Embodied Environmental Damage in interregional trade: A MRIO-based assessment within China

Feng Wang ^a, Beibei Liu ^{a, b *}, Bing Zhang ^{a, c, d*}

^a State Key Laboratory of Pollution Control & Resource Reuse, School of Environment,

Nanjing University, Nanjing 210023, PR China

^b The Johns Hopkins University-Nanjing University Center for Chinese and American

Studies, Nanjing 210093, PR China

^c Jiangsu Collaborative Innovation Center of Atmospheric Environment and Equipment

Technology (CICAEET), Nanjing University of Information Science & Technology, Nanjing

210044, PR China

^d School of Government, Nanjing University, Nanjing 210093, PR China

*Corresponding authors: lbeibei@nju.edu.cn, zhangb@nju.edu.cn.

Abstract: A new lifelong accountability system for ecological and environmental damage will be established for local officials in China. However, if this new production-based accountability system does not consider the responsibilities of consumers, it is likely to aggravate the imbalance of regional development. Using a multi-regional input–output model, this paper tracked the environmental damage transfers in interprovincial trade. Trade-related damage from four major pollutants was quantified for each province in 2007. The results show that nearly 45% of the environmental damage that occurs at home to meet consumption in other regions can be ascribed to the interprovincial trade flows in China. In 2007, the North Municipalities, the East Coast, and the South Coast, where the share of production-based environmental damage in relation to the local GDP is lower, transferred environmental damage to the developing Northwest and Central regions to make the local GDP greener via interregional trade, leading to inequality in regional development. It is suggested that the importance of environmental damage from a consumer perspective should be integrated into the future implementation of the new lifelong accountability system.

Keywords: embodied environmental damage, multi-regional input–output analysis, interregional trade, regional inequality.

1. Introduction

Extraordinary economic achievements in China have been accompanied by the expenses of mounting environmental damage and public health issues. In the past four decades, China has averaged approximately 10 percent annual GDP growth and has become the world's second-largest economy after the United States. China has also become the largest emitter of almost all pollutants, including emissions of organic wastewater, sulfur dioxide, and various greenhouse gases (Wang, 2013). The surge of emissions in the last several decades has produced increasingly serious environmental and health damage. According to studies by the World Bank, the World Health Organization, and the Chinese Academy for Environmental Planning, there are nearly 350,000-500,000 pollution-induced premature deaths each year due to outdoor air pollution in China (Chen et al., 2013).

Faced with increasingly severe environmental pollution and resource pressure, China has embarked on a lifelong accountability system for ecological and environmental damage. For a long time, economic performance, i.e. regional GDP assessment, has been related to the career advancement of government officials. In 2015, the Chinese government decided to evaluate provincial officials with regard to the environmental consequences of their decisions. Based on the two documents that were promulgated centrally, the Decision of the Central Committee of the Communist Party of China on Some Major Issues Concerning Comprehensively Deepening the Reform and the Integrated Reform Plan for Promoting Ecological Progress (Politburo of China's Communist Party, 2013; State Council, 2015), a lifelong accountability system for ecological and environmental damage will be established for local officials. Specifically, local resource consumption and environmental damage will be highlighted in the career assessment

system of government officials on the basis of the natural resource balance sheet and natural resource audits.

By urging local government officials and producers to control emissions, the new lifelong accountability system aims at greening local GDP within China, namely, to lower the share of monetary value of ecological and environmental damage in the regional GDP as much as possible. However, as interregional trade plays an increasingly critical role in regional economic development, the ecological and environmental damage that occurs in one region may be provoked by demand from other regions, due to substantial regional heterogeneities in the population, economic structure, resource endowment, technological capabilities and life styles in China. Taking the frequently hazy weather as an example, Hebei has not only suffered from severe haze pollution but has also faced criticism as the chief culprit of Beijing's haze because of emission drifting. In fact, Hebei has provided for Beijing's consumption, including five percent of the electricity consumption in Beijing (MEP, 2014). Under this new lifelong accountability system, governmental officials in Hebei would be held accountable because of the emissions and damage that were produced by Beijing but that occurred in Hebei. This understanding would influence the development of the related power and steel industries in Hebei, on which the local residents rely. At the same time, by exploiting the comparative advantages in the field of technological capabilities and natural endowments, interregional trade could be beneficial in the optimization of the overall use of natural resources within China. Once the new lifelong accountability system has imposed more restrictions and pressure on the development of these resource- or energy-intensive regions, where the emission intensities are generally higher, the imbalance of regional development in China is likely to further increase.

Therefore, to guarantee nation-wide sustainable development, environmental damage transfers caused by interregional trade should be considered with caution in environmental policies and in associated officials' accountability systems.

Recently, the inter-regional emissions transferred by trade have attracted increasing attention. Growing evidence has indicated that the geographical separation of production and consumption caused by trade can bring about emission transfers both internationally and inter-provincially (Jiang et al., 2015; Lin et al., 2014; Meng et al., 2013; Peters et al., 2011; Takahashi et al., 2014; Wiedmann et al., 2013). Liu et al. (2015a) has established a multi-regional input-output (MRIO) model to track the interregional carbon emissions flows, and found that the proportion of interregional carbon flows in total national emissions has grown increased from 15.2% in 2002 to 21.1% in 2007. Moreover, Feng et al. (2013) concluded that nearly 80% of carbon emissions related to goods consumed in highly developed coastal regions were imported from less-developed provinces in 2007. Zhao et al. (2015b) found that in 2007, the virtual water flows accounted for 35% of national water, varying from 11% to 65% for different provinces. Zhao et al. (2015a) also found that nearly 23% of all Chinese primary PM_{2.5} emissions, 33% of all SO₂ emission, 31% of all NO_x emissions, and 23% of all NMVOC emissions from a production-based perspective are attributable to consumption in other provinces or regions in the country. Liang et al. (2014) also demonstrated the existence of significant interregional atmospheric mercury emission transfers that generally moved from the developing inland areas to the developed east coast in 2007.

