Energy and Air Emissions Embodied in China−U.S. Trade: Eastbound Assessment Using Adjusted Bilateral Trade Data

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It is critical to understand environmental impacts embodied in the bilateral trade between China and the United States, given the political, economic, and geographical importance of the two countries and the fact that few studies have investigated this before. This article studies the environmental impacts, particularly energy consumption and air emissions, embodied in the eastbound (from China to the U.S.) trade from 2002 to 2007 using an environmental input−output analysis technique and the adjusted bilateral trade data. In general, trade volume increased until the panic of 2008, and shifting trade patterns cause fluctuating embodied energy and air emissions in trade in China. Results show that embodied energy ranges from 7 to 11 exajoule (EJ) and takes about 12−17% of China's energy consumption. Embodied CO_2 ranges between 400 and 800 Mt and represents about 8−12% of China's CO_2 emissions. SO_2 and NO_x embodied in the eastbound trade generally grow over this period, from 4.2 to 6.3 Mt and from 1.4 to 2.9 Mt, and account for 10−15% and 8−12% of China's total emissions, respectively.

Introduction

International trade can function as a mechanism to improve efficiency in economic development by improved allocation of resources, typically capital, labor, and materials (*1*). Especially in this era of globalization, corporations in industrialized countries are shifting their manufacturing factories to lower cost developing countries, such as China. As the world's largest economy, U.S. exports accounted for 8.42% of its gross domestic product (GDP) in 2007. About 16.63% of its imports, accounting for 323 billion dollars, are from its largest importing partner, China. At the same time, China also ranks as the second and third largest partner of the U.S. in terms of total trades and exports, respectively (*2*). Both China and the U.S. benefit economically from their bilateral trade. However, international trade also brings considerable environmental consequences in both countries of origin and destination (*3*). Generally, environmental performance in China and other developing countries is poorer than that in industrialized countries. Given that manufacturing is generally a polluting phase in the life cycle of products, import countries displace not only manufacturing, but also embodied environmental impact, to export countries. In other words, exporting countries and people who live there must bear the environmental impact embodied in the exported commodities.

Much of the existing research on environmental impacts embodied in trade has been primarily focused on air emissions (*4*−*6*) and so-called "emissions embodied in trade" (EET). Other focal areas include embodied natural resource consumption and ecological impact (*7*, *8*). The recent emphasis on climate change has encouraged studies on carbon dioxide (CO_2), primarily at a national level (*9*−*11*), but also at bilateral (*12*−*14*) and global levels (*15*, *16*). Despite debates about whether China or the U.S. recently lead in CO_2 emissions (*17*), it is clear that the two countries dominate the world's CO_2 emissions, as well as energy consumption and other environmental impacts. Shui and Harriss, for example, studied embodied CO_2 in China−U.S. trade from 1997 to 2003 (*12*) and found about 7−14% of China's CO_2 emissions should be attributed to exports for U.S. consumption.

Given the importance of China and the U.S. to global economic and environmental regimes and the trends of increasing bilateral trade, rising about 19% annually since 2000 in terms of total value (*2*), there is an obvious need for more detailed studies on the energy and air emissions embodied in their bilateral trade, especially in regard to Chinese exports to the U.S. This work contributes in this area by quantitatively studying the embodiment of energy and selected air emissions in the eastbound (from China to the U.S.) trade from 2002 to 2007 using an environmental input−output analysis (IOA) technique, a common tool which has been applied in this area for years (*18*).

Methods and Data

Model. Fundamental concepts and theories of IOA, dating back to Leontief's development in the 1930s (*19*), can be referred to various reputable literature (e.g., ref *20*). This economic technique has been widely used to assess environmental impact at the national level (*21*, *22*), as well as environmental impacts embodied in trade (*23*). The main idea is to multiply the economic value of imported products by the associated environmental impact factor for the same category of products manufactured in the export country. In this paper, we use this technique to quantify energy and air emissions embodied in the eastbound trade from China to the U.S.

