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Key Points:

- We traced China's economic gains and SO₂ emissions embodied in global trade since 2002
- China suffered larger shares of SO₂ emissions than that of value added from developed trade partners from 2002 to 2015
- Less developed regions always suffered similar unequal exchange from China from 2002 to 2015

Supporting Information:

- Supporting Information S1

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China's Trade-Off Between Economic Benefits and Sulfur Dioxide Emissions in Changing Global Trade

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Abstract China has been suffering from air quality degradation since its ascension into the World Trade Organization in 2001. The unequal exchange that occurs with international trade—that is, developed countries obtaining larger shares of trade-related value added relative to the shares of trade-related air pollution incurred locally—may obstruct the greening of global supply chains. In this study, we conduct a multi-regional input-output analysis to examine the change in the distribution of economic benefits and sulfur dioxide emissions underlying China's international trade from 2002 to 2015. The results show that both net trade-related economic benefits and SO₂ emissions in China rapidly increased from 2002 to 2007 and then decelerated after 2007 due to changes in China's green development strategy. In the past 13 years, China has suffered from economic-environmental inequality due to trade with most developed countries, for example, the United States, the European Union, East Asia, and Canada. East Asia, particularly Japan and South Korea, became both an economic and environmental winner while trading with China in 2015. China has also outsourced emissions to less developed regions, such as Sub-Saharan Africa. We propose policy implications to further reduce the economic-environmental inequality underlying China's international trade.

Plain Language Summary China's ascension into the World Trade Organization has boosted its economy at a price of serious air pollution rendering the country as the largest emitter in the past decades. As China has become a pivotal trading partner of major economies, examining how its economic benefits and air pollution embedded in international trading have been changing provides key knowledge for decision makers to develop fair, environmentally friendly trading policies. By exploring this issue during 2002–2015, we found that rich countries obtained much larger shares of value added compared to the shares of air pollutant (e.g., SO₂) emissions related to commodities and services consumed in China. Similarly, the undeveloped regions (i.e., Sub-Saharan Africa) are burdening more pollution while gaining a smaller proportion of economic benefits through trading with China. Such change necessitates the ever-increasing cross-boundary collaborations and technology transfers between China and its main trade partners to achieve fair and sustainable trade.

1. Introduction

Since the ascension into the World Trade Organization (WTO) in 2001, China has become the world's factory within the global supply chain with the value of its exports rocketing from 0.27 trillion dollars to 2.26 trillion dollars—a nearly 8.5-fold increase—from 2001 to 2017 (National Bureau of Statistics (NBS), 2017). In 2017, China's exported products accounted for approximately 13% of the global total exports (WTO, 2017). This globalization has caused serious environmental problems, particularly the degradation of regional air quality particularly due to the consumption of fossil fuels (Liu & Diamond, 2005; Muradian et al., 2002). Since 2001, the usage of coal has kept growing at an annual rate of 6.3% as the main source of sulfur dioxide (SO₂) and nitrogen oxides (NO_x) emissions (NBS, 2017). China is currently the largest coal consumer worldwide and consumed 3.85 billion tons of coal in 2016, accounting for 62% of national energy consumption

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(Wang et al., 2019). The huge fossil energy consumption and increasing industrialization make China the top globally among emitters of anthropogenic atmospheric pollutants (Zheng et al., 2018), which has become a major threat to public health, leading to approximately 350,000 to 1 million premature deaths in recent years (Chen et al., 2013; Cohen et al., 2017). Manufacturing for export has critically contributed to this serious air pollution (Liu & Wang, 2015). Research suggests that approximately 36%, 27%, and 17% of discharged sulfur dioxide (SO₂), nitrogen oxides (NO_x), and black carbon (BC), respectively, in China has been the result of manufacturing exports, especially exports to the United States, which account for approximately 21% of each pollutant in 2006 (Lin et al., 2014). Nearly 19% (208.5 thousand) of PM_{2.5}-related premature deaths that occurred in China in 2007 could be attributable to the production of exported goods (Zhang et al., 2017).

International trade can create massive employment and thus boosts economic development. From 2002 to 2007, China's national employment increased by 9.1% annually driven by export-oriented sectors (Tang et al., 2015). Accompanied with such economic benefit is the disproportionally higher share of global energy consumption and emissions. For example, 13% of the global CO₂ emissions triggered by the U.S. consumption of the motor vehicle happens in China, which only obtained a much smaller proportion of the associated value added (2%) (Prell & Feng, 2015). The distribution of environmental losses and economic embodied in trade has gained more attention by academic communities. In particular, the aggregate embodied energy/emission intensity, which has been defined as the ratio between energy/emissions and value added embodied in trade, has been introduced by Su and Ang (2017) and widely used to analyze the environmental-economic nexus related to trade (Su et al., 2019; Wang, Ang, et al., 2017; Wang et al., 2020; Zhou et al., 2020). Furthermore, this unbalanced distribution of economic benefits and emissions also changes over time. Duan and Yan (2019) revealed a faster decline of China's environmental losses compared to that of its major trading partners, which is mostly attributed to technology advances from the investigation the driving forces of China's pollution intensity embodied in the international trade from 1995 to 2015. Since 2008, the growth in worldwide trade has been negatively influenced by the financial crisis and the cooperation among emerging economies has been enhanced (Riad et al., 2012). This has affected China's international trade in the following ways. First, China's international trade growth has slowed down. Although the total value of the country's exports and imports increased nearly sevenfold from 2001 to 2017, most of that growth, nearly a fivefold surge, occurred from 2001 to 2008 (NBS, 2017). Second, China's cooperation with developing regions has become increasingly frequent. From 2008 to 2017, the share of China's exports to developing regions (i.e., developing countries in Asia, Africa, and Latin America) has increased by approximately 6.8 percentage points, while the share of China's exports to developed countries (i.e., Europe, East Asia, and Canada) has decreased by nearly 8 percentage points (NBS, 2017). Due to economic growth, China has transformed from being highly dependent on emission-intensive exports to developed countries to increasingly trading with developing countries through its Belt and Road Initiative (Meng et al., 2018; Mi et al., 2017). These changes in China's international trade may also cause a reallocation of economic gains and air pollution.