The interregional emission transfers may induce ecological and environmental damage shift. In terms of air pollutants, PM_{2.5} and the main precursors, namely, sulfur dioxide (SO₂)

and various oxides of nitrogen (NO_x), were not only associated with lung cancer, cardiopulmonary disease and all-cause mortality (Matus et al., 2012; Pope III et al., 2002), but also can lead to agriculture loss (Van Dingenen et al., 2009; Wei et al., 2014), and damage in forest ecosystem (Smith, 2012). With regard to local water pollutants, poor water quality, which generally is higher in chemical oxygen demand (COD), ammonia nitrogen ($\text{NH}_3\text{-N}$), also been found to related to disease burden (Prüss et al., 2002). For regions that show imbalanced development, especially in China, more affluent and technologically advanced regions have been subject to more stringent reduction targets than areas with less advanced technologies (Liu et al., 2012b). This situation may cause regional emission leakage, and the accompanying ecological and environmental damage may further reinforce regional inequities. Furthermore, one region may be a net emission exporter of one pollutant via the interregional trade, but it could also be a net importer of another pollutant because of diversities in regional economic structure. On this occasion, the regional ecological and environmental damage from these two pollutants caused by the interregional trade become unclear. Therefore, how does the interregional trade in China exert influence to ecological and environmental damage regionally? Assessing the ecological and environmental damage can present a clearer picture of the design of environmental policies and officials' accountability across the nation.

This study investigates the ecological and environmental damage that is transferred by interregional trade within China. In this paper, a multi-region input–output model, which has the ability to account for different emission technologies associated with different regions' products, is applied to estimate the embodied ecological and environmental damage in interprovincial trade. In China, the total amount control nationally in the last ten years on SO_2 ,

NO_x, COD and NH₃-N has laid a good data foundation. Therefore, in this framework, ecological and environmental damage caused by COD, NH₃-N, SO₂ and NO_x, which have been targeted in national emission control policies in China, are chosen to represent the ecological and environmental damage in 30 major regions in China in 2007. The results can provide a quantitative and comprehensive image of how the emissions embodied in interprovincial trade shape a country's environmental profile and inform effective and equitable policies for sustainable development nationally as well as the design of a lifelong accountability system for ecological and environmental damage.

This paper is organized as follows. Section 2 presents the major methodology of the production-based and consumption-based environmental damage accounting and the multi-regional input–output model. Section 3 discusses the production-based and consumption-based pollutant emissions and environmental damage at the regional level. The paper concludes with some policy suggestions for sustainable regional development in China in Section 4.

2. Methodology

To estimate the ecological and environmental damage transferred by interregional trade within China, the production and consumption-based emissions for each region were first calculated by using the MRIO model. Using environmental damage per unit of pollutant emission for each region, this paper further quantified the ecological and environmental damage transferred by interregional trade within China.

2.1. Multi-regional input–output model

The multi-regional input–output model can capture the economic relationships among different regions and sectors and therefore can trace the spatial transfers of ecological and

environmental damage. In the past several years, the MRIO model has been widely used to analyze emissions embodied in the global and regional supply chains (Atkinson et al., 2011; Bruckner et al., 2012; Kanemoto et al., 2014; Liu et al., 2015b; McGregor et al., 2008; Wiedmann et al., 2007). With regard to the materials and emission flows embodied in the domestic supply chains in China, the MRIO model has been used to investigate virtual water footprints (Zhao et al., 2015b), air pollutant transfers (Zhao et al., 2015a), atmospheric mercury footprints (Liang et al., 2014), and carbon displacements in China (Zhang et al., 2014)

In the input-output model, economic output can be expressed as the sum of intermediate consumption and final demand. The basic Leontief input-output relationship can be given as follows¹:

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

where $\mathbf{x}$ is the vector of economic output, $\mathbf{I}$ represents the identity matrix, $\mathbf{A}$ stands for the direct input-output coefficients matrix, and $\mathbf{y}$ is the vector of the final demand.

In this study, a MRIO model has been employed to quantify the inter-regional environmental damage flows. Equation (1) can thus be generalized to include imports from other regions, as formulated in Equation (2):

$$\begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \vdots \\ \mathbf{x}_n \end{bmatrix} = \begin{bmatrix} \mathbf{A}_{11} & \mathbf{A}_{12} & \cdots & \mathbf{A}_{1n} \\ \mathbf{A}_{21} & \mathbf{A}_{22} & \cdots & \mathbf{A}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}_{n1} & \mathbf{A}_{n2} & \cdots & \mathbf{A}_{nn} \end{bmatrix} \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \vdots \\ \mathbf{x}_n \end{bmatrix} + \begin{bmatrix} \mathbf{y}_{1j} \\ \mathbf{y}_{2j} \\ \vdots \\ \mathbf{y}_{nj} \end{bmatrix} \quad (2)$$

¹ In this paper, matrices are indicated by bold, italicized capital letters, vectors are presented by bold, italicized lower case letters, and scalars are denoted by italicized lower case letters. In addition, the notation " $\wedge$ " diagonalizes the column vectors.

where $\mathbf{x}_j$ indicates the total output of in region j . $\mathbf{y}_{ij}$ indicates each sector's output produced in region i and consumed in region j , and $\mathbf{A}_{ij}$ reflects the intermediate consumption, where each column denotes the input from each sector in region i required to produce one unit of output from each sector in region j .

To calculate the emissions embodied in goods and services, we extended the MRIO table with environmental extensions by using major pollutant emissions as environmental indicators, as shown in Equation (3):

$$\mathbf{E}_k = \hat{\mathbf{f}}_k (\mathbf{I} - \mathbf{A})^{-1} \mathbf{Y} \quad (3)$$

where k is the category of the major emissions, $\mathbf{E}_k$ is the total major pollutant emissions embodied in goods and services used for final demand, and $\mathbf{f}_k$ is a vector of major pollutant emissions per unit of economic output for all economic sectors in all regions.