To briefly introduce the fundamental principles of environmental IOA, assume there are n sectors (or commodities) and m categories of environmental impacts in the export country. Thus, the environmental impacts embodied in trade from the export country to the import country can be expressed as

$$\boldsymbol{P_m} = \boldsymbol{F}(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{T}$$

where $\boldsymbol{P}_\mathbf{m}$ is a $m \times n$ matrix whose element $\boldsymbol{p}_{\mathbf{m}(ij)}$ indicates environmental impact in category i embodied in the export of commodity in sector j, $\boldsymbol{F}$ is a $m \times n$ matrix whose element $\boldsymbol{f}_{ij}$ quantitatively represents the environmental impact in category i produced by unit total output of the sector j in the export country, $\boldsymbol{I}$ is the identity matrix, $\boldsymbol{A}$ is the $n \times n$ matrix of export country's direct requirements (*20*), and $\boldsymbol{T}$ is an $n \times n$ diagonal matrix of exports sorted by sectors or commodities. Using this basic equation, one can quantify

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environmental impacts embodied in trade between China and the U.S. and distinguish effects of different commodities. For further information on this technique, see the literature (*22*).

While the Chinese economic input–output table has the resolution of 122 sectors, the environmental impacts can only be located into 45 sectors. Therefore, the fundamental equation presented above must be adjusted to fit the data structure. There are two options to make such an adjustment. On one hand, one can aggregate the 122-sector Chinese economic input–output table into a 45-sector table, as well as the trade diagonal matrix $\boldsymbol{T}$. This aggregation will, of course, lower the resolution of the analysis and make the impacts of some trade flows unidentified. To avoid such an increase of uncertainties, on the other hand, one can also compute the accumulated economic requirements using the economic input–output table and trade data with higher resolution and then assign environmental impacts with lower resolution to them. To do so, the above equation needs to be adjusted as

$$\boldsymbol{P_m} = \boldsymbol{FK}(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{T}$$

where $\boldsymbol{F}$ is $m \times k$, $\boldsymbol{I}$, $\boldsymbol{A}$, and $\boldsymbol{T}$ are $n \times n$, and $\boldsymbol{K}$ is a $k \times n$ matrix whose elements are either 1 or 0. By multiplying $\boldsymbol{K}$ with $(\boldsymbol{I}-\boldsymbol{A})^{-1}\boldsymbol{T}$ which is $n \times n$, the product is $k \times n$ and indicates the accumulated economic requirements in k sectors to manufacture exported commodities in n sectors. By doing this, one can identify environmental impacts in m categories of exported commodities in n sectors.

Data Sources. Using the adjusted equation, we can then determine the embodied energy and air emissions in eastbound China–U.S. trade. To do so, we use nine subcategories in energy consumed, including coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, natural gas, and electricity. Although official statistics do not provide CO_2 emissions in China, energy mix consumed by each economic sector (*24*) can be used to estimate CO_2 emissions as well as other air emissions such as sulfur dioxide (SO_2) or nitrogen oxide (NO_x). In this research, we adopt the estimation from literature (*25*) where emissions are computed based on emission factors, based on literature (*26*) using country specific values where available, of different fuels in different processes. In particular, given the complex mix of combustion technologies and processes, SO_2 and NO_x emissions are more difficult to estimate than CO_2 emissions which are primarily related to carbon content in the fuel. Overall, the SO_2 and NO_x emissions are overestimated because abatement technologies are not considered due to lack of data. Details about emission estimations can be found in the literature (*25*).

Besides the energy use and emission data for each sector, this research also needs economic input–output tables, Chinese sectoral economic data, and eastbound trade data disaggregated to the commodity level. In particular, the most recent Chinese economic input–output table dates from 2002 and identifies 122 sectors (*27*). Sectoral economic data for China are taken from government statistics (*28*) and converted into the common unit of 2002 constant U.S. dollar by using purchasing power parity (PPP) (*29*) together with trade data. Details about classification of economic sectors are available in the Supporting Information.

Adjustment for Bilateral Trade Data. Bilateral trade data between China and the U.S. are available from reputable statistics in both countries (*2, 39*) which are integrated by the United Nations Statistics Division (UNSD) (*31*). Generally, since environmental impacts embodied in trade are computed based on economic input–output data of the country of origin, it could be helpful to reduce uncertainties by using data reported by the country of origin. However, there are obvious discrepancies, even though they have been reduced recently, between the bilateral trade data reported by China and the U.S. Without careful adjustment, there is the potential that relying only on data reported by either country could generate huge uncertainties in further analysis.