Previous research has examined the ecologically unequal exchange embodied in international trade (Jorgenson, 2006). In recent years, a growing body of scientific literature concluded that the developed countries generally outsourced the undesired environmental burden such as carbon emissions (Zhang, Zhao, et al., 2018), biodiversity threats (Lenzen, Moran, et al., 2012), air emissions (Xu et al., 2009), aerosols (Lin et al., 2016), ozone precursors (Román et al., 2016), land use (Steen-Olsen et al., 2012), and water resources (Yang et al., 2012) to undeveloped countries through international trade. Although suffering from ecological deficits, undeveloped regions can also economically benefit from international trade. In China, export-oriented sectors, which incurred massive transfers of embodied energy consumption, are generally also labor intensive, indicating that export can help create scores of jobs in China (Tang et al., 2015). Taking the consideration of economic benefits and environmental burdens together, scholars further investigated the economic-environmental inequity embodied in international trade (Prell et al., 2015). In the global trade structure, countries can be classified into one of the three categories: the "core" countries, "peripheral" countries, and "semicore" countries depending on how pivotal they are (Wallerstein, 1976). The core countries, for example, the United States, generally dominate the global economic chains and concentrate on high-tech, high-profit production, and they usually acquire larger shares of economic benefits embodied in global trade relative to the shares of environmental burdens suffered (Kick & Davis, 2001). By

comparing the embodied environmental burdens (SO_2 , CO_2 , water, and land) and economic benefits (value added), Yu et al. (2014) have revealed that developed regions, such as North America, the EU, and East Asia, just paid relatively small shares of economic values in exchange of higher shares of transfers in virtual pollution and resources in 2010. Meanwhile, peripheral countries, generally undeveloped regions focusing on low-tech, low-profit production, exhibit the opposite trend (Prell et al., 2014). China has behaved as a semi-core country within the global trade network as the world's factory (Prell, 2016). The country has emitted more carbon per unit of value-added gained from trade than developed countries and also has outsourced some of its environmental degradations (e.g., air pollution and resource depletion) by importing goods from less developed countries in Asia and Africa (Prell & Sun, 2015; Yu et al., 2014). In this way, such disproportional distribution of economic gains and air pollution has obstructed the greening of international supply chains and has engendered international trade-environment disputes for the country (Zhang, Wang, et al., 2018). Therefore, on the occasion that China has gradually moved into “new normal” economy and its international trade pattern changed, it is necessary to uncover how and why the environmental and economic inequality embedded in global trade patterns change for the country. Such knowledge would help picture the typical changing path of a developing country in the global value chain and thus benefit the policy-making for not only China but also other developing countries to approaching sustainable trade and greener energy strategy in the global market.

To fill this knowledge gap, this paper investigates the relationship between economic gains and air pollution burden embodied in China's international trade in 2002, 2007, 2012, and 2015 by conducting a multi-regional input-output (MRIO) analysis with the Eora database, which contains 26 economic sectors and 187 countries (Lenzen, Kanemoto, et al., 2012; Lenzen, Moran, Kanemoto, et al., 2013). In this study, we use sulfur dioxide (SO_2) as a gauge of air pollution mainly for the following reasons. First, as the main source of acid rain and one of the major precursors of $\text{PM}_{2.5}$, SO_2 causes substantial negative impacts on ecosystems, architecture, and public health and thus has been the focus of national environmental policy since 1990. Second, SO_2 would remain a priority of air pollution control in China for decades to come provided its coal-based energy structure. Since 2016, China had been the world's largest emitter of SO_2 (Li et al., 2017), mainly due to most coal-fired power plants burning high-sulfur coal (Zhang et al., 2010). Considering China's energy endowment, coal may still be China's major energy source, and thus control of SO_2 emissions in China should not be ignored in future. Moreover, the relatively successful experience of SO_2 control can provide important policy implications for other air pollutant control in developing countries. This study compares how the distribution of economic benefits and air pollution for China's trade partners has adjusted in the ever-changing global trade network. Our findings provide policy implications in lowering China's energy consumption and air pollution while sustaining economic growth via a combination of eco-friendly international trade policies, energy structure adjustment, air pollution control, and so forth.

2. Materials and Methods

2.1. Environmental-Extended MRIO Framework

The MRIO model can trace a specific product's direct and indirect impacts generated along cross-regional supply chains. It is thus considered a sound and relevant methodology for consumption-based accounting when studying trade-related impacts at global or national levels. Linked with inventories of emissions (e.g., air pollutants and CO_2), resources (e.g., water and land), and other environmental indicators, the environmental-extended multiregional input-output analysis can quantify different types of environmental impacts through complex cross-regional supply chains, including air pollutants (Lin et al., 2014), CO_2 emissions (Chen et al., 2019; Feng et al., 2013; Pan et al., 2017), energy use (Mi, Zheng, et al., 2018), resource consumption (Wiedmann, 2009), and environmental damage (Wang, Liu, et al., 2017). We also use the MRIO model to quantify the value added along supply chains, following previous studies (Ou et al., 2019; Wu et al., 2018; Zhang, Li, et al., 2018).

In MRIO framework, there are m regions, each with n sectors. r and s represent regions in the MRIO model, and i and j represent production sectors for each region. The total output of an economy is the sum of intermediate consumption and final consumption, such that

$$x_i^r = \sum_s \sum_j a_{ij}^{rs} x_j^s + \sum_s y_i^{rs} \quad (1)$$

Here, x_i^r represents the total output of sector i in region r ; $a_{ij}^{rs} x_j^s$ represents the goods or services of sector i in region r as intermediate input consumed by sector j in region s . a_{ij}^{rs} represents the matrix of direct requirement coefficients calculated by $a_{ij}^{rs} = z_{ij}^{rs} / x_j^s$, in which z_{ij}^{rs} denotes the intersector monetary flow from sector i in region r to sector j in region s , and y_i^{rs} represents commodities of sector i from region r consumed finally in region s . Using \mathbf{x} , \mathbf{A} , and \mathbf{y} to, respectively, replace x_i^r , a_{ij}^{rs} , and y_i^{rs} , equation (1) can be expressed as follows:

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y} \quad (2)$$

Solving for \mathbf{x} , we obtain

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \mathbf{y} \quad (3)$$

where \mathbf{x} refers to the total output vector caused by international exports; $(\mathbf{I} - \mathbf{A})^{-1}$ represents the Leontief inverse matrix, and \mathbf{I} is the identity matrix.