To present the total environmental burden transferred by interregional trade, environmental damage has been monetized in this study. According to the System of Environmental Economic Accounting (EC et al., 2012), the environmental damage caused by major water pollutants should include the virtual treatment cost, the damage to human health and agricultural losses, etc. However, due to regional data limitations on the damage to human health and agricultural losses, only the virtual treatment cost has been considered in local environmental damage. In this study, we assumed that, once all pollutants had been effectively removed from the discharges to meet national emission standards through the help of best available emission control technologies, the damage to human health, agriculture and forest ecosystem, etc., caused by the pollutants, can also be reduced to the minimum. In other words, the virtual treatment cost can be viewed as the lowest bound of the environmental damage. The

environmental damage D_k^s caused by pollutants k can be represented as

$$D_k^s = E_k^s \times \hat{q}_k^s \quad (4)$$

where $\hat{q}_k^s$ is a vector of the virtual abatement cost per unit of pollutant emission for region s .

To examine domestic interregional environmental damage transfers, we calculated each region's production-based and consumption-based environmental damage within China's domestic economy. It is noteworthy that international trade can exert an important influence on regional environmental damage, however, the lifelong accountability system for ecological and environmental damage is the local policy in China. Therefore, in this paper, only the domestic supply chains in China has been considered to quantify each region's production- and consumption-based environmental damage. Production-based environmental damage measures damage embodied in the final products that are produced in a particular region, whereas consumption-based damage describes the environmental damage embodied in a region's consumption.

The production-based environmental damage of region s can be presented as follows:

$$D(p^s) = \sum_k \hat{f}_k (I - A)^{-1} \times \hat{p}^s \times \hat{q}_k^s \quad (5)$$

The consumption-based environmental damage of region s can be presented as follows:

$$D(c^s) = \sum_k \hat{f}_k (I - A)^{-1} \times \hat{c}^s \times \hat{q}_k^s \quad (6)$$

where p^s represents product flows from region s to satisfy the final demands of all regions, and c^s indicates the product flows from all regions to meet the final requirements of region s .

By comparing the production-based and consumption-based environmental damage for

region s , the net virtual environmental damage import can be calculated as follows:

$$\Delta D = D(c^s) - D(p^s) = f_k(I - A)^{-1} \times [\hat{c}^s - \hat{p}^s] \times \hat{q}_k^s \quad (7)$$

2.2. Data Sources

To calculate the environmental damage embodied in interregional trade, three sets of data, the national MRIO table in 2007, the sectoral pollutant emissions for each region, and the provincial pollutant virtual abatement cost have been used in this study.

The MRIO table in 2007, which was compiled by an augmented gravity model (Liu et al., 2012a), has been used in this paper. In the MRIO table, China is divided into 30 regions (i.e., 26 provinces and 4 cities), with Tibet, Hong Kong, Macau and Taiwan excluded due to data limitations, and each region covers 30 sectors, as shown in Table S1. To better understand the differences between production-based and consumption-based environmental damage, 30 regions in China was also aggregated into eight regions according to the similarity of the economic structure and spatial location (see Table S3) (Feng et al., 2013; Meng et al., 2013).

To obtain the regional emission inventory by sector, the database of the environmental statistics of 2007 was used in this study. The environmental statistics database of 2007 covers the detailed major pollutant emission data at the firm level for each region (MEP, 2007). However, two issues should be paid attention to when deriving the production-based pollution emission inventory for each sector and region. First, the agricultural non-point wastewater and COD discharge are not included in Chinese official environmental statistics. We acknowledge that non-point emission sources are excluded from this study due to a lack of data availability and the emission inventory from the point source in the environmental statistics database was used as a proxy for the agricultural emission inventory. Second, the pollutant discharge from

both household consumption and most construction and service sectors is included in residential pollution discharge. In other words, only emissions from agriculture and industrial point sources (sector 1-23 in Table S1) and some emissions from the construction and service sectors can be obtained by sector for 30 regions from the database of the environmental statistics. More than a hundred thousand key industrial emitters are included in the environmental statistics database, accounting for about 85% of the national industry emissions. In this paper, by amending the emission inventory from the environmental statistics database with the national total amount, we can obtain the production-based pollution emission inventory for agriculture and industrial sectors for each region.

Water pollutant emissions for construction and service sectors are derived from the Chinese Environmental Statistics Yearbook in 2007 (NBS and SEPA, 2008). In the Chinese Environmental Statistics Yearbook, emission data for the construction and service sectors as well as data for household consumption have all been categorized as "household waste water discharged"; these data are difficult to differentiate. To obtain the sectoral emission inventory for the construction and service sectors, we first derive the ratio of the regional water pollutant emissions of the construction and service sectors to total household discharge according to China Pollution Source Census in 2007 (MEP and NBS, 2011). Then we allocated the emissions from household waste water discharged in Chinese Environmental Statistics Yearbook 2007 to construction and service sectors based on the respective ratio derived. Finally, sectoral emissions for the construction and service sectors for each region can be averaged based on the respective sectoral output for each region.

Air pollutant emissions for construction and service sectors are mainly calculated based

on the energy consumption according to Chinese Energy Statistics Yearbook 2007 (NBS, 2008).