Scholars have studied the statistical discrepancies in bilateral trade between the two countries and identified some underlying reasons. For eastbound trade from China to the U.S., the data reported by the U.S. are much higher than the data reported by China. This is mainly due to the re-exports through intfrmediate third destinations (*32, 33*). In particular, a significant volume of Chinese goods is not directly exported to the U.S. from Chinese ports, but first shipped to third destinations, primarily Hong Kong (*34*), and re-exported to the U.S. In the Chinese statistics, those re-exports are not recorded as exports to the U.S. but to Hong Kong. However, in the U.S. statistics, imports are recorded on a "country of origin" basis which attributes the imports to the ultimate original country of production. Therefore, the re-exports through Hong Kong should be taken into account when studying the environmental impacts embodied in trade given that those re-exports are manufactured in China and finally consumed in the U.S. Moreover, it is also essential to estimate the markups of re-exports through Hong Kong to properly adjust the discrepancies (*35, 36*). In this study, the adjustment has been done by multiplying the commodity quantity recorded in the U.S. with the unit economic value recorded in China given the fact that physical quantities do not change no matter how much markups are made. Adjusted trade data disaggregated to the 6 digits level of the Harmonized Commodity Description and Coding Systems (the Harmonized System or HS) are available. Details about the adjustment can be found in the literature (*37*).

Results

Based on the adjustment on data reported by both countries, eastbound trade data from 2002 to 2007 are aggregated into ten commodity groups. Although its share in total Chinese exports decreases from 34.70% in 2002 to 10.67%, Chinese exports to the U.S. have been increasing steadily from 2002 to 2006, but dipped slightly in 2007. Among the ten aggregated commodity groups, "textiles", "electric and electronic equipment", and "other equipment", take 60–70% of the total eastbound trade. It is notable that Chinese exports on food and tobacco have been decreasing dramatically, from 16.42 in 2002 to 3.62 billion dollars in 2007, primarily due to the decrease of tobacco exports. Moreover, textile exports increase by 88.00% in 2003 but drop by 12.79% in 2004 and then grow so slightly that the trade value in 2007 is still below its peak in 2004. This is obviously due to the trade fight between China and the U.S. regarding textiles in 2004 and 2005 and the agreement on Chinese textile exports quotas concluded by the two countries in November 2005.

Embodied Energy. Unlike the steadily increasing trade value, the embodied energy associated with Chinese exports to the U.S. shows a different picture in Figure 1. As shown in the upper-left quadrant, the embodied energy decreases from 10.64 exajoule (EJ) in 2002 to 7.13 in 2004, then increases to 10.76 in 2006 and 9.08 in 2007. In the same period, energy embodied in total Chinese exports ranges from 23.55 to 39.27 EJ. The share of energy embodied in the eastbound trade to the U.S. in the energy embodied in the total Chinese exports decreases from 45.20% in 2002 to 23.11% in 2007. From 2002 to 2003, particularly, although embodied energy associated with textiles increased by 68.56%, reductions in "electric and electronic equipment", "metals", "other equipment", and "other products" are sufficient enough to offset and lead to the decrease of total embodied energy. In 2004, embodied energy in most of the commodity groups, even including "textiles" due to the trade fight, decreased. In fact, the reduction in "textiles" is the largest contributor to the total embodied energy decrease. From 2004 to 2006, embodied