Let $\mathbf{e} = (e_i^r)_{mn \times 1}$ and $\mathbf{f} = (f_i^r)_{mn \times 1}$ refer to column vectors of country-level sectoral SO₂ emissions intensities and value-added coefficients, respectively. The elements $e_i^r = t_i^r / x_i^r$ and $f_i^r = v_i^r / x_i^r$ describe the number of environmental factors emitted and the value added per unit total output, respectively. t_i^r and v_i^r refer to SO₂ emissions and value added generated by sector i in region r , respectively. Then, equation (3) can be written as the following equations:

$$\mathbf{T} = \hat{\mathbf{e}} \mathbf{x} (\mathbf{I} - \mathbf{A})^{-1} \hat{\mathbf{y}} \quad (4)$$

$$\mathbf{V} = \hat{\mathbf{f}} \mathbf{x} (\mathbf{I} - \mathbf{A})^{-1} \hat{\mathbf{y}} \quad (5)$$

\mathbf{T} and \mathbf{V} are matrixes in which each element, t_{ij}^{rs} and v_{ij}^{rs} , respectively, indicates sector wise supply-chain SO₂ emissions and value added of each country, divided into direct emissions or value added by the sector itself and indirect emissions or value added caused by intersectoral trades from region r to region s . The notation $\hat{\cdot}$ indicates the diagonalization of corresponding column vectors.

Assuming that \mathbf{T}^{rs} and \mathbf{V}^{rs} indicate embodied SO₂ emission flows and value-added flows from region r to region s , respectively, we have:

$$\mathbf{T}_{net}^{rs} = \mathbf{T}^{rs} - \mathbf{T}^{sr} \quad (6)$$

$$\mathbf{V}_{net}^{rs} = \mathbf{V}^{rs} - \mathbf{V}^{sr} \quad (7)$$

\mathbf{T}_{net}^{rs} and \mathbf{V}_{net}^{rs} represent SO₂ emission and value-added flows, respectively, embodied in net trade between region r and s . If the value of \mathbf{T}_{net}^{rs} or \mathbf{V}_{net}^{rs} is greater than 0, then region r exports net SO₂ emissions or net value added to region s . Otherwise, region r would import net SO₂ emissions or net value added from region s . By using the above equations, we obtain China's imported or exported SO₂ emissions and value added embodied in trade with other countries or regions.

Furthermore, we also develop an *EI* (environmental inequality) index, \mathbf{EI}^r , to further evaluate the mismatch between atmospheric pollutant emissions and value added embodied in China's international trade with region r . As shown in equations (8) to (10), \mathbf{T}^{c-r} and \mathbf{T}^{r-c} represent China's SO₂ emissions related to exports and imports with region r , respectively; \mathbf{V}^{c-r} and \mathbf{V}^{r-c} represent China's value added related to exports and imports with region r , respectively. \mathbf{AEI}^{c-r} and \mathbf{AEI}^{r-c} represent China's aggregate embodied emission intensity, which has been first introduced by Su and Ang (2017) and widely used in the existing literature (Wang et al., 2020; Zhou et al., 2020), related to exports and imports with region r , respectively. If $\mathbf{EI}^r > 1$, it indicates that in China's mutual trade with region r , the difference between China's export- and import-related SO₂ emissions is greater than the difference between China's export- and import-related values added. In other words, China experiences more pollution relative to value-added gains from trade when

trading with region r . If $EI^r < 1$, it indicates that region r experiences more pollution relative to value-added gains from trade when trading with China.

$$AEI^{c-r} = T^{c-r} / V^{c-r} \quad (8)$$

$$AEI^{r-c} = T^{r-c} / V^{r-c} \quad (9)$$

$$EI^r = AEI^{c-r} / AEI^{r-c} \quad (10)$$

2.2. Data Sources

Global MRIO databases have been developed and published by several research teams. Among current global MRIO databases, many (e.g., Eora, EXIOBASE, GTAP, and WIOD) have been extensively used to study environmental issues (Moran & Wood, 2014; Owen et al., 2014). Because the Eora database (www.worldmrio.com) is the most up to date, with the latest update in 2015, we use Eora MRIO data in our analysis. We refine our focus to the post-2001 period since the frequent and considerable trade interaction with other countries began with China's accession to WTO in 2001 as well as the redistribution of economic benefit and environmental burden in the global trade network. Current studies on the embodied emission issues in China's international and interregional trade generally used the official IO tables issued by the NBS for China in 2002, 2007, and 2012. Therefore, this study has selected the Eora MRIO data in 2002, 2007, and 2012 to for verification of our results with existing literature. In addition, Eora MRIO data in 2015 have also been chosen to include the latest information for the detailed analysis. Eora is an environmentally extended global MRIO database developed by the Integrated Sustainability Analysis group at the University of Sydney using a continuous iteration method (Lenzen, Kanemoto, et al., 2012; Lenzen, Moran, Kanemoto, et al., 2013). Each Eora MRIO table contains a complete account of monetary transactions between 26 economic sectors in 187 countries. Moreover, it includes sectoral environmental and satellite data covering greenhouse gas emissions, air pollution, energy use, water requirements, land occupation, N and P emissions, and primary inputs to agriculture, mainly from multiple reliable data sources (e.g., EDGAR, CDIAC, and FAOSTAT). In particular, the SO₂ emission inventory used in this study is drawn from the EDGAR database. Multiple studies of global environmental issues, such as air pollution (Kanemoto et al., 2014), water scarcity (Lenzen, Moran, Bhaduri, et al., 2013), biodiversity threats (Lenzen, Moran, et al., 2012), and nitrogen pollution (Oita et al., 2016), have been conducted using information from this database. In this study, we classify each country into one of 14 regions according to their geographical location and economic development level: the USA, Canada, Russia, India, China, East Asia, Southeast Asia, the European Union (EU), Non-EU Europe, Middle East and North Africa, Sub-Saharan Africa, the Rest of Asia, Latin America, and Oceania (Table S1 in the supporting information).

