Environmental responsibility for sulfur dioxide emissions and associated biodiversity loss across Chinese provinces

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Abstract

Recent years have witnessed a growing volume in Chinese interregional trade, along with the increasing disparities in environmental pressures. This has prompted an increased attention on where the responsibilities for environmental impacts should be placed. In this paper, we quantify the environmental responsibility of SO_2 emissions and biodiversity impacts due to terrestrial acidification at the provincial level for the first time. We examine the environmental responsibility from the perspectives of production, consumption, and income generation by employing a Multi-Regional Input-Output (MRIO) model for 2007, 2010, and 2012. The results indicate that ~40% of SO_2 emissions were driven by the consumption in provinces other than where the emissions discharged. In particular, those developed provinces were net importers of SO_2 emissions and mainly outsourced their emissions to nearby developing provinces. Over the period of analysis, environmental inequality among 30 provinces was larger than GDP inequality. Furthermore, environmental inequality continued to increase while GDP inequality decreased over the time period. The results of a shared income- and consumption-based responsibility approach suggest that the environmental responsibility of SO_2 emissions and biodiversity impacts for developed provinces can reach up to ~4- to 93-fold the environmental pressure occurred within those provinces. This indicates that under these accounting principles the developed northern provinces in China would bear a much larger share of the environmental responsibility.

Capsule: We calculate the shared responsibilities for SO_2 emissions in China and find them to differ significantly from the production-based reduction targets set by governments.

Keywords: environmental inequality, impact assessment, multi-regional input-output analysis, responsibility sharing, soil acidification

1. Introduction

China has experienced rapid economic development over the last four decades. The GDP of China (at constant 2010 prices) increased from $264 billion to $9.50 trillion during 1997-2016, with an average annual growth rate of 9.6% (WB, 2018). However, this remarkable economic growth came at a cost of environmental damage. China has become one of the largest emitters of SO_2, NO_X, and greenhouse gases in the world (Liu et al., 2016; Meng et al., 2013). Along with ecological impacts, many emissions are linked to multiple health problems, including lung cancer (Tie et al., 2009), respiratory illness (Tao et al., 2014), and heart diseases (Wong et al., 2002), leading to a shorter life expectancy (Ebenstein et al., 2017). It has been estimated by Rohde & Muller (2015) that the air pollution contributed to 1.6 million deaths per year in China, roughly 17% of all deaths.

To mitigate environmental impacts, the Chinese government has promoted a series of measures, including increasing the share of non-fossil fuels (Yuan et al., 2018b), lowering CO_2 emission intensities (Cui et al., 2014), developing a trading scheme of carbon emissions (Wang et al., 2015), and formulating the accountability systems for local authorities (Schreifels et al., 2012). Although several environmental targets in China have been proposed at the national level, they are assigned to provinces according to the emissions of each province in policy formulation (Meng et al., 2011; Liu & Wang, 2017). However, the emissions discharged in one region are not necessarily driven by the local consumption only but by the demand from other regions as well through the interregional and international trade (Yuan et al., 2018c). Since China is a country with large regional disparities in the levels of economic development, resource endowment, and industrial development, such disparities may result in the emission transfers via the interprovincial trade: a spatial differentiation between direct emissions of production and indirect emissions of consumption. It was estimated by Wang et al. (2017) that ~45% of the environmental damage in 2007 in China was driven by the interprovincial trade. Moreover, the emissions embodied in interprovincial trade usually flow from developing to developed regions, making developed regions become net importers and developing regions become net exporters (Su and Ang, 2014; Wang et al., 2018; Yang et al., 2018b; Yuan et al., 2018a).

Considering these embodied emissions, an important debate is underway on the appropriate approaches to allocating the environmental responsibility. The production-based approach attributes full responsibility to the producers who benefit from the production of goods (e.g., the Kyoto protocol). On the contrary, the consumption-based approach attributes full responsibility to the final consumers who benefit from the consumption of goods (Davis & Caldeira, 2010; Peters, 2008). Since producers and consumers both benefit from the transactions along the value chain, these two responsibility allocation principles may be viewed as two extremes in a continuum (Sato, 2012). A compromise is the scheme of shared environmental responsibility, as a weighted combination of the production- and consumption-based responsibilities (Andrew and Forgie, 2008; Lenzen et al., 2007; Marques et al., 2012; Peters, 2008; Rodrigues et al., 2006; Rodrigues and Domingos, 2008). Besides, it is also possible to assign the responsibility to the earners of income from the production of goods (i.e., the income-based perspective) (Liang et al., 2017; Marques et al., 2012), and define the environmental responsibility as a combination of either of the three perspectives (production, consumption, and income) (Andrew and Forgie, 2008; Lenzen et al., 2007; Marques et al., 2012; Peters, 2008; Rodrigues et al., 2006; Rodrigues and Domingos, 2008).