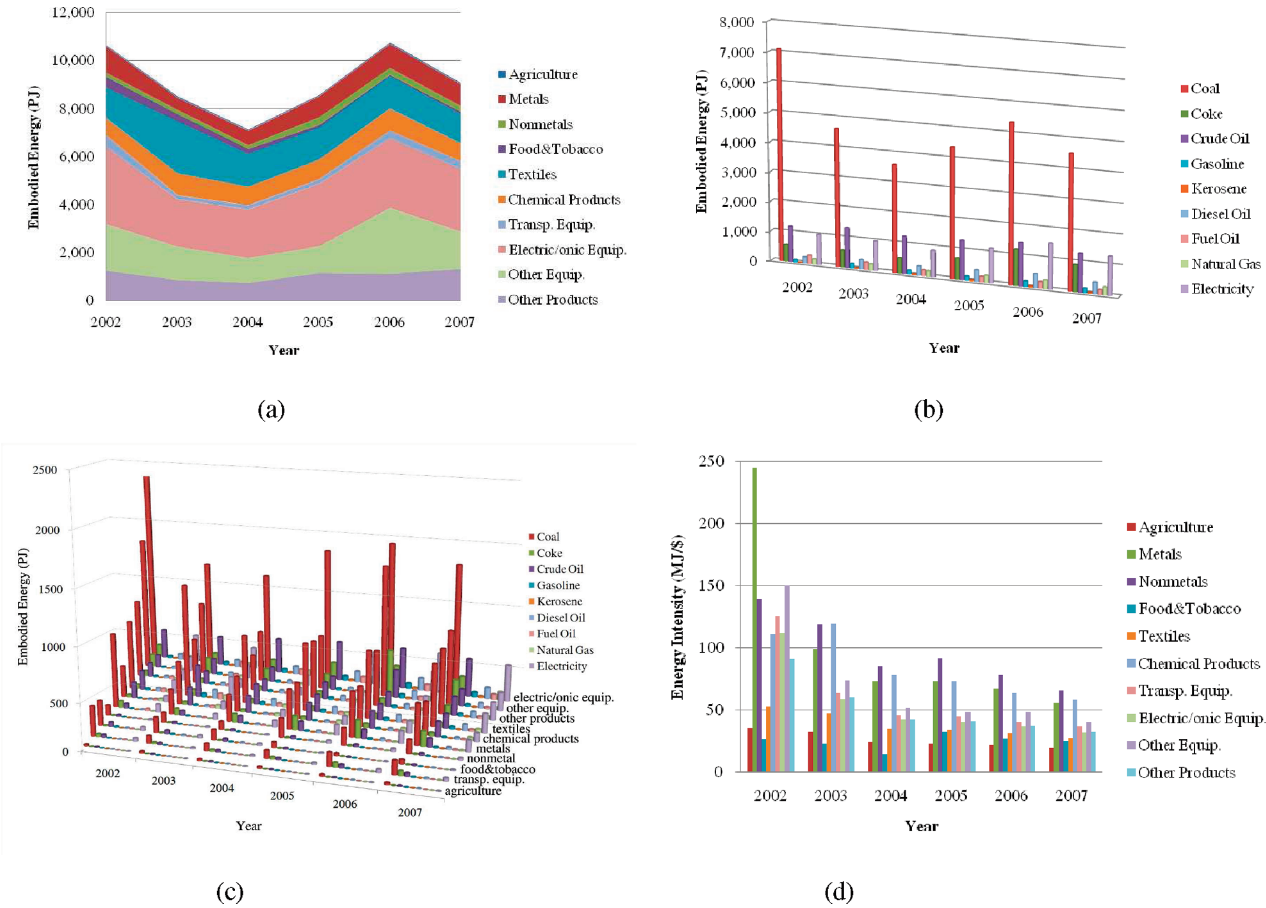

FIGURE 1. Embodied energy in Chinese exports to the U.S. by (a) commodity group, (b) energy type, (c) both, and (d) per unit economic output in each commodity group.

energy associated with "electric and electronic equipment" and "other equipment" is the primary reason for the increase of total embodied energy. However, embodied energy in "other equipment" decreases significantly in 2007, leading to an overall decrease in embodied energy. It is clear that, although the total trade value has been increasing, the composition of Chinese exports to the U.S. is dynamic. As a result, embodied energy associated with trade is also dynamic. Nevertheless, it is also obvious that "textiles", "electric and electronic equipment", and "other equipment" are the primary driving forces of the embodied energy in Chinese exports to the U.S.

From an energy production perspective, the upper-right quadrant of Figure 1 shows that coal dominates the total embodied energy in Chinese exports to the U.S., followed by crude oil, electricity, and coke. In particular, coal takes more than 50%, even 66.75% in 2002, in the composition of total embodied energy. As a result, the development of total embodied energy follows the path of embodied coal. Overall, the embodied energy in the eastbound China−U.S. trade takes about 12−17% of the total domestic energy consumption in China, which is impressive given that the value of eastbound trade is only about 7−10% of China's GDP.