3. Results

3.1. Change in China's Value Added and SO₂ Emissions Embodied in Trade

The net value added embodied in China's international trade increased and then decreased from 2002 to 2015. Since its entry into the WTO, ever-increasing participation in international trade has caused China's export-related economic benefits to continually increase (Figure 1a). From 2002 to 2015, China's exports increased at an average annual growth rate of 14.8% (NBS, 2017). As a result, China's export-related value added increased about fivefold, amounting to about \$1 trillion in 2015. During the same period, the import-related value added increased about sevenfold, partly due to imports increasing at an annual rate of 12.9%, which brought about \$930.8 billion to other countries in 2015 (NBS, 2017). Taken together, the net value added embodied in China's international trade increased first from \$69.0 billion in 2002 to \$201.8 billion in 2007 and then decreased to \$77.8 billion in 2015. The reduction of net economic benefits after 2007 can be partly attributed to the global economic crisis in 2008 and the new normal development in China, both of which have slowed the increase in national exports (Mi et al., 2017; Mi, Meng, et al., 2018).

The contributions to trade-embodied economic benefits have concentrated in several industrial sectors. As shown in Figure 1c, *Services* and *Heavy Industry* were the two largest contributors to net economic benefits (31.8–35.5%) and export-related economic benefits (20.2–22.5%) in the years studied. In contrast, *Equipment* and *Others* contributed most to the net economic losses and import-related value added between 2002 and

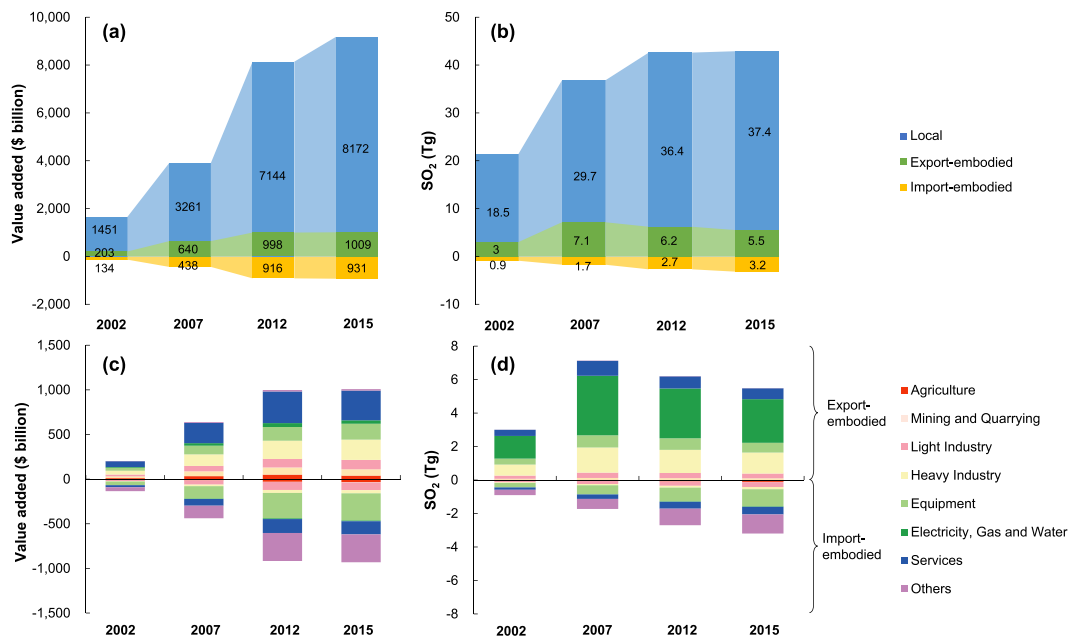


Figure 1. (a–d) Total embodied SO₂ and value added associated with China's trade in the period from 2002 to 2015. China's territorial SO₂ emissions are the sum of export-embodied and local SO₂ emissions, and China's consumption-based SO₂ emissions are the sum of import-embodied and local SO₂ emissions. Note that the 26 sectors in the Eora database are further aggregated into eight sectors for the ease of result presentation and discussion (see Table S2).

2015, as the share of import-related value added increased from 30.6% to 32.8% and from 31.8% to 33.4%, respectively. From 2002 to 2012, export-related economic benefits for each sector increased by approximately 2.9-fold to 5.1-fold. However, this upward tendency continued only in the major manufacturing sectors, including the *Light Industry Products*, *Heavy Industry*, and *Equipment* and largely slowed in other sectors from 2012 to 2015. A similar change also occurred in sectoral import-related economic losses, which increased by approximately 4.3-fold to 7.1-fold for each sector from 2002 to 2012 but decreased, mainly in *Light Industry Products*, *Services*, and *Others*, after 2012.

Similar to the value added, the SO₂ emissions embedded in international trade also experienced a reverse U-shaped change. China's export-related SO₂ emissions first increased from 3.01 Tg in 2002 to 7.14 Tg in 2007 but then decreased to 5.49 Tg in 2015 (Figure 1b). The decrease in export-related SO₂ emissions from 2007 to 2015 could be attributed to China's strong antipollution drive. During the 11th 5-year period (2005–2010), control of total SO₂ emissions and the increased use of clean energy came into play. As a measure to achieve the policy target, local governments were required to replace small inefficient thermal power generating units with larger ones and install desulfurization facilities (National Development and Reform Committee and State Environmental Protection Administration, 2007). Consequently, SO₂ emissions from *Electricity, Gas and Water*, the sector with the most export-related emissions, decreased significantly (State Electricity Regulatory Commission et al., 2011). Due to the aggressive implementation of these measures, export-related SO₂ emissions in *Electricity, Gas, and Water* abated approximately 9.52 Tg. Emissions from producing exports in another major contributor, the *Services* sector, decreased by approximately 2.39 Tg between 2007 and 2015, with its share of export-related SO₂ emissions dropping from 12.4% to 11.8%. On the other hand, import-related SO₂ emissions increased from 0.90 Tg in 2002 to 3.20 Tg in 2015. As a result, the net SO₂ emissions embodied in international trade first increased from 2.11 Tg in 2002 to 5.41 Tg in 2007 and then decreased to 2.30 Tg in 2015. Given the net trade-related economic gains and SO₂ emissions increased from 2002 to 2015, China captured economic gains via international trade at the cost of SO₂ emissions occurring domestically in the following sectors: *Mining and Quarrying*, *Light Industry Products*, *Heavy Industry*, *Electricity, Gas and Water*, and *Services*. Moreover, China experienced both economic deficits and SO₂ inflows in the international trade of the *Others* sector. Notably, the international trade in *Equipment* experienced a double loss in terms of economics and the environment in 2002 and 2007 and an economic gain at the cost of environmental quality in 2015. This was due to outdated production technology and coal-

