China has experienced a continuous economic recession and industry shrinkage in recent decades. In the "14th Five-Year" period, Northeastern China is expected to realize economic revitalization under a series of policy stimuli, which might alter Northeastern China's industrial shares and result in an increase in CO_2 emissions. At the provincial level, the provinces with high CO_2 reduction potentials are mainly located in the southern regions. Ten out of the fifteen provinces with decreasing CO_2 emissions induced by DIR are southern provinces, and the decreases will amount to 1353 Mt, accounting for over 70% of the total decreases of the fifteen provinces. The provinces with CO_2 increase potentials induced by DIR are mainly located in Central and Northeastern China. In particular, Heilongjiang in Northeastern China and Henan and Anhui in Central China show the highest CO_2 increase potentials during 2017–2025 (Figure 7).

DISCUSSION

The existence of the pollution haven effect is a classic debate when investigating the effects of industry redistribution on CO_2 emissions. Although a few previous studies have tested and confirmed the pollution haven effect hidden in industry redistribution, it is critical to inspect the associated impacts from a comprehensive and dynamic perspective. We find in this study that during 2007–2012, the CO_2 emission changes induced by DIR in Eastern China with relatively more stringent environmental regulations decreased, whereas they significantly increased in regions with relatively more lenient environmental regulations, such as Central and Western China. This result is consistent with the findings from previous studies that found a spillover of CO_2 emissions from Eastern to Western China,[35,50] which, in a sense, verifies the existence of pollution haven effects in China during 2007–2012. Nevertheless, we also find that the CO_2 emission changes induced by DIR revealed different regional patterns in the subsequent period of 2012–2017 when it was characterized by a widespread decrease in all four zones. This finding does not support the pollution haven hypothesis. We argue that the carbon impacts of DIR are a dynamic process with a "turning point" and that the pollution haven effect is an interim phase of this process. Specifically, DIR leads to carbon leakage before the "turning point" but reduces CO_2 emissions over the "turning point". In the primary phase of industry redistribution when economic growth is placed in a paramount place, carbon-intensive industries tend to be strongly motivated to move from regions with more stringent environmental

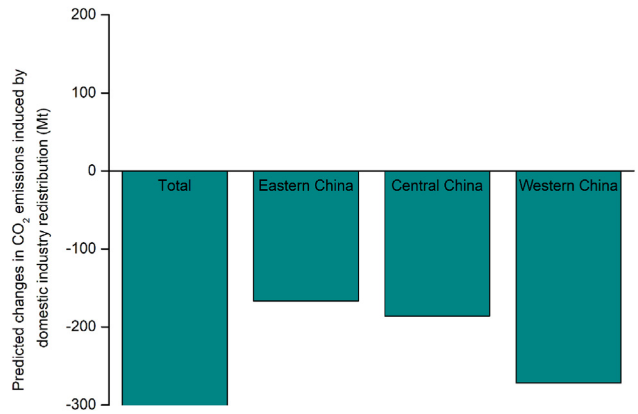

Figure 6. Regional potential changes in CO_2 emissions induced by China's domestic industry redistribution (2017–2025) (by zone) (Unit: Mt)

constraints to regions with relatively laxer environmental regulations. The regions accepting the transferred carbon-intensive industries are generally inclined to choose local economic growth brought by these industries over environmental protection. However, once passing the "turning point", particularly under certain policy stimuli, industry redistribution can optimize resource allocation, produce technology spillovers, and thus upgrade the regional industry structure over time.

The "turning point" for China is speculated to have occurred at the beginning of the 12th Five-Year" period (2011–2015). Theretofore, economic growth was prioritized in regional development strategies, which resulted in carbon leakage accompanied by DIR. In the early 2000s, China's regional economic disparities were continuously widening despite the unprecedented success in economic growth it had achieved. To narrow regional disparities and promote balanced regional development, the Chinese central government enacted a succession of regional policies including "*The Western Development Strategy*" in 1999, "*The*