The lower-left quadrant of Figure 1 disaggregates embodied energy by both commodity group and energy type. It is clear that "electric and electronic equipment" has the most embodied energy for all energy types while agriculture products have the least. Obviously, coal embodied in electric and electronic equipment dominates the development of entire embodied energy. Given the continuously increasing trade in electric and electronic equipment, the energy mix used in manufacturing is the underlying driver of the total embodied energy. For example, the less coal used in producing electric and electronic equipment, the less total energy is embodied in the trade. Numerous factors have effects on the energy use mix, such as production capacity, price, transportation capacity, or policy. Interestingly, coal embodied in "textiles" in 2003 becomes as high as coal embodied in "electric and electronic equipment" due to the huge increase in textile exports which instigates the trade fight on textile products between the two countries. As a result, textiles exports from China, as well as embodied energy, decrease in 2004. After that, embodied energy in textiles relatively slowly increases by around 10% annually because Chinese textile exports follow the quotas agreed upon between China and the U.S.

The lower-right quadrant of Figure 1 presents the energy embodied in per unit economic output, or energy intensity, of each commodity group. Overall, the energy intensity has been decreased from 94.22 megajoule (MJ) per dollar, or MJ/$, in 2002 to 36.01 in 2007, which implies the improvement of energy efficiency in China's economic system, especially in manufacturing. In each year, "metals", "nonmetals", and "chemical products" generally have the highest energy intensities among all commodities. Note that the energy intensity is highly influenced by the fluctuation of commodity prices at the global scale. For example, the energy intensity of "metals", including metal products, dramatically dropped from 245.15 MJ/$ in 2002 to 99.54 in 2003 and 73.24 in 2004, which is partially due to the global price increase in iron, steel, and nonferrous metals. After 2005, although the global metal prices are still unstable, energy intensity in "metals" keeps decreasing primarily due to the improvement of energy efficiency, especially in smelting and processing. Overall, the general decreasing energy intensity in all categories indicates the improvement of energy efficiency.