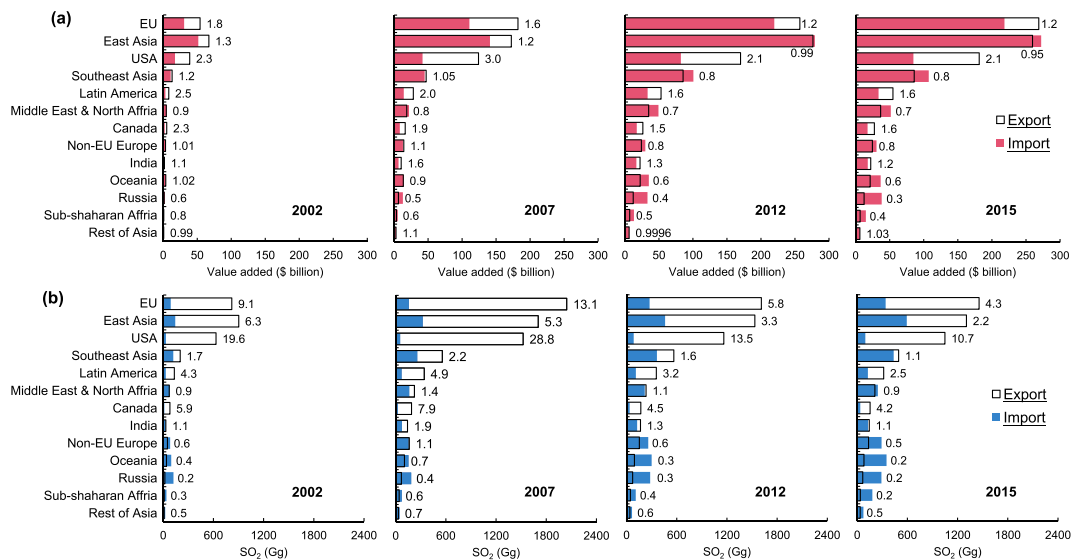


Figure 2. (a, b) Value added and SO_2 transfer embodied in China's trade with other countries, from export and import perspectives, between 2002 and 2015. The numbers on the right side of bars indicate the ratio of export-related SO_2 emissions (or value added) to import-related SO_2 emissions (or value added). The countries and regions are listed by rank in export-embodied value added and SO_2 in 2015.

dominated energy infrastructure, which resulted in the critically high emission intensity of *Equipment* in 2002 and 2007. The decrease that took place during the period from 2007 to 2015 was primarily driven by energy restructuring, technology upgrades, and the widespread deployment of emission abatement facilities.

3.2. Regional Changes in Trade-Related Value-Added and SO_2 Emissions

China's trade-related value added for each trading partner also increased rapidly first and then decelerated from 2002 to 2015. As shown in Figure 2, the value added gained by exporting to each region grew continuously from 2002 to 2015, with the annual growth rates ranging from 11.0% to 21.4%. However, growth slowed from 2007 to 2015 largely due to the global economic crisis, with the annual growth rate ranging from 4.9% to 10.6% compared to the 20.8% to 42.3% rates from 2002 to 2007. The export-related economic benefits from regions such as Sub-Saharan Africa, Oceania, and East Asia continued to decrease after 2012. Similar changes occurred in the import-related value added, which grew quickly for every region at annual rates of 19.3% to 39.9% between 2002 and 2007. Growth rates then decreased to 14.5% to 20.7% from 2007 to 2012. Various levels of the annual decrease occurred with the EU, East Asia, and Oceania (−0.2%, −0.8%, and 20.2%, respectively) after 2012. During the study period, East Asia, the EU, and the United States ranked as the top three contributors of export-related value added, but their combined contribution declined from 79.0% in 2002 to 70.4% in 2015. In 2002, the top three contributors of import-related value added were East Asia, the EU, and the United States, accounting for approximately 74.36% of national import-related value added. After 2007, Southeast Asia replaced the United States as the third largest contributor of import-related value added, and the share of import-related value added for East Asia and the EU to China's national total declined from 32.2% to 29.3% and from 25.3% to 23.5%, respectively. In contrast, the shares of trade-related value added to the national total from other countries increased by varying degrees, especially for Southeast Asia, Latin America, Middle East and North Africa, India, and Russia. This growth could be attributed to the rapid growth in South-South trade during the past 13 years.

SO_2 emissions embodied in China's international trade from 2002 to 2015 exhibited different trends. The SO_2 emissions which occurred in China to produce goods consumed in all other regions increased between 2002 and 2007 but decreased from 2007 to 2015. Imports from East Asia, Russia, and Southeast Asia induced approximately 42.9% of national import-related emissions in 2002, which increased to 44.3% in 2007. After 2007, Oceania surpassed Russia to become the third highest contributor to China's import-related SO_2 emissions, representing 11.0% of national import-related emissions in 2015. Similar to the export-related value added, the top three contributors of export-related SO_2 emissions were East Asia, the EU, and the United