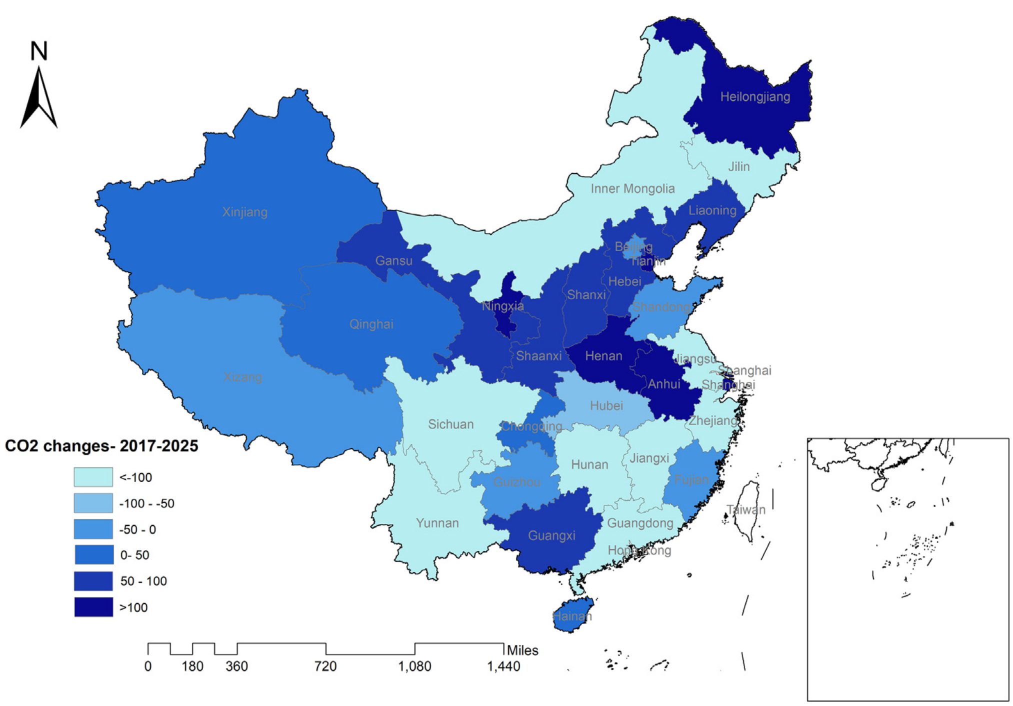

Figure 7. Regional potential changes in CO_2 emissions induced by China's domestic industry redistribution (2017–2025) (by province) (Unit: Mt)

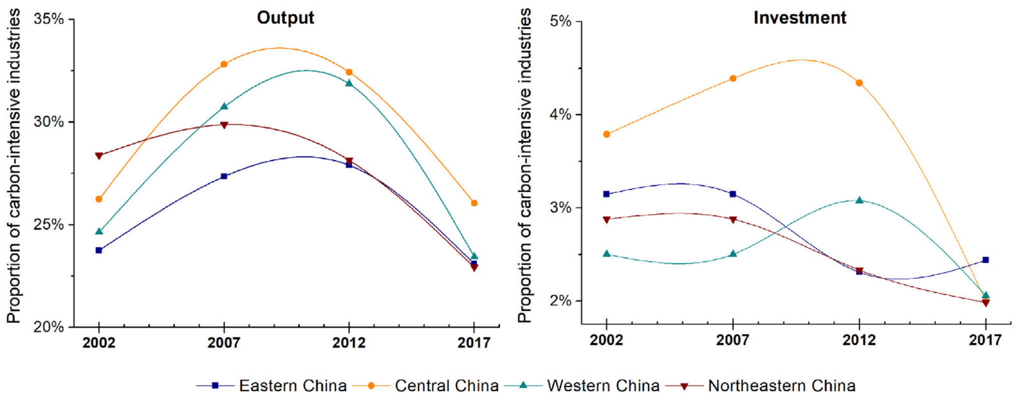

Figure 8. Changes in the proportion of output & investment of the carbon-intensive industries in the four zones in China (2002–2017)

Northeast Revitalization Strategy" in 2003, and *"The Rise of Central China Strategy"* in 2006. These strategies promoted massive industry transfers from Eastern China to Central and Western regions. Many carbon-intensive industries constrained by the strict environmental regulations in the east moved to the central and western regions, leading to an increase in CO_2 emissions. Since the 12^{th} Five-Year Plan period, China had started to transform its development patterns from rapid economic growth to a high-quality and sustainable mode at both the national and regional levels. Cleaner production and lower CO_2 emissions had been considered equally important to or even more important than economic growth. Many central and western regions made their high-quality development plans, including industry structure upgrading and emission reduction, as important components. The western and central regions gradually transformed the economic growth mode by reducing the dependency on carbon-intensive industries. Therefore, the relocation of "dirty" CO_2 emissions along with carbon-intensive industries transfer decreased, and the scales of the existing carbon-intensive industries also contracted. As shown in Figure 8, the curves of the proportion of carbon-intensive industries in terms of output and investment in the central and western regions show inverted-U shapes, verifying the above speculations.