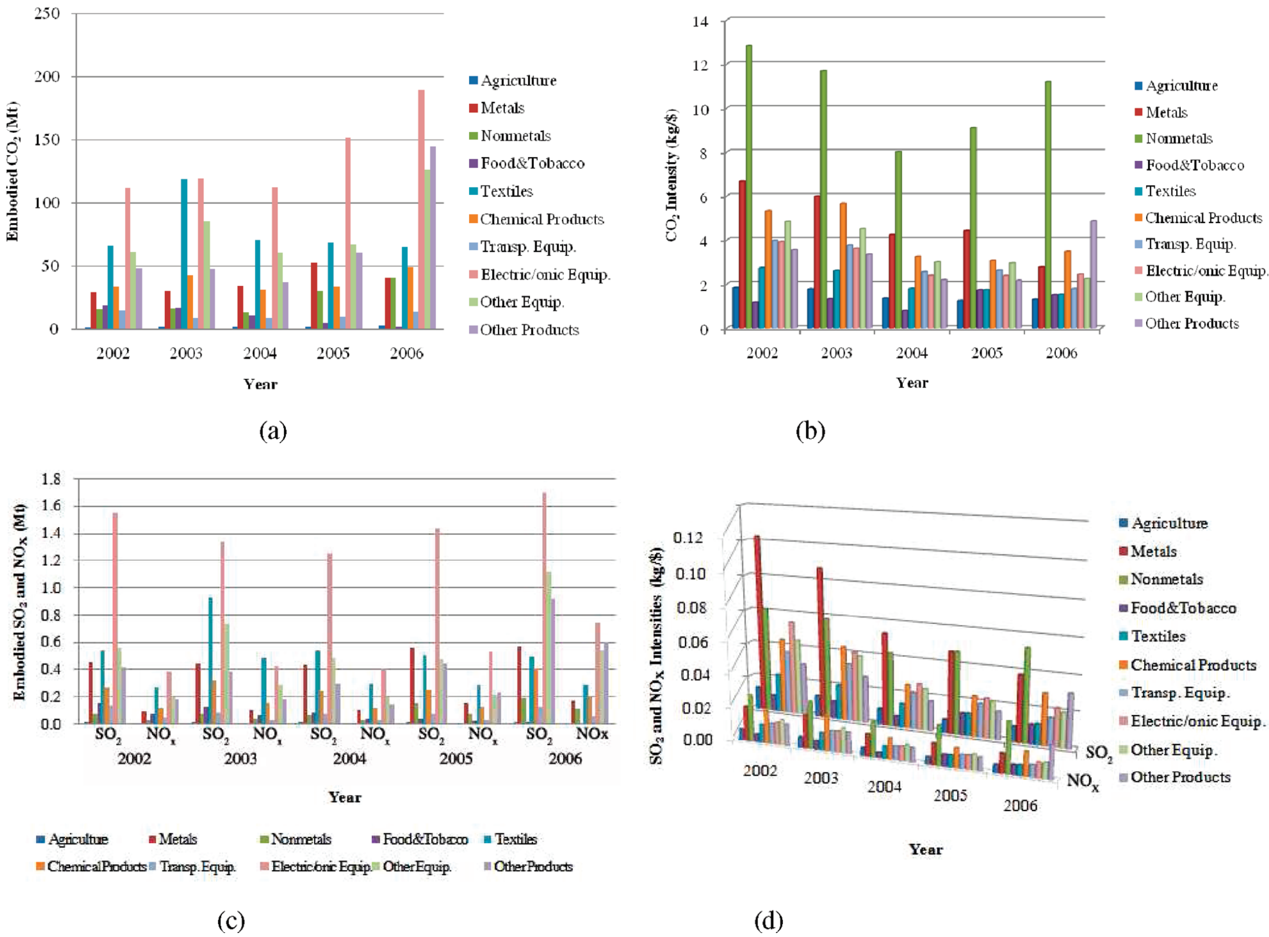

FIGURE 2. Embodied air emissions in Chinese exports to the U.S. for (a) CO_2, (b) CO_2 intensity, (c) SO_2 and NO_x, and (d) SO_2 and NO_x intensities.

Notably, energy intensities of some commodities, including “metals”, “nonmetals”, and “food & tobacco”, have increased in 2005 while other commodities’ energy intensities slightly decrease. Although the trade data have been converted into the common unit to eliminate influences of inflation and currency exchange, it is possible that this obvious irregularity is a result of China’s transition to a floating exchange rate system from the fixed rate system in 2005, which is beyond the scope of this research.

Embodied Air Emissions. Although China does not publish statistics for CO_2 and NO_x emission data, estimations based on energy mix have been studied specifically for China (*25, 38*). In this research, CO_2, SO_2, and NO_x emissions are computed based on China’s energy consumption mix in each year by adopting the method in the literature (*25*). Figure 2 presents the embodied air emissions in Chinese exports to the U.S. Overall, the CO_2 embodied in Chinese exports to the U.S. ranges from 400 to 800 Mt, which take about 22−30% of the CO_2 embodied in total Chinese exports. Embodied SO_2 is around 5 Mt, or 20−25% of the SO_2 embodied in total Chinese exports, while embodied NO_x is about 2 Mt, or 23−29% of the NO_x embodied in total Chinese exports. Moreover, embodied CO_2, SO_2, and NO_x emissions all increase slightly in 2003, then shrink in 2004, and steadily grow afterward.

The upper-left quadrant of Figure 2 shows the embodied CO_2 emissions in Chinese exports to the U.S. by commodity group. Due to the 88.00% growth of textile exports in 2003, the embodied CO_2 in “textiles” increases by 78.96%, which dominates the overall rise of embodied CO_2 in 2003. In 2004, however, Chinese textile exports shrinks by 12.79%, due to the trade fight between China and the U.S. on textile products, which leads to the embodied CO_2 in “textiles” decreasing by 40.14%, and the overall embodied CO_2 emissions decreasing by 21.49% in 2004. After 2004, embodied CO_2 emissions in Chinese exports steadily increase driven by growth of embodied CO_2 in “electric and electronic equipment” which follows its pattern of embodied coal. Moreover, embodied CO_2 in “other equipment” and “other products” also contributes significantly in the overall embodied CO_2 increase in 2006, also due to the increase of embodied coal. Overall, the CO_2 emissions embodied in the eastbound China−U.S. trade is about 8−12% of China’s total CO_2 emissions from 2002 to 2006, which is comparable with the previous study (*12*).

On the other hand, the upper-right quadrant of Figure 2 represents the CO_2 intensity of per unit economic value in each commodity group. In general, CO_2 emissions required to produce one dollar of eastbound trade decrease from 3.59 kg in 2002 to 2.69 in 2006. Particularly, given the relatively lower prices of nonmetal products such as clay or cement, CO_2 intensity of “nonmetals” is about one magnitude higher than those of other commodity groups. Overall, although energy efficiency has been improved (Figure 1 frame d), CO_2 intensity is still primarily driven by coal embodied in each commodity group. Given that emission intensity is driven by energy efficiency in manufacturing and commodity price, it is possible that the increase of energy efficiency in coal and commodity prices have offset with each other so that the overall effect on CO_2 intensity relies on the use of coal.