In the official environmental statistics, the residential air pollutant discharge is calculated according to energy consumption. For SO₂ emissions, only emissions from coal consumption are considered. The SO₂ emissions, e_s , can be calculated as

$$e_s = w \times \eta \times 0.8 \times 2 \quad (8)$$

where w is coal consumption, η is the sulfur content of the coal, 0.8 refers to the rate of sulfur in the coal combusted to produce SO₂ emissions, and 2 implied the emission multiplier of SO₂ on the basis of the chemical equation for sulfur combustion². The average sulfur content of the coal can also be obtained from the Handbook of the emissions coefficient for residential sources for the first national pollution census (LGFNSP, 2008). For NO_x emissions, the empirical coefficient was used. In the official environmental statistics, 2 kg NO_x are emitted from 1 tonne of coal consumption on average, and 8 kg NO_x are averagely produced from the combustion of 10⁴ cubic meters of natural gas (LGFNSP, 2008). To obtain the SO₂ and NO_x emission for the construction and service sectors for each region, data on the sectoral coal and natural gas consumption were obtained from the Chinese Energy Statistics Yearbook 2007. However, the Chinese Energy Statistics Yearbook 2007 only provides sectoral energy consumption data at the national level. To obtain the regional energy consumption data, we

² In this study, according to the Handbook of the Emission Coefficient for Residential Source for the First Nationwide Survey of Polluters in China (LGFNSP, 2008), the estimates of SO₂ emissions from residential coal use are based on the chemical equation of sulfur combustion. On basis of the principle of mass conservation, we can find that the SO₂ emissions should be 2 times of the sulfur quality in the coal combusted. Moreover, the handbook assumed that about 80% of the sulfur in the coal would be combusted to produce SO₂ emissions, via multiplying the coal consumption by the sulfur content of the coal by the sulfur combustion rate, we can calculate the total SO₂ emissions from residential coal consumption.

averaged the energy consumption based on the sectoral output for each region. Moreover, the service sectors do not match the sectors in our MRIO table. Therefore, we also disaggregated the energy consumption in the Chinese Energy Statistics Yearbook into the sectors in the MRIO table according to the corresponding sectoral output, as shown in Table S2 (Liu et al., 2012b).

As mention above, the virtual treatment cost for each pollutant can be viewed as the lowest bound of the environmental damage. In this study, the actual treatment cost of the four major local pollutants was adopted to calculate the virtual treatment cost, as shown in the Chinese Environmental and Economic Accounting (Yu et al., 2009). In 2004, State Environmental Protection Administration and National Bureau of Statistics has jointly launched the Chinese Environmental and Economic Accounting in China. In the Chinese Environmental and Economic Accounting, the environmental degradation cost for each region has been calculated by using the average treatment cost as the lowest bound of the environment damage. In this paper, we also assumed that there were no differences in the damage caused by a specific pollutant in one region; therefore, the average provincial pollutant abatement cost, instead of sectoral abatement cost, was used to gauge the environmental damage in this study. We acknowledge that the simple average provincial pollutant abatement cost can't provide the precise producing and consuming relationship, but only as a proxy for the lowest bound for environmental damage for each region. By amending the data on the provincial pollutant abatement cost in 2004 with the GDP deflator, the average provincial pollutant abatement cost in 2007 was obtained, as shown in Table S4 (Wang et al., 2009).

3. Results

3.1. Emissions Embodied in Interregional Trade

In 2007, approximately 36.5% of COD emissions, 41.85% of NH₃-N emissions, 45.67% of SO₂ emissions and 47.6% of NO_x emissions were discharged in the production of commodities and services to meet the final consumption of regions in China through interregional trade, respectively. As shown in Figure 1, regions with much higher GDP per capita generally had higher consumption-based emissions than production-based emissions in 2007. Specifically, the more developed North Municipalities (i.e., Beijing–Tianjin), the East Coast, and the South Coast all consumed substantial emission-intensive products or services imported from other regions in both direct and indirect ways, mainly from the Central, the Northwest and the Southwest where the GDP per capita was much lower. In 2007, the North Municipalities transferred more than 80% of the consumption emissions for all four pollutants to other regions. Similarly, approximately 56.9% of COD emissions, 63.8% of NH₃-N emissions, 63.5% of SO₂ emissions and 55.5% of NO_x emissions embodied in commodities and services consumed in the East Coast occurred in other regions, respectively. To meet the requirements of the South Coast, 47.1% of COD emissions, 68.2% of NH₃-N emissions, 54.4% of SO₂ emissions and 63.5% of NO_x emissions were embodied in trade, respectively.

At the provincial level, Shanghai transferred the highest COD emissions, representing 2.35 times the amount of local emissions, to satisfy local consumption to other regions via interregional trade. The largest net importer of ammonia nitrogen and nitrogen oxide emissions is Guangdong, with 73.6% and 71.2% of consumption-based emissions occurred in other regions within China. Moreover, Zhejiang is the largest net SO₂ emissions importer, outsourcing approximately 437,543 tonnes of SO₂ emissions, equal to the total amount of emissions in Guizhou, to other regions through interregional trade. In contrast, the largest net

exporter of COD and ammonia nitrogen is Guangxi, which emitted the most water pollutants with regard to the interregional trade, mainly in the sectors of paper making and printing, food processing and tobacco. Due to the huge exports in the sectors of electricity and heat power, production of non-metallic mineral products, and metallurgy, Inner Mongolia ranked first in net exports of SO₂ and nitrogen oxide emissions.

A comparison of consumption-based emissions to production-based emissions for each region shows that although one region may be the net importer of one pollutant, the same region may be a net exporter of another pollutant. For example, in Inner Mongolia, the consumption-based emissions for COD, SO₂ and NO_x were 25%–64% less than the production-based emissions. With regard to ammonia nitrogen emissions, Inner Mongolia became a net emissions exporter, with net emissions of 0.02 kg per capita in other regions to meet the local consumption. In 2007, approximately 1936 tonnes of ammonia nitrogen emissions, representing 53% of the emissions in Inner Mongolia, were used to meet the development needs of other regions, mainly from the chemical industry (330 tonnes), food processing and tobaccos (626 tonnes), paper making, printing and stationery (165 tonnes) and metallurgy (281 tonnes). All of the commodities and services consumed in Inner Mongolia also produced 2396 tonnes of ammonia nitrogen emissions in other regions, especially from ammonia nitrogen emission-intensive sectors, such as the chemical industry (1060 tonnes), food processing and tobacco (319 tonnes) and paper making and printing (257 tonnes). Similar results using these two accounting methods can be observed in the cases of Sichuan, Hunan and Hubei; the differences between these two accounting methods are not significant. In consideration of the opposite results for the differences among various types of pollutants using the two accounting methods, it is

difficult to assess the environmental influence caused by the domestic supply chains. The results necessitate the simultaneous assessment of more than one pollutant when investigating how the emissions embodied in interregional trade shape China's environmental profile.