The results of this study indicate that China has overpassed the stage of pollution haven effect in its process of industry redistribution, which ensures the role of DIR in facilitating its CO_2 emission mitigation. China's experiences confirm that the pollution haven effect is crossable and the policies play a significant role in the process. It provides the following policy implications for other countries that have not overcome their "turning point" in their processes of industry redistribution. First, less-developed regions are highly encouraged to ensure economic development and environmental sustainability in tandem when undertaking industry transfers from developed regions. They can consider formulating stringent access to polluting industries, for example, making a negative list restricting the access of some specific polluting industries. In 2010, the Chinese central government released a national-level regulation named *"Opinion of the State Council on the Transfer of Industries to the Central and Western Regions"*, which elaborated environmental policies to avoid emission relocation accompanied by industry transfer. To facilitate better implementation, such regulations need to be refined to the regional level.

Second, avoiding the pollution haven effect and mitigating the aggregated pollutant emissions should be one of sharing responsibilities between less-developed and developed regions. Our empirical results show that Chinese central and western regions had been emitting more CO_2 due to producing "dirty" products for the coastal regions. Therefore, it is essential for both the central government and regional governments to co-ordinate the design and implementation of policies to share the responsibility of emission mitigation. In this regard, China has already established a national emissions trading system. It is a market-based instrument that creates incentives to reduce emissions where these are most cost effective. Other measures include strengthening the research to develop renewable energy and enhance innovations of low-carbon production technologies. It is also highly desired to accelerate the diffusion of emission mitigation technologies to the less-developed regions.

Third, less-developed regions should accelerate efforts to upgrade their energy efficiency and low-carbon production technology. It is suggested that they promote the use of cleaner inputs, mitigate their fossil fuel dependencies, and improve the share of low-carbon and renewable energy in their energy consumption basket. Financial tools (e.g., carbon tax and green bonds) can also be adapted to direct investment at relatively greener production and consumption activities. The pollution haven effect would decrease and even disappear if the measures above significantly narrow the emission intensity gap between less-developed and developed regions.

Limitations of the study

This paper investigates the four key years due to the limitation of data availability. The multi-regional input-output tables employed in this study are officially released every five years. Nevertheless, the pattern change in industrial distribution is a gradual process. Five-year period is generally a proper time quantum to observe industrial redistribution. Therefore, we believe the results of this study are still capable of providing references for the pattern changes in industrial redistribution. It is worth noting that this paper predicts China's future emission reduction potential based on a normal scenario which does not consider the possible interference of extreme events. In reality, extreme events, such as major public health events, natural disasters, inter-country conflicts, and wars, could bring great uncertainties to China's future industrial development and its domestic distribution. Further research may consider such uncertainties, which may lead to other effective policies targeting disaster preparedness and losses mitigation.

STAR★METHODS

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

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  - Data and code availability
- METHOD DETAILS
  - Accounting for CO_2 emission changes induced by DIR in the multi-regional input-output framework
  - Estimation of China's CO_2 emission reduction potential induced by DIR during 2017-2025
  - Data source, collection and analysis

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2023.106844.

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AUTHOR CONTRIBUTIONS

Z.Z. and K.T. conceived the idea and study design. Z.Z., X.G., and K.T. collected data and conducted the research. Z.Z., X.G., K.T., C.Y., and S.W. contributed to writing and revising the paper.

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		
Chinese provincial multi-regional input-output tables	Development Research Center of the State Council of China	Li et al. (2021)[51]
Carbon emission for Chinese provinces and sectors	Carbon Emission Accounts & Datasets	https://www.ceads.net/
Data generated by this paper	This paper	Tables S4 and S5
Software and algorithms		
ArcGIS	ESRI	https://www.arcgis.com/index.html
MATLAB 2018a	Mathworks	https://www.mathworks.com/products/matlab.html
Origin 2022b	OriginLab	https://www.originlab.com/OriginProLearning.aspx

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and reagents should be directed to the corresponding author (tiankailan12@163.com).