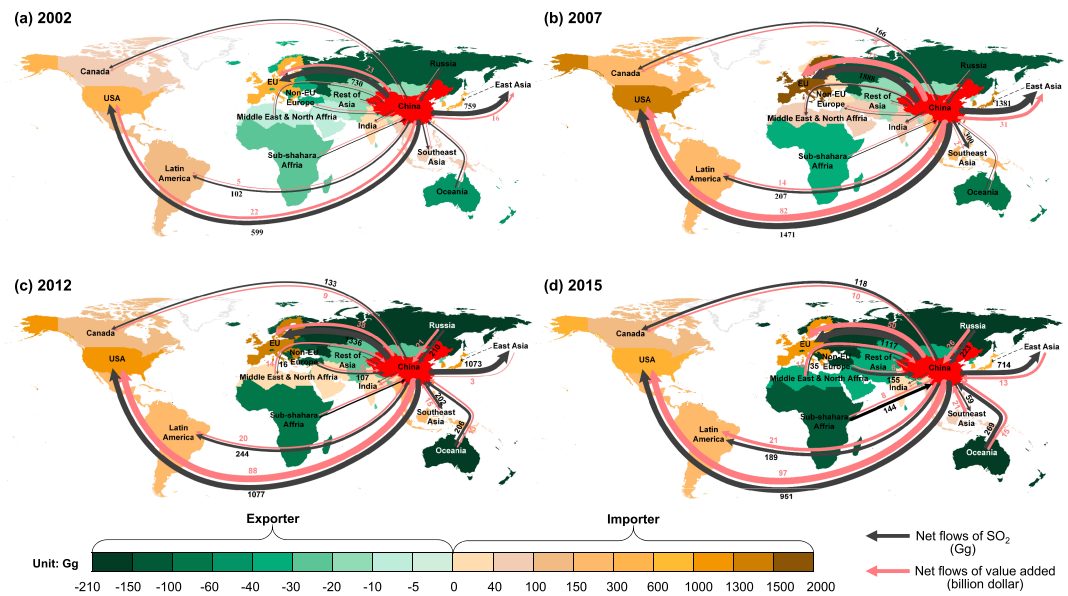


Figure 3. (a–d) SO₂ and value added transfers embodied in China's trade with other countries. The numbers by the arrows indicate the net flow quantities of embodied SO₂ and value added.

States. The combined share of export-related SO₂ emissions in the national total for these three developed regions declined from 78.3% in 2002 to 69.4% in 2015. In contrast, the share of export-related SO₂ emissions in the national total for other regions increased in varying degrees. Overall, the value added embedded in international trade increased more rapidly for trade partners in the developed world, while partners in the developing world tended to be burdened with more pollution.

3.3. Net Transfers of Trade-Related Value Added and SO₂ Emissions for Each Region

The trends in net transfers of value added embodied in China's international trade varied for each trade partner from 2002 to 2015. As shown in Figure 3, the EU, the United States, Latin America, Canada, and India were net exporters of value added, indicating that China continually gained net economic benefits from trading with these regions between 2002 and 2015. The majority of the growth in net value added, earned by China from these net exporters of value added, mainly occurred between 2002 and 2007, as China achieved rapid export development following the entry into the WTO. In contrast, Russia, Middle East and North Africa, and Sub-Saharan Africa were consistently net importers of value added from 2002 to 2015. China experienced increasing economic losses from trading with these regions, especially between 2007 and 2015, when South-South trade became more frequent. Moreover, developing countries which were net exporters of value added in 2002 gradually became net importers of value added in 2015. For example, Southeast Asia, Oceania, and Non-EU Europe were net exporters of value added in 2002, and the net economic benefits increased in different degrees by 2007. However, a significant decrease in net trade-related value added occurred between 2007 and 2015, as these countries became net importers by 2015. This happened possibly because China boosted exports to these developing regions after 2007, especially after the 2008 global economic recession. For example, the share of exports to Southeast Asia in China's national total increased from 0.76% to 0.99% between 2002 and 2007 and then jumped to 1.87% in 2015 due to the full integration of China into the Association of Southeast Asian Nations Free Trade Area. Meanwhile, the share of imports from Southeast Asia in China's national total increased from 1.16% to 1.46% between 2002 and 2007 and then climbed relatively slowly to 1.55% in 2015 (NBS, 2017).

The trends for SO₂ emissions were different. As shown in Figure 3, East Asia, the United States, the EU, Latin America, Southeast Asia, Canada, and Non-EU Europe were consistently net importers of embodied SO₂ emissions, indicating that these countries outsourced the SO₂ emissions to China via mutual trade. For these net importers of embodied SO₂ emissions, their net-outsourced SO₂ emissions increased significantly between 2002 and 2007 and then began to decrease after 2007 due to China's strong antipollution

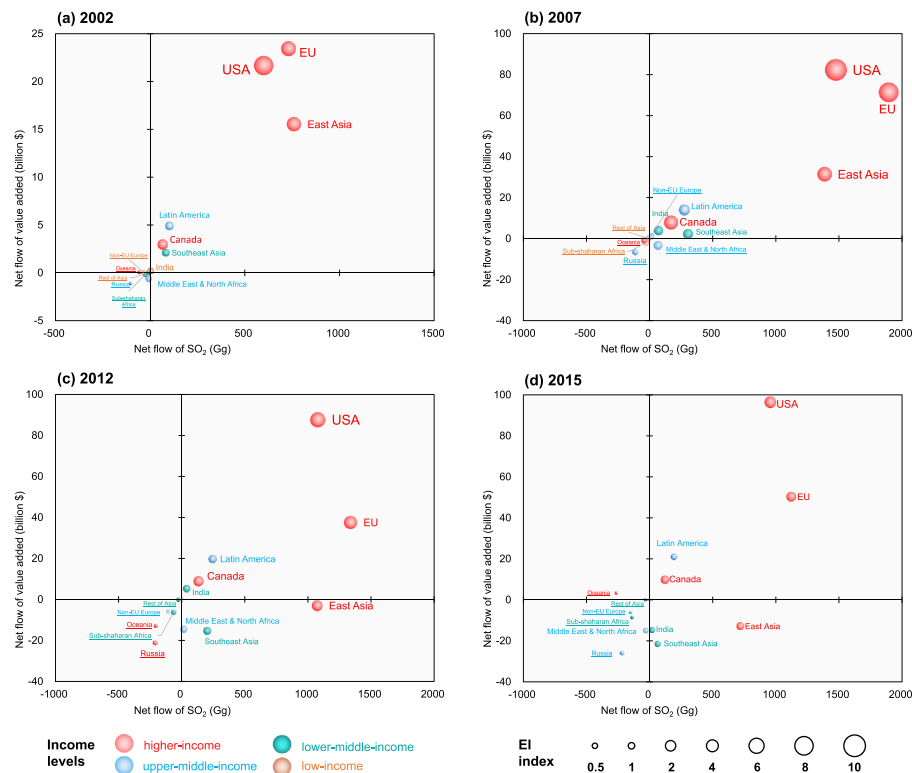


Figure 4. (a–d) Scatter diagrams of net flows for China’s embodied SO₂ and value added in global trades with other regions. The gross national income (GNI) and populations of each country were obtained from the World Bank Open Data (<http://data.worldbank.org/>), which provides a variety of economic indicators and statistical data for more than 200 countries. Positive net flows of trade-related value added indicated that these regions transferred net flows of value added to China via international trade, and positive net flows of trade-related SO₂ indicated that these regions avoided net flows of emissions via international trade with China. Thus, regions in Group I (the upper right-hand quadrant) were the economic losers and environmental winners, and regions in Group III (the lower left-hand quadrant) were the economic winners but environmental losers, in the course of trade with China. Regions in Group II were both economic and environmental losers, while the regions in Group IV were both economic and environmental winners. The higher-income regions, upper-middle-income regions, lower-middle-income regions, and low-income regions are distinguished by red, light blue, mint, green, and orange circles, respectively. Circle size indicates the EI index. Underlined regions generally have *EI* indices less than 1, while non-underlined regions generally have *EI* indices larger than 1.