For the case of China, it has been argued that some form of responsibility sharing is required for various emissions along value chains (Homma et al., 2012; Meng et al., 2013; Zhao et al., 2015). However, most of the studies focus on the production- and consumption-based approaches for China, and the studies on shared responsibility are conducted mainly at the national level (Andrew & Forgie, 2008) or at the sectoral level (Cadarso et al., 2012). This paper sets out, for the first time to the best of our knowledge, to apply a responsibility sharing approach to direct and indirect air pollution within China at the provincial level. We focus on SO_2 emissions and related terrestrial acidification impacts on biodiversity as the environmental indicators, since SO_2 is the precursor of ambient sulfate and plays a crucial role in the formation of acid rain and fine particles (Tao et al., 2012; Yan & Wu, 2017; Zhang et al., 2015). The sulfur deposition in soils and acidification can lower the pH, leach nutrients, and increase the bioavailability of toxic heavy metals (Kumar, 2017), which may further lead to changes in the ecosystem services of vegetation (Aherne & Posch, 2013; Lovett et al., 2009; Pandey et al., 2014). Particularly, China is facing a major threat to ecosystems since the sulfur deposition exceeds critical loads in many areas (Duan et al., 2016). In this paper, we investigate the changes of SO_2 emissions and biodiversity impacts due to the terrestrial acidification over time between 2007, 2010, and 2012. The responsibility sharing approach, the time series, the inclusion of biodiversity impacts, and the Gini coefficient analysis differentiate this work from the few earlier studies on SO_2 emissions and interprovincial trade (Huang et al., 2018; Zhang et al., 2018a, 2018b).

2. Materials and methods

2.1 Production and consumption-based environmental responsibility

In this paper we allocate the SO_2 emissions discharged in different regions of China in 2007, 2010, and 2012 by an input-output approach according to three perspectives (production-based, consumption-based, and income-based). Assuming that there are m regions and n sectors, the expression of monetary output flows in an input-output framework is:

$$x_i^r = \sum_{s=1}^{m} \sum_{j=1}^{n} z_{ij}^{rs} + \sum_{s=1}^{m} y_i^{rs} + ex_i^r \quad (1)$$

where x_i^r denotes the total output of sector i in region r, z_{ij}^{rs} denotes the intermediate requirement of sector j in region s from sector i in region r, y_i^{rs} denotes the final demand of region s from sector i in region r, and ex_i^r denotes the international exports of sector i in region r.

Since the total inputs and outputs of industries are identical, it is possible to formulate a similar expression for monetary input flows:

$$x_j^s = \sum_{r=1}^{m} \sum_{i=1}^{n} z_{ij}^{rs} + v_j^s + imp_j^s \quad (2)$$

where v_j^s is the primary inputs of sector j in region s and imp_j^s is the corresponding imports.

Furthermore, denoting S_i^r the SO_2 emissions of sector i in region r and S_h^r the SO_2 emissions from households in the same region, the production-based SO_2 emissions (PBE) of region r in this setting are the sum of emissions discharged in every production sector and household sector of that region:

$$PBE^r = \sum_{i=1}^{n} S_i^r + S_h^r \quad (3)$$

The consumption-based emissions are calculated using the Leontief model, which captures the upstream indirect impacts embodied in final demand along the supply chain (Miller & Blair, 1985). However, besides the emissions embodied in the final consumption of a region that originate either from that region or from other regions in China, there are three other types of SO_2 emissions that we need to address: (a) emissions discharged outside China but embodied in the final demand of China; (b) emissions discharged in China but embodied in the exports of China; (c) and emissions from households.

Because this paper focuses on comparing the responsibility for SO_2 emissions among Chinese regions we make the following methodological choices. Concerning (a) we do not allocate the emissions discharged outside China, as that would demand the data on international emissions and flows or apply the assumption of domestic technology for imported goods (Tang et al. , 2012; Zhao et al., 2015). Considering (b) we allocate the impacts embodied in exports to none of Chinese provinces but to the rest of the world (RoW). Concerning (c) we allocate the emissions from households to the region where the household consumption takes place.

Mathematically, the consumption-based SO_2 emissions (CBE) of region *s* are:

$$CBE^s = \sum_{r=1}^{m} \sum_{i=1}^{n} u_i^r \, y_i^{rs} + S_h^r \tag{4}$$

The first term on the right-hand side of Eq. (4) denotes the emissions embodied in the final demand of region *s*, which is calculated as the sum of the emissions embodied in the purchases of every product from every region by the final demand of region *s*. The second term accounts for the emissions from households. The consumption-based responsibility of the RoW for the emissions discharged within China is $\sum_{s=1}^{m} \sum_{i=1}^{n} u_i^s \, ex_i^s$.

The consumption-based (or upstream) emissions embodied in the final demand are quantified as the product of the upstream intensity (total SO_2 emissions discharged along the supply chain over unit of output) and the volume of final demand. By the Leontief model, the vector of upstream intensities, *u*, is calculated as:

$$u = b'(I - A)^{-1} \tag{5}$$

where b is the column vector of direct intensities, whose entries are $b_i^r = S_i^r / x_i^r$, b' denotes the transpose of b, $(I - A)^{-1}$ is the Leontief inverse matrix, and A is the technical coefficient matrix whose entries are $A_{ij}^{rs} = Z_{ij}^{rs} / x_j^s$.