At the sector level, Figure 2 and Figure 3 highlight the sectors that contribute to the emissions of four major pollutants in interregional trade. We can observe that major contributors to China's embodied emissions for water pollutants are paper making, printing and stationery, the chemical industry, and food processing and tobacco. The sectors of electricity and heat power, the chemical industry, non-metallic mineral products, and metallurgy contribute the most to China's emissions for air pollutants. Specifically, 29.9%, 22.2% and 14.1% of the COD emissions embodied in interregional trade are attributable to paper making and printing, food processing and tobacco, and the chemical industry, respectively. With regard to the ammonia nitrogen emissions embodied in interregional exports, the contribution of the chemical industry (45.3%), food processing and tobacco (15.0%), and paper making and printing (10.0%) contribute nearly 70%. Moreover, nearly 8 million tonnes of SO₂ emissions were emitted in the production of commodities and services that were demanded by other regions in China, dominated by electricity and heating power (57.6%), metallurgy (12.1%), the production of non-metallic mineral products (7.1%) and the chemical industry (6.3%). Similarly, 4.66 million tonnes of nitrous oxide have been discharged, primarily from electricity and heating power (62.9%), the chemical industry (9.1%), metallurgy (9.0%) and the production of non-metallic mineral products (6.7%).

3.2. Environmental Damage Embodied in Interregional Trade

As shown above, the geographical separation of production and consumption caused by

interregional trade led to the presence of emission transfers. However, the emissions transferred via interregional supply chains may produce environmental damage to the export regions to various degrees. On the basis of data from Chinese Environmental and Economic Accounting, the total national environmental damage amounted to ¥95.4 billion in 2007, nearly 0.35% of the national GDP. Turning to the GDP growth from 2006 to 2007, environmental damage with regard to the domestic supply chains almost occupied 8% of the national GDP growth (at a constant price in 2007). Moreover, the environmental damage caused by emissions embodied in interregional trade can reach ¥43.8 billion, representing 45.9% of all the environmental damage that occurs at home to meet consumption in other regions. Disaggregating the environmental damage into four pollutant categories, nearly 34.71% of damage from COD emissions, 41.55% of damage from NH₃-N emissions, 46.91% of damage from SO₂ emissions and 47.96% of damage from NO_x emissions, were embodied in interregional trade, respectively.

In the comparison of the environmental damage from both the production and consumption perspectives, as shown in Figure 4, we can observe that the North Municipalities, the East Coast, and the South Coast greened the local GDP by outsourcing environmental damage via interregional trade in 2007. Regions with higher GDP per capita, mainly the North Municipalities, the East Coast, and the South Coast, were generally net importers of environmental damage due to the net emission inflows embodied in interregional trade. The East Coast was by far the largest net domestic importer of embodied environmental damage that occurred in other areas of China. The net embodied environmental damage import amounted to ¥4.1 billion, representing 0.07% of the regional GDP. Similarly, the North Municipalities and the South Coast transferred environmental damage equal to 0.18% and

0.06%, respectively, of the regional GDP to make the local development greener. In contrast, the main net domestic environmental damage receivers were mostly dominated by the less affluent provinces, such as the Northwest, Southwest and Central regions of China. In particular, to fulfill the demand of developed regions, such as the North Municipalities and the coast areas, the Northwest was the largest net exporter of the embodied environmental damage, amounting to ¥5.8 billion (Figure 4), followed by the Central region.

At the sector level, electricity and heating power was by far the largest contributor (55%) to environmental damage embodied in interregional trade, followed by metallurgy (9.7%), the chemical industry (9.1%), the production of non-metallic mineral products (5.6%), paper making, printing, and stationery (3.9%), and food processing and tobacco (3.7%). Especially for provinces in which the net exports of environmental damage are large, such as Inner Mongolia, Shanxi, Hebei and Henan, a majority of environmental damage was embodied in the energy-intensive heavy industries, such as electricity and heating power, metallurgy and the chemical industry (Figure 5). As the main coal and steel bases, the coal use in these regions accounted for more than 80% of the regional fuel mix, producing high net environmental damage exports.

It is noteworthy that the virtual abatement cost per unit of pollutant emission was chosen as the environmental damage per unit of pollutant in this study. When the total amount of net sectoral embodied environmental damage for each province is decomposed into four major pollutants, as shown in Figure S1-Figure S4, the total net damage was generally dominated by air pollutants. We acknowledge that this result is mainly caused by the lowest bound of environmental damage for unit pollutants. Therefore, in addition to the sectoral distribution in

the total net environmental damage, the net sectoral damage caused by COD and ammonia nitrogen emissions should also be given more attention. As shown in Figure S1 and Figure S2, food processing and tobacco, paper making, printing and stationery and the chemical industry contributed most to the net environmental damage caused by COD and ammonia nitrogen emissions. Hebei and Shanxi were the two largest net exporters of environmental damage caused by water pollutants, and this damage was mainly driven by the dominance of the production of the pulp and paper industry and the chemical industry. As the coal and resource base, the sectors of coal mining and metallurgy also contributed nearly 22% and 17% of the exported damage caused by COD and ammonia nitrogen, respectively. Due to the lower damage per unit of emissions, the largest net COD and ammonia nitrogen exporter, Guangxi, ranked third in terms of the net exporters of environmental damage caused by water pollutants. As the largest sugar producer, Guangxi has produced nearly 60% of the total national sugar output. Consequently, the processing of food is responsible for 66.5% and 50.2% of the export-related environmental damage caused by COD and ammonia nitrogen, respectively.