Materials availability

This study did not generate new unique materials.

Data and code availability

Data: All data needed to evaluate the conclusions in the paper are present in the paper and/or the supplemental information. Additional data related to this paper can be requested from the authors.

Code: This paper does not report original code.

METHOD DETAILS

Accounting for CO_2 emission changes induced by DIR in the multi-regional input-output framework

In this study, industry redistribution is defined from a multi-regional input-output perspective as the changing of the sourcing region. That is, if an intermediate or a final product is no longer purchased from one source region but a new source region. More specifically, we assume that the inter-regional sourcing structure in year t1 is hypothetically replaced by the structure in t0.

This paper adopts the Chinese provincial multi-regional input-output model (see Table S3 for the stylized table) to account for the CO_2 emission changes induced by DIR. The accounting identity (or product market-clearing condition) of the model is

$$\begin{pmatrix} y^1 \\ \vdots \\ y^n \end{pmatrix} = \begin{bmatrix} Z^{11} & \cdots & Z^{1n} \\ \vdots & \ddots & \vdots \\ Z^{n1} & \cdots & Z^{nn} \end{bmatrix} \begin{pmatrix} u \\ \vdots \\ u \end{pmatrix} + \begin{bmatrix} f^{11} & \cdots & f^{1n} \\ \vdots & \ddots & \vdots \\ f^{n1} & \cdots & f^{nn} \end{bmatrix} \begin{pmatrix} u \\ \vdots \\ u \end{pmatrix} + \begin{pmatrix} e^1 \\ \vdots \\ e^n \end{pmatrix} \quad \text{(Equation 1)}$$

where n and g represent the numbers of regions (provincial units) and the sectors (or industries) in each region, respectively. The matrix $\mathbf{Z}^{sr}$ presents the intermediate deliveries from region s to region r, and $\mathbf{f}^{sr}$

gives the deliveries for final demand. The value of the export and the output in region s are given by $\mathbf{e}^s$ and $\mathbf{y}^s$, respectively. $\mathbf{u}$ indicates the summation vector of appropriate length consisting entirely of ones.

The matrix $\mathbf{A}^{sr} = \mathbf{Z}^{sr}(\hat{\mathbf{y}}^r)^{-1}$ gives the direct intermediate input coefficients. This yields

$$\begin{pmatrix} \mathbf{y}^1 \\ \vdots \\ \mathbf{y}^n \end{pmatrix} = \begin{bmatrix} \mathbf{A}^{11} & \cdots & \mathbf{A}^{1n} \\ \vdots & \ddots & \vdots \\ \mathbf{A}^{n1} & \cdots & \mathbf{A}^{nn} \end{bmatrix} \begin{pmatrix} \mathbf{y}^1 \\ \vdots \\ \mathbf{y}^n \end{pmatrix} + \begin{bmatrix} \mathbf{f}^{11} & \cdots & \mathbf{f}^{1n} \\ \vdots & \ddots & \vdots \\ \mathbf{f}^{n1} & \cdots & \mathbf{f}^{nn} \end{bmatrix} \begin{pmatrix} \mathbf{u} \\ \vdots \\ \mathbf{u} \end{pmatrix} + \begin{pmatrix} \mathbf{e}^1 \\ \vdots \\ \mathbf{e}^n \end{pmatrix} \qquad \text{(Equation 2)}$$

Equation 2 can be written as $\mathbf{y} = \mathbf{A}\mathbf{y} + \mathbf{F}\mathbf{u} + \mathbf{e}$ and the solution is given by $\mathbf{y} = (\mathbf{I} - \mathbf{A})^{-1}(\mathbf{F}\mathbf{u} + \mathbf{e}) = \mathbf{L}(\mathbf{F}\mathbf{u} + \mathbf{e})$, where $\mathbf{L} \equiv (\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse, with $\mathbf{I}$ representing the identity matrix.