The lower-left quadrant of Figure 2 illustrates the embodied SO_2 and NO_x emissions in Chinese exports to the U.S. by commodity group. Although SO_2 embodied in “electric and electronic equipment” shrinks in 2003, the increase in "textiles" and "other equipment" causes an overall growth of embodied SO_2 emissions. In 2004, the trade fight leads to a reduction of embodied SO_2 in textile exports. The embodied SO_2 also decreases in all other commodity groups, which causes the reduction of embodied SO_2 in the entire system. However, exports in "electric and electronic equipment", "other equipment", and "other products" grow afterward and thus contribute to the increase of embodied SO_2 emissions. Overall, embodied SO_2 emissions are about 10−15% of the total estimated SO_2 emissions in China as estimated in this research. On the other hand, the growth of textile exports causes the overall increase of embodied NO_x in 2003. Moreover, the embodied NO_x in "textiles" is even higher than that in "electric and electronic equipment" in 2003. In 2004, the embodied NO_x in "textiles" shrinks due to the trade fight and stays around 0.3 Mt afterward. NO_x embodied in "electric and electronic equipment" keeps increasing after 2004 and dominates the total embodied NO_x emissions. Notably, embodied NO_x emissions in "other equipment" and "other products" increase by 151.58% and 154.49%, respectively, in 2006. Similar with embodied energy, the coal embodied in eastbound trade is the underlying driver of embodied SO_2 and NO_x emissions. Overall, the embodied NO_x takes about 8−12% of the total estimated China NO_x emissions.

The lower-right quadrant of Figure 2 shows SO_2 and NO_x intensities of per unit economic value in each commodity group. Similar with CO_2 intensity, the NO_x intensity of "nonmetals" is higher than intensity of any other commodity category due to relatively lower prices of nonmetal products. On the other hand, SO_2 intensity of "metals" is within the same range of that of "nonmetals" primarily due to emissions in smelting and processing of metals. Similar with CO_2 intensity, intensities of SO_2 and NO_x primarily rely on the use of coal embodied in the trade in most commodity categories. Exceptionally, the increasing price of metals, whose impact is higher than the effect of energy efficiency improvement, causes the continuous decrease of SO_2 and NO_x intensities. Overall, 0.02−0.03 kg of SO_2 and 0.01−0.02 kg of NO_x emissions are generated in the manufacturing of one dollar of eastbound trade. Note that our assumption of no abatement technology overestimates the intensities of SO_2 and NO_x.

Uncertainties. There are inherent uncertainties of the IOA method caused by sector aggregation, time-lag, and assumptions of linear intersector relationship and homogeneity of products. Theoretical analysis on these uncertainties has been profoundly discussed although quantitative analysis is rarely done due to lack of information (*39*). Particularly in this research, extra uncertainties are brought by trade and environmental performance data. First, the results on energy and emissions embodied in eastbound trade can be increased by about 18% and decreased by about 38% if using trade data reported by China and the U.S., respectively. It is obviously inappropriate to adopt government data without proper adjustment. Using data from other adjustments (*33*, *36*), our results can be increased by 10% or decreased by 16%. Second, the sectoral energy use and emissions data are either from government statistics or estimation, which lead to other uncertainties. In particular, government statistics are the primary source of energy use in each sector and also used as the basis to estimate air emissions. Therefore, it is difficult to quantify the uncertainty involved in these data as well as associated estimation due to lack of information on data collection and specific technologies in different industrial processes. However, in this research SO_2 and NO_x emissions are obviously overestimated because abatement technologies are not considered. Despite all that, for a national economic system, government statistics are still relatively reliable and are the most common data source for environmental IOA such as this study.