3.3. Interregional Environmental Damage Transfers

To further illustrate how interprovincial trade shapes the environmental profile in China, Figure 6 highlights transfers of environmental damage in interregional trades. We can observe that areas with higher per capita GDP generally have transferred environmental damage to the areas in the Central, Southwest and Northwest regions via interregional trade within China to make the local GDP much greener. Specifically, the North Municipalities, the North Coast and the East Coast are the main regions that have transferred environmental damage (as shown in Figure 6). In 2007, the East Coast regions transferred a total of ¥4.1 billion in environmental

damage to other regions in China, including ¥2.18 billion in environmental damage to the Central region, ¥1.77 billion to the Northwest region, ¥1.55 billion to the North Coast and ¥0.99 billion to the Northeast. The South Coast also had ¥2.6 billion in net embodied environmental damage inflows, which mainly originated from the Northwest (¥1.1 billion), the North Coast (¥0.9 billion), and the Central region (¥0.6 billion). Similarly, the North Municipalities transferred environmental damage totaling ¥2.5 billion to the Southwest (¥0.9 billion), Central (¥0.79 billion) and Northwest (¥0.63 billion) regions. The Northwest suffered most because of environmental damage from interregional trade. Specifically, the domestic consumption of the Northwest region produced only 24.5% of the total regional environmental damage, whereas the Northeast, North Municipalities, North Coast, East Coast, and South Coast contributed 21.54%, 12.71%, 16.76%, 19.74% and 7.01% of the total regional environmental damage, respectively.

Furthermore, as shown in Figure 4 and Figure 6, regions with higher environmental damage intensity (i.e., the share of production-based environmental damage to the local GDP) are generally net exporters of embodied environmental damage, whereas regions with greener GDP are generally net receivers of embodied environmental damage, rendering a disproportionate outsourcing of environmental damage from affluent regions in China and inequality in regional development. This phenomenon can be explained by the shift of regional development in the last several decades. In the 1990s and 2000s, to alleviate regional disparities, several government-sponsored regional development strategies, such as the "Western Development Strategy" and the "Rise of Central China Strategy", promoted a large amount of state funds to invest in infrastructure, energy and resource projects in those areas.⁴¹

Consequently, the Central and Northwest regions became energy and resource bases for economic development in China. Inner Mongolia can be viewed as a typical example of the Northwest. In 2007, approximately ¥4.2 billion in net embodied environmental damage, accounting for 13.1% of the local GDP growth (at a constant price in 2007), occurred in Inner Mongolia because of the final consumption of other regions in China. By comparing the environmental damage embodied in regional imports and exports, we can observe that the role of net environmental damage exporters in Inner Mongolia is mainly dominated by the energy-intensive heavy industry, especially electricity and heating power, metallurgy, coal mining, and the production of non-metallic mineral products, which contributed approximately ¥3.9 billion in net environmental damage exports.

4. Discussion

This study employed a MRIO model to calculate the environmental damage caused by four major pollutant emissions for each province in 2007 from both the production and consumption perspectives. In 2007, the environmental damage amounted to ¥95.4 billion, which hold at least 7.97% of the national GDP growth in 2007 (at a constant price). GDP has long been the primary and entrenched indicator of local government performance. However, ignorance of the environmental impacts and social costs of domestic development has made it increasingly difficult to use GDP as a measurement of human well-being (Bockstael et al., 2000; Costanza et al., 2014). Therefore, shifting officials' career achievement assessments from GDP-based measurements to a lifelong accountability system for ecological and environmental damage represents great progress. In the lifelong accountability system, Natural Capital Balance Sheet, which covers soils, air, water and other natural resources, will generally be used

as the accounting basis. However, considering the enormous ecological and environmental damage embodied in interregional trade, the importance of environmental damage from a consumer perspective should be integrated into the implementation of the new lifelong accountability system. In the future the compilation Natural Capital Balance Sheet, the environmental damage embodied in interregional trade can be taken into account to conduct a more comprehensive officials' career achievement assessments.

In 2007, nearly 45% of environmental damage could be ascribed to interprovincial trade flows in China. By outsourcing environmental damage to the Central and West regions, the affluent North Municipalities and Coastal areas generally moved toward a greener growth path. In other words, the developed North Municipalities and Coastal areas are partly responsible for environmental damage to the Central and West regions. In China, mandatory emission reduction targets have been set by the central government and disaggregated to the regional level since the 11th Five-Year Plan. Generally, the targets of the Central and West regions are lower than those in the developed regions. Subject to stricter binding targets, the developed coastal provinces may further transfer environmental damage to the less affluent regions to seek sustainable and steady growth. As mentioned above, the share of export-related environmental damage in developing provinces, especially the Central and Western regions, is much higher than that of the developed regions, rendering national pollutant control inefficient and regional development inequitable. The emission trading scheme has been tested in China for traditional pollutants such as COD, NH₃-N, SO₂ and NO_x. However, the reserved amount for emission trading is relatively small. Therefore, extending the scale of the emission trading scheme can effectively encourage transfers of advanced abatement technologies and funds from developed

regions to the Central and West regions.

At the sector level, we also observe that the major contributors to China's embodied damage from water pollutants are paper making, printing and stationery, the chemical industry, and food processing and tobacco. The major contributors to China's damage from air pollutants are electricity and heating power, the chemical industry, non-metallic mineral products, and metallurgy. These key emitters, especially the net damage exporters, should be highlighted in the future. The government should reinforce mandatory command and control policies, such as eliminating backward production capacity, elevating standards for emissions and promoting cleaner production for the key emitters. Moreover, economic instruments should be encouraged. For example, for energy- and resource-intensive regions, raising the energy price can play an effective role in controlling energy consumption and air emissions as well as related environmental damage.