policies. The major Belt and Road countries (Russia and the Rest of Asia), Oceania, and Sub-Saharan Africa were net exporters of SO₂ emissions, and increases in the net transfer of SO₂ emissions from China mainly occurred between 2007 and 2015. This finding aligns with Li and Liu (2019), which found that the net trade-embodied SO₂ flows from China to the Belt and Road countries have been further aggravated from 2010 to 2015. The Middle East and North Africa, a net exporter of SO₂ emissions in 2002, became a net importer of SO₂ emissions from 2007 to 2012 but reverted back as a net exporter of SO₂ emissions by 2015. The main reason is that since 2007, the demand of Middle East and North Africa for Chinese products has been increasing, leading to the surge of SO₂ emissions in China’s emission-intensive sectors (such as Electricity; Gas and Water; Petroleum, Chemical, and Non-Metallic Mineral Products; Metal Products; and Transport). Such demand has decreased later and made Middle East and North Africa a net exporter of SO₂ emissions again by 2015.

3.4. Economic Gains and Environmental Losses in China’s International Trade

To uncover the economic and environmental nexus in China’s international trade, we classify the major trade partners into four groups according to the net value added and net SO₂ emissions embodied in trade. As shown in Figure 4, most of the high-income regions, such as the United States, the EU, and Canada, are located in Group I (the upper right-hand quadrant), which shows the economic losers (positive net outflows of trade-related value added) and environmental winners (positive net outflows of trade-related SO₂) in trading with China. These economies mainly imported pollution-intensive and low value-added commodities from China and exported high value-added but less emission-intensive

goods and services to China from 2002 to 2007, when the Chinese environmental regulations were less stringent. For example, in 2002, \$1 of value added embodied in China's exports to the United States incurred approximately 16.2 g of SO₂ emissions in China, which was nearly 8.7 times the emissions in the United States due to China's imports. This difference gradually enlarged between 2002 and 2007. It then rapidly narrowed from 2007 to 2015, because of the 2008 economic crisis and China's antipollution drive. India and Latin America, two fast-growing developing regions, were also located in Group I. In comparison, Russia and Sub-Saharan Africa persistently were located in Group III (the lower left-hand quadrant), indicating that these regions were economic winners (i.e., had negative net outflows of trade-related value added) but environmental losers (i.e., had negative net outflows of trade-related SO₂) through trade with China. From 2002 to 2015, \$1 value added embodied in China's imports from Russia and Sub-Saharan Africa incurred embodied SO₂ emissions of approximately 1.1–3.4 times that of their exports to China. Hence, China also caused the unequal exchange of economic benefits and environmental pollution with Russia and Sub-Saharan Africa. Compared to the unequal gap experienced by China, China induced less inequality onto Russia and Sub-Saharan Africa, especially between 2007 and 2015. Both the unequal exchange of economic benefits for environmental pollution with high-income regions (i.e., United States, EU, and Canada) and the imbalanced exchange of environmental benefits for economic losses with low- and middle-income regions (i.e., Russia and Sub-Saharan Africa) gradually narrowed from 2002 to 2015.

After 2007, the economic and environmental losses suffered by regions in Group II (the upper left-hand quadrant) substantially decreased, while economic and environmental benefits enjoyed by economies in Group IV (the lower right-hand quadrant) increased sharply. Regions located in Group II were economic and environmental losers (i.e., had positive net outflows of trade-related value added and negative net outflows of trade-related SO₂) due to their trade with China. Oceania and Non-EU, the two largest economic and environmental losers in 2002, both entered into Group III in 2015. Furthermore, from 2002 to 2007, East Asia, another important high-income region, transferred SO₂ emissions to China at a less economic cost, relative to that cost incurred locally. However, after 2012, East Asia became both an economic and environmental winner (i.e., had positive net outflows of trade-related SO₂ and negative net outflows of trade-related value added, Group IV) through trade with China, rendering China the loser in their mutual trade. Similar trends also occurred in China's trade with Southeast Asia. Additionally, the Middle East and North Africa, an economic winner but environmental loser in 2002, also entered into Group IV between 2007 and 2012 and then became an economic winner but environmental loser after 2012. The expansion of Group IV during the period from 2007 to 2015 illustrated the increasingly unequal exchange in economic benefits for environmental pollution.

A comparison of the *EI* index for each region reveals that China suffered environmental and economic inequality from trade with highly developed regions, while also bringing simultaneously similar inequality to relatively low income regions. As shown in Figure 4, high-income regions, such as the United States, the EU, Canada, and East Asia, generally had much higher *EI* indices (1.1–9.7) when trading with China, indicating that China mainly exported relatively pollution-intensive and low value-added commodities to these developed regions while importing pollution-extensive and high value-added commodities from these regions. This situation occurred particularly with the United States and the EU, which persistently had the largest *EI* indices (3.5–9.7) over the study period. In contrast, low-income regions (e.g., the Rest of Asia, Sub-Saharan Africa, and Non-EU Europe) and resource-intensive regions (e.g., Russia and Oceania) generally had much smaller *EI* indices (0.3–0.9). Thus, for these regions trading with China, the differences between export- and import-related SO₂ emissions were more substantial than the value added differences. Consequently, these peripheral regions experienced an unequal mismatch in the international trade of pollution-intensive and low value-added commodities with China. Furthermore, this mismatch became more significant between 2002 and 2007 and then gradually narrowed between 2007 and 2015. For example, the *EI* index for the United States, a typical core region in the global trade network, increased from 8.7 in 2002 to 9.7 in 2007 and then decreased to 5.0 in 2015. The *EI* index in Sub-Saharan Africa, a typical peripheral region, increased from 0.7 in 2002 to 0.8 in 2007 and then decreased to 0.5 in 2015. Changes in the *EI* index from 2002 to 2015 indicated the continuous optimization of the international trade structure of China, a semicore region in the global trade network.