Discussion

This study contributes in the growing field of environmental IOA by studying the role of international trade at global and domestic scales. Our analysis quantifies embodied energy and air emissions in Chinese exports to the U.S. from 2002 to 2007. As a comparison, energy and air emissions embodied in the total Chinese exports to the world are also available for the same period in the Supporting Information. In general, although the total export value measured in constant price has been steadily increasing, the ten commodity groups classified in this research show different patterns of development in terms of trade values. As a result, embodied energy and air emissions change dynamically in the studied period. Overall, these dynamics are dominated by the use of coal in major commodity categories such as "electric and electronic equipment". Moreover, note that several factors have significant impacts on this dynamics. First, decreasing energy and emission intensities over the period indicate the improvement of energy efficiency in the entire Chinese economic system. The primary underlying driver for efficiency improvement perhaps is the advancement of manufacturing technologies. Additionally, the improvement in enterprise management may contribute in improving energy efficiency. Second, the dynamics of embodied energy and emissions are also significantly affected by international and domestic policies. For example, Chinese exports of tobacco have been significantly decreased in 2005 which may be the result of the Framework Convention on Tobacco Control (FCTC), under the auspices of the World Health Organization (WHO), which took effect in China in the same year. As a result, energy and emissions embodied in tobacco exports have also decreased after 2005. Additionally, the decrease of embodied energy in "textiles" in 2004 due to the trade fight between China and the U.S. on textile products causes the reduction of embodied energy and emissions as a whole. After 2004, embodied energy and emissions in "textiles" stay almost constant due to the export quotas agreed upon by the two countries. From the domestic point of view, the reduction of embodied energy and associated emissions is also a result of various policies in different sectors implemented by local governments instigated by the Chinese central government's ambition to improve energy efficiency by 20% within the period from 2005 to 2010, or the Eleventh Five-Year. Moreover, the global dynamics of commodity price, especially for metals, also have significant impacts on energy and emissions embodied in the eastbound trade between China and the U.S. Finally, the commodity composition in each category is dynamic, which also affects energy use and emissions embodied in the exports of each commodity group. Note that the overall dynamics of embodied energy and emissions emerge from the collective effects of the technology, policy, and price factors as well as other underlying drivers which interact with each other in a complex way. In the future, studies should be conducted to understand the complexity of the China−U.S. trade system incorporating with technology, policy, economics, commodity structure, and other factors from international and domestic aspects.

By quantifying embodied energy and air emissions, these results show that consumable products exported to the U.S. are significant in generating embodied environmental impacts in China. Given the current role of China in the global economy as the "world factory", such embodied environmental impacts will be significant if taking export trades with other countries into account. Although further investigations are required for international or general domestic policy making, this study supports specific cases regarding the China−U.S trade. For instance, although the trade fight on textiles between China and the U.S. in 2004 and 2005 has been settled through negotiation, environmental concerns were not taken into account. Both countries might rethink the trade-offs if embodied energy, air emissions, and other environmental impacts are considered. For example, China may voluntarily set quotas for textile exports in order to reduce domestic energy consumption and environmental pollution. On the other hand, the U.S. may take advantage in the negotiation by taking embodied air emissions, especially CO_2 whose impacts are globally, into account. Moreover, it is even more critical to quantify embodied CO_2 for the increasingly international concerns on climate change given the political, economic, and geographical importance of China and the U.S. in the world.

In this article, we have aggregated the commodities into ten groups. However, more information could be extracted by studying disaggregated data, available in the Supporting Information. Moreover, the underlying reality of embodied energy and air emissions in the China−U.S. trade is much more complex than what we can draw from the database developed in this article. More detailed studies are required to better understand the complexity of international trade and its impacts on sustainability from various aspects such as economic structure or technology development. First, up-to-date data for environmental IOA in the U.S. are under development (*40*). With this database, similar analysis could be conducted for the westbound China−U.S. trade using adjusted trade data (*37*). Moreover, the database can also be improved by quantitatively identifying other environmental impacts, such as water pollutants or municipal waste, in the same framework although their impacts are mainly domestic rather than international. Second, recent empirical studies in this field have concentrated on embodied environmental impacts only caused by input and output between economic sectors. However, besides the activities of economic sectors, there is also labor input which contributes in every stage of the life cycle of the exported products. Because of the differences between export and import countries in terms of employees' work cost, work style, life style, and environmental consequences of household consumptions, it is also important to study the environmental impacts embodied in trade due to employee consumption in the exporting country. Given the huge difference in employees' social characteristics between China and the U.S., bilateral trade between these two countries is a prime candidate for an empirical analysis on the comprehensive environmental impacts embodied in trade including the environmental overhead of labor.

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Supporting Information Available

Details about methodology and analysis. This information is available free of charge via the Internet at http://pubs.acs.org.

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