It should be noted that, in this study, due to data limitations, only four major pollutants included in the nationwide quantity control were considered in this paper. As shown in this study and in the study by Steen-Olsen (Steen-Olsen et al., 2012), to further assess the sustainable challenge of regional development, additional dimensions of the environmental challenge should be considered in future work. Furthermore, the selection of the virtual abatement cost as a proxy for environmental damage underestimates the real loss caused by pollutant emissions, such as human health losses, harm to agriculture, forestry and fishery, and environmental degradation. Factoring all of the above-mentioned environmental damage into local development assessment can provide useful insights into national and regional sustainable development. Last but not the least, spatial and sector aggregation has significant effect on the

accuracy of results in the environmentally extended input-output analysis (Su and Ang, 2010; Su et al., 2010). Su and Ang (2010) found that estimates with more detailed regional information can have much more refined results. Lenzen (2011) and Steen-Olsen et al. (2014) also concluded that environmentally extended input-output analysis with higher sector disaggregation can be more representative of true situation. In this paper, estimates on the basis of 30-region input-output table can precisely hold true representations of Chinese economy. However, we should acknowledge that estimates at 30-sector level may be not the best option, MRIO tables at a disaggregate level for sectors, such as the MRIO tables constructed by Wang et al. (2015), which distinguished 30 regions and 135 industry sectors for each region from 1997 to 2011, can be employed to capture more detailed time-series information of China in the future work.

Acknowledgements

This paper was supported by the National Science Foundation of China (Grant Nos. 71403117, 71273004 & 71322303), Natural Science Foundation of Jiangsu Province (No. BK20130572), and the Outstanding PhD Candidate Program of Nanjing University (201601B011). We also appreciate the two anonymous reviewers for their constructive suggestions and comments.

References

- Atkinson, G., Hamilton, K., Ruta, G., Van Der Mensbrugghe, D., 2011. Trade in ‘virtual carbon’: Empirical results and implications for policy. *Global Environmental Change* 21, 563-574.
- Bockstael, N.E., Freeman, A.M., Kopp, R.J., Portney, P.R., Smith, V.K., 2000. On Measuring Economic Values for Nature. *Environmental Science & Technology* 34, 1384-1389.
- Bruckner, M., Giljum, S., Lutz, C., Wiebe, K.S., 2012. Materials embodied in international trade – Global material extraction and consumption between 1995 and 2005. *Global Environmental Change* 22, 568-576.
- Chen, Z., Wang, J.-N., Ma, G.-X., Zhang, Y.-S., China tackles the health effects of air pollution. *The Lancet* 382(9909), 1959-1960.
- Costanza, R., Kubiszewski, I., Giovannini, E., Lovins, H., McGlade, J., Pickett, K.E., Ragnarsdóttir, K.V., Roberts, D., Vogli, R.D., Wilkinson, R., 2014. Time to leave GDP behind. *Nature* 505, 283-285.
- EC(European Commission), FAO(Food and Agriculture Organization), IMF(International Monetary Fund), OECD(Organisation for Economic Co-operation and Development), UN(United Nations), WB(World Bank), 2012. System of Environmental Economic Accounting: Central Framework.
- Feng, K., Davis, S.J., Sun, L., Li, X., Guan, D., Liu, W., Liu, Z., Hubacek, K., 2013. Outsourcing CO₂ within China. *Proceedings of the National Academy of Sciences* 110, 11654-11659.
- Jiang, X., Zhang, Q., Zhao, H., Geng, G., Peng, L., Guan, D., Kan, H., Huo, H., Lin, J., Brauer, M., Martin, R.V., He, K., 2015. Revealing the Hidden Health Costs Embodied in Chinese Exports. *Environmental Science & Technology* 49, 4381-4388.
- Kanemoto, K., Moran, D., Lenzen, M., Geschke, A., 2014. International trade undermines national emission reduction targets: New evidence from air pollution. *Global Environmental Change* 24, 52-59.
- Lenzen, M., 2011. Aggregation versus disaggregation in input–output analysis of the environment. *Economic Systems Research* 23, 73-89.

- LGFNSP(Leading Group for the First Nationwide Survey of Polluters), 2008. Handbook of the Emission Coefficient for Residential Source for the First Nationwide Survey of Polluters.
- Liang, S., Zhang, C., Wang, Y., Xu, M., Liu, W., 2014. Virtual Atmospheric Mercury Emission Network in China. *Environmental Science & Technology* 48, 2807–2815.
- Lin, J., Pan, D., Davis, S.J., Zhang, Q., He, K., Wang, C., Streets, D.G., Wuebbles, D.J., Guan, D., 2014. China's international trade and air pollution in the United States. *Proceedings of the National Academy of Sciences* 111, 1736–1741.
- Liu, L.-C., Liang, Q.-M., Wang, Q., 2015a. Accounting for China's regional carbon emissions in 2002 and 2007: production-based versus consumption-based principles. *Journal of Cleaner Production* 103, 384-392.
- Liu, W., Chen, J., Tang, Z., Liu, H., Han, D., Li, F., 2012a. Theory and practice for compiling China's 2007 multi-regional input-output table containing 30 regions. China Statistics Press, Beijing.
- Liu, Z., Davis, S.J., Feng, K., Hubacek, K., Liang, S., Anadon, L.D., Chen, B., Liu, J., Yan, J., Guan, D., 2015b. Targeted opportunities to address the climate-trade dilemma in China. *Nature Climate Change* 6, 201–206.
- Liu, Z., Geng, Y., Lindner, S., Guan, D., 2012b. Uncovering China's greenhouse gas emission from regional and sectoral perspectives. *Energy* 45, 1059-1068.
- Matus, K., Nam, K.-M., Selin, N.E., Lamsal, L.N., Reilly, J.M., Paltsev, S., 2012. Health damages from air pollution in China. *Global Environmental Change* 22, 55-66.
- McGregor, P.G., Swales, J.K., Turner, K., 2008. The CO₂ 'trade balance' between Scotland and the rest of the UK: Performing a multi-region environmental input–output analysis with limited data. *Ecological Economics* 66, 662-673.
- Meng, B., Xue, J., Feng, K., Guan, D., Fu, X., 2013. China's inter-regional spillover of carbon emissions and domestic supply chains. *Energy Policy* 61, 1305-1321.
- MEP(Ministry of Environmental Protection), 2007. Dataset of Environmental Statistics in 2007.
- MEP(Ministry of Environmental Protection), 2014. Environmental injustice.
- MEP(Ministry of Environmental Protection), NBS(National Bureau of Statistics), 2011. Dataset of China's Polluter Census. China Environmental Science Press, Beijing.
- NBS(National Bureau of Statistic), 2008. China Energy Statistical Yearbook 2007. China

Statistics Press, Beijing.