4. Discussion and Conclusion

Our results indicate that both the net trade-related economic benefits and SO₂ emissions in China rapidly increased from 2002 to 2007 and slowed down after 2007. Moreover, highly developed core regions such as the United States, the European Union, and Canada, with their superiority in technology and capital, obtained larger shares of value added compared to the shares of SO₂ emissions related to commodities and services consumed in China. Consequently, China experienced economic-environmental inequality from trading with core countries. China, a semicore country, also caused economic-environmental inequality to peripheral regions, such as Sub-Saharan Africa. This phenomenon can be partly attributable to the higher productivity, stricter environmental management, and more advanced abatement technology in core and/or semicore countries. More importantly, the core position of high-income nations in the global supply chain can externalize pollution-intensive manufacturing to low-income countries by importing natural resources and high ecological-impact commodities. The imbalanced economic-environment exchange in China's international trade increased from 2002 to 2007 and decelerated after 2007. This reversal was mainly due to changes in China's development strategy, including the deceleration of export growth, the upgrade of production technology, and the implementation of stricter environmental protection policies in recent years. The recent escalation in trade conflicts between China and the United States may have a negative influence on China's trade flow with other developed countries. Meanwhile, the rise of South-South cooperation and further implementation of the Belt and Road Initiative may boost China's international trade with developing countries and further impose economic-environment inequity to these emerging economies. Therefore, more efforts are needed to further reduce economic-environment inequity within global supply chains.

China could improve its own national industrial competitiveness in order to reduce the unequal economic-environment exchange with core countries. From 2002 to 2015, net trade-related economic benefits in China mainly stemmed from the *Services* and *Heavy Industry* sectors. However, the *Heavy Industry* sector generally has been emission intensive, and the contributions from the *Equipment* and *Services* sectors have been decreasing. These factors have hindered further reductions in economic-environment inequality. Specifically, China currently maintains low-end production in equipment manufacturing and relies heavily upon imports from other countries for advanced technology. For instance, although nearly half of the supply of iPhones is from China, the country receives no more than 2% of the total profits, while firms in other East Asian countries such as Japan and Korea are responsible for core high-tech components and own the proprietary intellectual property rights (Kraemer et al., 2011). As a result, East Asia has become both an economic and environmental winner when trading with China. In April 2018, the U.S. government lifted its ban on technical communication and trade with Zhongxing Telecommunications Equipment Corporation (ZTE Corporation). This ban almost killed the telecommunications giant in China, because ZTE Corporation depends greatly on Qualcomm processors and Android software from the United States. This dependence on foreign design and high-tech contributions can diminish most of the profit going to Chinese firms. China could transform from copycat to high-tech innovator by establishing its own proprietary intellectual property rights, promoting technology upgrades, and enhancing its export structure. For example, the implementation of "Made in China 2025," under fair and reasonable market mechanisms, could increase the value of industrial products and competitiveness. This effort would further reduce the emission deficit and achieve the goals of "Ecological Civilization and Beautiful China," especially given a new Sino-U.S. trade war.

Such inequality can be further lowered by adjustment of energy structure and the improvement in energy efficiency. The coal-dominated energy structure has long been a major source of air pollution emissions including SO₂. This necessitates the development of cleaner energy including solar, wind, hydrological, and nuclear power. Meanwhile, considering the dominant role of coal in China's energy supply structure for decades to come, coal should be predominantly used in sectors with the implementation of ultralow emissions technology, such as thermal power industry and iron and steel industry, to further lower the SO₂ emissions. Advanced technologies, particularly the clean coal techniques, can also contribute to the reduction of such inequality.

Strengthening economic and environmental cooperation with other peripheral countries could reduce the economic-environmental imbalances between China and these countries. Through the Belt and Road Initiative, China could expand their international communication with regions alongside the Belt and

Road and simultaneously minimize the unequal exchange of economic benefits and environmental losses, especially with regions such as Non-EU Europe, Middle East, and North Africa. China could help these regions to achieve high-quality economic development. Direct trade and investment in energy, natural resources, or other traditional goods alone may not bring these regions long-term economic development. Thus, strong cross-boundary collaborations and technology transfers between China and its main trade partners would be required. Notably, technology transfers from China to these peripheral regions could be based on sharing advanced technology—rather than direct transfers of backward and outdated production capacities—and thus could effectively achieve future efficiency improvements and emission reductions along global supply chains. China also could promote technological and environmental cooperation with these regions. Such cooperation between China and other countries would require strict environmental management of the cooperative projects in order to minimize local ecological damage. Additionally, China could provide funding for emission abatement technologies and advanced environmental management to help developing countries cope with potentially adverse environmental and climate effects. Examples include the 20 billion CNY South-South climate cooperation fund and the launch of the China-Africa Environmental Cooperation Centre. By combining economic and environmental cooperation with developing countries, China could effectively reduce the economic-environmental inequity between China and these countries and significantly contribute to regional and global sustainable development.

There are several limitations in this study as an initial attempt to explore the pathways to sustainable trade policy in China. First, this paper mainly aims at revealing the change of environmental and economic inequality induced by China's international trade. This very inequity may be however influenced by the changes in trade patterns, technical progress, pollution intensity, population, production structure, and so on. Uncovering the driving forces in SO₂ emissions, value added, aggregate embodied energy/emission intensity, and *EI* induced by China's international trade can provide better implications for the economic and environmental nexus in the global trade network and will be addressed in our future work (Su et al., 2017, 2019; Zhu et al., 2018). Second, the accuracy of results by using the environmentally extended input-output model can be significantly influenced by the temporal, spatial, and sector aggregation (Su et al., 2010; Su & Ang, 2010, 2012). The further link between the Eora and Chinese time series multi-regional and multi-sectoral input-output tables can reduce the uncertainty of results and capture more detailed and refined information for the design and optimization of China's sustainable trade policies.

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