We define $\boldsymbol{\lambda}'$ as the row vector of the CO_2 emission coefficient representing the sector-wise CO_2 emissions per unit of output by region. Then CO_2 emissions (**em**) generated by domestic final demand and exports are given by

$$\begin{bmatrix} \mathbf{em}^{11} & \cdots & \mathbf{em}^{1n} \\ \vdots & \ddots & \vdots \\ \mathbf{em}^{n1} & \cdots & \mathbf{em}^{nn} \end{bmatrix} = \begin{bmatrix} \widehat{\boldsymbol{\lambda}^1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \widehat{\boldsymbol{\lambda}^n} \end{bmatrix} \begin{bmatrix} \mathbf{L}^{11} & \cdots & \mathbf{L}^{1n} \\ \vdots & \ddots & \vdots \\ \mathbf{L}^{n1} & \cdots & \mathbf{L}^{nn} \end{bmatrix} \left(\begin{bmatrix} \mathbf{f}^{11} & \cdots & \mathbf{f}^{1n} \\ \vdots & \ddots & \vdots \\ \mathbf{f}^{n1} & \cdots & \mathbf{f}^{nn} \end{bmatrix} + \begin{bmatrix} \widehat{\mathbf{e}^1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \widehat{\mathbf{e}^n} \end{bmatrix} \right) \qquad \text{(Equation 3)}$$

where the element em_i^{sr} of vector $\mathbf{em}^{sr}$ indicates the production-based emissions of industry i in region s generated by the final demands and exports in region r. The summation of $\mathbf{em}^{sr}$, $\sum_{r=1}^{n}\mathbf{em}^{sr}$ gives the production-based emissions in region s generated by the whole country's final demands and exports, and $\sum_{s=1}^{n}\mathbf{em}^{sr}$ gives the consumption-based emissions of region r, i.e., the emissions in all regions generated by region r's final demands and exports.

DIR not only influences the inter-regional intermediate trade structure but also influences domestic final demand and export patterns. The simulations used to capture the impact of regional industry relocation on CO_2 emissions are carried out by assuming that the structure of inter-regional intermediate trade, domestic final demand, and exports in year $t1$ would be reverted to the structure in year $t0$.

Thus, the first step is to isolate the change in the structure of inter-regional intermediate trade, domestic c final demand, and exports. The inter-regional domestic intermediate input matrix $\mathbf{A}$ is split into three parts: a part that gives the overall production technology ($\mathbf{A}^*$), reflecting the total inputs that are required per unit of output; a part that gives the national shares ($\mathbf{S}$), reflecting the substitution effect between domestic and imported intermediate inputs; and a part that gives the regional shares ($\boldsymbol{\Phi}$), which captures the inter-regional intermediate trade structure. Define the matrices $\mathbf{A}^*$, $\mathbf{S}$ and $\boldsymbol{\Phi}$ as

$$\mathbf{A}^* = \begin{bmatrix} \mathbf{A}^{*1} & \cdots & \mathbf{A}^{*n} \\ \vdots & \ddots & \vdots \\ \mathbf{A}^{*1} & \cdots & \mathbf{A}^{*n} \end{bmatrix}, \mathbf{S} = \begin{bmatrix} \mathbf{S}^1 & \cdots & \mathbf{S}^n \\ \vdots & \ddots & \vdots \\ \mathbf{S}^1 & \cdots & \mathbf{S}^n \end{bmatrix}, \text{and } \boldsymbol{\Phi} = \begin{bmatrix} \boldsymbol{\Phi}^{11} & \cdots & \boldsymbol{\Phi}^{1n} \\ \vdots & \ddots & \vdots \\ \boldsymbol{\Phi}^{n1} & \cdots & \boldsymbol{\Phi}^{nn} \end{bmatrix},$$

with the sub-matrix $\mathbf{A}^{*r} = \sum_{s=1}^{n}\mathbf{A}^{sr} + \mathbf{M}^r$ $(r = 1,\cdots,n)$. These technology matrices give the total amount of inputs per unit of output irrespective of their geographical source. Here $\mathbf{M}^r$ is the matrix with imported input coefficients, which is derived as $\mathbf{M}^r = \mathbf{Z}^{Mr}(\hat{\mathbf{y}}^r)^{-1}$. The matrix with domestic shares is given by $\mathbf{S}^r = (\sum_{s=1}^{n}\mathbf{A}^{sr})//\mathbf{A}^{*r}$. They express the shares of all required inputs that are sourced domestically. Here $//$ denotes element-wise division. The matrix with regional shares is given by $\boldsymbol{\Phi}^{sr} = \mathbf{A}^{sr}//(\sum_{s=1}^{n}\mathbf{A}^{sr})$. This yields $= \boldsymbol{\Phi} \otimes \mathbf{S} \otimes \mathbf{A}^*$, where the Hadamard product $\otimes$ indicates cell-by-cell multiplication.