NBS(National Bureau of Statistic), SEPA(State Environmental Protection Administration), 2008. China Environmental Statistical Yearbook 2007. China Statistics Press, Beijing.

Peters, G.P., Minx, J.C., Weber, C.L., Edenhofer, O., 2011. Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the National Academy of Sciences* 108, 8903-8908.

Politburo of China's Communist Party, 2013. Decision of the Central Committee of the Communist Party of China on Some Major Issues Concerning Comprehensively Deepening the Reform.

Pope III, C.A., Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K., Thurston, G.D., 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *Jama* 287, 1132-1141.

Prüss, A., Kay, D., Fewtrell, L., Bartram, J., 2002. Estimating the burden of disease from water, sanitation, and hygiene at a global level. *Environmental health perspectives* 110, 537-542.

Smith, W.H., 2012. Air pollution and forests: interactions between air contaminants and forest ecosystems. Springer Science & Business Media.

StateCouncil, 2015. Integrated Reform Plan for Promoting Ecological Progress.

Steen-Olsen, K., Owen, A., Hertwich, E.G., Lenzen, M., 2014. Effects of sector aggregation on CO₂ multipliers in multiregional input–output analyses. *Economic Systems Research* 26, 284-302.

Steen-Olsen, K., Weinzettel, J., Cranston, G., Ercin, A.E., Hertwich, E.G., 2012. Carbon, land, and water footprint accounts for the European Union: consumption, production, and displacements through international trade. *Environmental Science & Technology* 46, 10883-10891.

Su, B., Ang, B., 2010. Input–output analysis of CO₂ emissions embodied in trade: The effects of spatial aggregation. *Ecological Economics* 70, 10-18.

Su, B., Huang, H., Ang, B., Zhou, P., 2010. Input–output analysis of CO₂ emissions embodied in trade: The effects of sector aggregation. *Energy Economics* 32, 166-175.

Takahashi, K., Nansai, K., Tohno, S., Nishizawa, M., Kurokawa, J.-i., Ohara, T., 2014. Production-based emissions, consumption-based emissions and consumption-based health

- impacts of PM_{2.5} carbonaceous aerosols in Asia. *Atmospheric Environment* 97, 406-415.
- Van Dingenen, R., Dentener, F.J., Raes, F., Krol, M.C., Emberson, L., Cofala, J., 2009. The global impact of ozone on agricultural crop yields under current and future air quality legislation. *Atmospheric Environment* 43, 604-618.
- Wang, J., 2013. Forty Years of Environmental Protection in China: Lessons Learned and Future Targets, Forty Years of Environmental Protection in China and the World: Retrospect, Prospect and Institutional Innovation, Beijing.
- Wang, J., Cao, D., Yu, F., Jiang, H., Gao, M., 2009. Chinese Environmental and Economic Accounting Report 2004. China Environmental Science Press.
- Wang, Y., Geschke, A., Lenzen, M., 2015. Constructing a Time Series of Nested Multiregion Input–Output Tables. *International Regional Science Review* 38, 1-24.
- Wei, J., Guo, X., Marinova, D., Fan, J., 2014. Industrial SO₂ pollution and agricultural losses in China: evidence from heavy air polluters. *Journal of Cleaner Production* 64, 404-413.
- Wiedmann, T., Lenzen, M., Turner, K., Barrett, J., 2007. Examining the global environmental impact of regional consumption activities—Part 2: Review of input–output models for the assessment of environmental impacts embodied in trade. *Ecological Economics* 61, 15-26.
- Wiedmann, T.O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., Kanemoto, K., 2013. The material footprint of nations. *Proceedings of the National Academy of Sciences* 112, 6271-6276.
- Yu, F., Wang, J., Cao, D., Jiang, H., 2009. Guideline for Chinese Environmental and Economic Accounting. China Environmental Science Press.
- Zhang, Y., Wang, H., Liang, S., Xu, M., Liu, W., Li, S., Zhang, R., Nielsen, C.P., Bi, J., 2014. Temporal and spatial variations in consumption-based carbon dioxide emissions in China. *Renewable and Sustainable Energy Reviews* 40, 60-68.
- Zhao, H., Zhang, Q., Davis, S., Guan, D., Liu, Z., Huo, H., Lin, J., Liu, W., He, K., 2015a. Assessment of China's virtual air pollution transport embodied in trade by a consumption-based emission inventory. *Atmospheric Chemistry and Physics* 14, 5443–5456.
- Zhao, X., Liu, J., Liu, Q., Tillotson, M.R., Guan, D., Hubacek, K., 2015b. Physical and virtual water transfers for regional water stress alleviation in China. *Proceedings of the National Academy of Sciences* 112, 1031–1035.

**Figure 1 Comparison of production-based and consumption-based regional pollutant emissions
in 2007.**

Note: CBE in Figure 1 denotes the consumption-based emission for each pollutant in 2007. Regions on the horizontal axis are ranked according to the GDP per capita from left to right, and the top eight regions in GDP per capita are highlighted in the parallelograms.

Figure 2 Share of the water pollutant emissions embodied in interregional trade for each sector

Figure 3 Share of the air pollutant emissions embodied in interregional trade for each sector

Figure 4 Net embodied environmental damage flows and environmental damage intensity

Figure 5 Net sectoral environmental damage embodied in interregional trade for each province

Figure 6 Interregional environmental damage transfers within China.

Notes: The numbers expressed by arrows in the China map indicate the amounts of net flows of embodied environmental damage, and regions with the inlet in the map indicates the net importer of environmental damage embodied in the interregional trade within China. The circular figure, created from <https://d3js.org/> based on our calculated data, denotes the major interregional environmental damage transfers within China at the regional level. Lines in the circular graph are colored by exporting regions, with larger width representing larger environmental damage.