The domestic final demands can be split similarly. Define

$$\mathbf{F}^* = \begin{bmatrix} \mathbf{f}^{*1} & \cdots & \mathbf{f}^{*n} \\ \vdots & \ddots & \vdots \\ \mathbf{f}^{*1} & \cdots & \mathbf{f}^{*n} \end{bmatrix}, = \begin{bmatrix} \mathbf{d}^1 & \cdots & \mathbf{d}^n \\ \vdots & \ddots & \vdots \\ \mathbf{d}^1 & \cdots & \mathbf{d}^n \end{bmatrix}, \text{and } \boldsymbol{\Pi} = \begin{bmatrix} \boldsymbol{\pi}^{11} & \cdots & \boldsymbol{\pi}^{1n} \\ \vdots & \ddots & \vdots \\ \boldsymbol{\pi}^{n1} & \cdots & \boldsymbol{\pi}^{nn} \end{bmatrix},$$

with $\mathbf{f}^{*r} = \sum_{s=1}^{n}\mathbf{f}^{sr} + \mathbf{f}^{Mr}$ for the vector of total final demands, $\mathbf{d}^r = \sum_{s=1}^{n}\mathbf{f}^{sr}//\mathbf{f}^{*r}$ for the vector with domestic shares for final demands, and $\boldsymbol{\pi}^{sr} = \mathbf{f}^{sr}//(\sum_{s=1}^{n}\mathbf{f}^{sr})$ for the vector with regional final demand shares. Then, $\mathbf{F} = \boldsymbol{\Pi} \otimes \mathbf{D} \otimes \mathbf{F}^*$ can be obtained.

For splitting the exports vector $\mathbf{e}$, define

$$\mathbf{e}^* = \begin{pmatrix} \sum_{s=1}^{n} \mathbf{e}^s \\ \vdots \\ \sum_{s=1}^{n} \mathbf{e}^s \end{pmatrix} \text{ and } \mathbf{x} = \begin{pmatrix} \mathbf{x}^1 \\ \vdots \\ \mathbf{x}^n \end{pmatrix},$$

with $\mathbf{x}^s = \mathbf{e}^s // (\sum_{s=1}^{n} \mathbf{e}^s)$ $(s = 1,\cdots,n)$, which gives the shares of exports (in total exports) by region s for each product. We then have $\mathbf{e} = \mathbf{x} \otimes \mathbf{e}^*$.

Let the subscript denote year $t1$; actual emissions in year $t1$ can be calculated as

$$\begin{bmatrix} \mathrm{em}_{t1}^{11} & \cdots & \mathrm{em}_{t1}^{1n} \\ \vdots & \ddots & \vdots \\ \mathrm{em}_{t1}^{n1} & \cdots & \mathrm{em}_{t1}^{nn} \end{bmatrix} = \begin{bmatrix} \widehat{\lambda_{t1}^1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \widehat{\lambda_{t1}^n} \end{bmatrix} \left(\mathbf{I} - \boldsymbol{\Phi}_{t1} \otimes \mathbf{S}_{t1} \otimes \mathbf{A}_{t1}^*\right)^{-1} \left(\boldsymbol{\Pi}_{t1} \otimes \mathbf{D}_{t1} \otimes \mathbf{F}_{t1}^* + \widehat{\mathbf{x}_{t1}} \otimes \widehat{\mathbf{e}_{t1}^*}\right)$$

(Equation 4)

In the hypothetical scenario, the emission intensity ($\boldsymbol{\lambda}'$), production technique ($\mathbf{A}^*$), total domestic final demands ($\mathbf{F}^*$), total exports ($\mathbf{e}^*$), and the substitution effect ($\mathbf{S}$ and $\mathbf{D}$) are assumed to remain unchanged, but the structure of inter-regional trade by sourcing region is replaced by the corresponding structure in year $t0$. Then, the CO_2 emissions changes induced by DIR can be calculated as

$$\begin{bmatrix} \Delta\mathrm{em}_{t1_h}^{11} & \cdots & \Delta\mathrm{em}_{t1_h}^{1n} \\ \vdots & \ddots & \vdots \\ \Delta\mathrm{em}_{t1_h}^{n1} & \cdots & \Delta\mathrm{em}_{t1_h}^{nn} \end{bmatrix} = \begin{bmatrix} \widehat{\lambda_{t1}^1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \widehat{\lambda_{t1}^n} \end{bmatrix} \underbrace{\left[\left(\mathbf{I} - \boldsymbol{\Phi}_{t1} \otimes \mathbf{S}_{t1} \otimes \mathbf{A}_{t1}^*\right)^{-1} - \left(\mathbf{I} - \boldsymbol{\Phi}_{t0} \otimes \mathbf{S}_{t1} \otimes \mathbf{A}_{t1}^*\right)^{-1}\right]}_{\Delta\boldsymbol{\Phi}} \mathbf{F}_{t1}$$

$$+ \begin{bmatrix} \widehat{\lambda_{t1}^1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \widehat{\lambda_{t1}^n} \end{bmatrix} \left(\mathbf{I} - \mathbf{A}_{t0}\right)^{-1} \underbrace{\left[\left(\boldsymbol{\Pi}_{t1} \otimes \mathbf{D}_{t1} \otimes \mathbf{F}_{t1}^* + \widehat{\mathbf{x}_{t1}} \otimes \widehat{\mathbf{e}_{t1}^*}\right) - \left(\boldsymbol{\Pi}_{t0} \otimes \mathbf{D}_{t1} \otimes \mathbf{F}_{t1}^* + \widehat{\mathbf{x}_{t0}} \otimes \widehat{\mathbf{e}_{t1}^*}\right)\right]}_{\Delta\boldsymbol{\Pi}\ \&\Delta\mathbf{x}}$$

(Equation 5)

Estimation of China's CO_2 emission reduction potential induced by DIR during 2017-2025

The structure of the final demand of each province in 2025 is the necessary data required to estimate China's CO_2 emission reduction potential induced by DIR during 2017-2025. The estimation of the structure of final demand of each province in 2025 includes three steps: (1) To determine the total economic scale of China in 2025. In this study, the production scale of China in 2025 is sourced from the prediction of the International Monetary Fund (IMF). It forecasted that China's GDP per capita, adjusted for purchasing power, would be $25,307 in 2025. (2) To determine China's regional industry structure in 2025. First, China's regional industry structures in 2012 and 2017 were calculated using the Chinese provincial multi-regional input-output tables 2012 and 2017, based on which the general evolutionary trend of China's regional and sectoral industry structures during 2012-2017 can be perceived. Then the regional industry structure was further adjusted based on "*The Outline of the 14th Five-Year Plan (2021-2025) for National Economic and Social Development and Long-Range Objectives Through the Year 2035*" enacted by the Chinese central government, and "*The Catalog for Guiding Industrial Restructuring*" enacted by National Development and Reform Commission of China, in which the information for the tendency of China's regional industry restructuring was provided. The specific data for China's regional industry structures in 2025 are provided in Table S4 and Table S5. (3) The structure of final demand of each province in 2025 can be obtained based on the data of total economic scale and regional and sectoral structure from the two steps above. Then China's CO_2 emission reduction potential induced by DIR during 2017-2025 can be calculated using the multi-regional input-output method as elaborated above.

China's sectoral industrial proportions in each province in 2025 are provided in the supplemental information (Table S5).

Data source, collection and analysis

The key data supporting the empirical analysis in this paper are the Chinese provincial multi-regional input-output tables and the associated carbon emission satellite account, which are provided by the Development Research Centre of the State Council of China and Carbon Emission Accounts & Datasets for emerging economies (CEADs). The tables cover 31 provinces in mainland China except for Tibet which is not included due to data unavailability. Given that the carbon emission and economic scale of Tibet is trivial, excluding Tibet will not affect the overall results.

The provinces and sectors covered in this study are provided in the supplemental information (Tables S1 and S2).