Later, we will quantify the flows of upstream emissions embodied in the interregional trade, which requires disaggregating the total upstream embodied emissions according to their sources. The matrix of disaggregated upstream intensity U, whose entry U_{ij}^{rs} denotes the emissions discharged in sector i of region r per unit of output of sector j in region s, and is calculated as $U = \vec{b} \cdot (I - A)^{-1}$ where $\vec{b}$ is the diagonalized matrix of b. The flow of emissions from region r to region s is now:

$$CBE^{rs} = \sum_{k=1}^{m} \sum_{i=1}^{n} \sum_{j=1}^{n} U_{ij}^{rk} \, y_i^{ks} \tag{6}$$

Notice that it is possible for there to be emissions flowing from region r to region s through the purchase of final consumption goods produced in region k (but whose supply chain in turn leads to emissions in region r).

2.2 Terrestrial acidification and biodiversity loss

Terrestrial acidification is characterized by the changes in soil chemical properties and caused mainly by the atmospheric deposition of acidifying pollutants including NO_X, SO_2, and NH_3 (Roy et al., 2014). The acidification impacts of emissions can be assessed with the characterization factors obtained from a characterization model investigating the cause-effect chain of the emissions to the potential impacts (e.g., human health or biodiversity loss) (Udo de Haes et al., 2002). The characterization factor for terrestrial acidification is expressed as a function of (1) an atmospheric fate factor representing the link between emissions and deposition locations,

(2) a soil sensitivity factor representing the change of H^+ concentration in soil related to acid deposits over a certain area, and (3) an effect factor representing the loss of vascular plant species due to the change of H^+ concentration in soil (Azevedo et al., 2013; Roy et al., 2014).

To assess the terrestrial acidification caused by SO_2 emissions derived from the MRIO model, the LC-Impact model is applied, which is a spatially differentiated method for global impact assessment. Compared to previous methods of life cycle impact assessment, the LC-Impact method incorporates new impact pathways, includes spatial differentiation for 11 major environmental mechanisms, and quantifies impacts on ecosystem quality as potential global species loss (Verones et al., 2016). When assessing the terrestrial acidification caused by SO_2 emissions, the characterization factors of SO_2 emissions at grid level (2.0 x 2.5° resolution) are obtained from the LC-Impact webpage (LC-Impact, 2013). The zonal statistics are performed in GIS software to aggregate them to the provincial level, i.e., the raster map of characterization factors for SO_2 emissions is overlaid with the spatial information on provinces, and then the averages of all raster cells within each province are calculated.

2.3 Inequality analysis using the Gini coefficient

The Gini index is used to analyze the inequality of GDP, SO_2 emissions, and biodiversity impacts among 30 Chinese provinces (excluding Tibet, Hong Kong, Macau, and Taiwan). The Gini index has been widely used to investigate economic inequality (Gastwirth & Glauberman, 1976), and is increasingly used to analyze environmental inequality too (Dong and Liang, 2014; Jacobson et al., 2005; Luo et al., 2016; Sun et al., 2010).

When analyzing the inequalities of GDP, SO_2 emissions, and biodiversity impact, they are visualized in Lorenz curves where the ordinate values represent the cumulative share of GDP and the abscissa values represent the cumulative shares of population, SO_2 emissions, and biodiversity impacts, respectively. The Gini indices are calculated from the Lorenz curves, with a value of 0 indicating the complete equality of allocation and a value of 1 indicating the complete inequality of allocation (in the case of income, it means one individual accrues all the national wealth). The Gini index is estimated as:

$$\mathrm{Gini} = 1 - \sum_{r=1}^{30} (z_r - z_{r-1})(gdp_r - gdp_{r-1}) \qquad (7)$$

where z_r denotes the cumulative share of population (or SO_2 emissions and biodiversity impacts when calculating the Gini indices of SO_2 emission and biodiversity impact) in province r, gdp_r denotes the cumulative share of GDP in province r with convention that $z_0 = 0$ and $gdp_0 = 0$.

2.4 Income-based and shared environmental responsibility

In the same way as the Leontief model quantifies the indirect impacts occurring upstream along a supply chain, the Ghosh model quantifies the indirect impacts occurring downstream along a supply chain (Ghosh, 1958). The Leontief model can be used to account for the upstream emissions embodied in final demand, defining the consumption-based responsibility. Analogously, the Ghosh model can be used to account for the downstream emissions embodied in primary inputs, defining the income-based responsibility (Marques et al., 2012).

As in the case of consumption-based perspective, it is necessary to decide how to allocate the emissions embodied in international trade and from final demand among different regions. We follow the same routine and (a) ignore the emissions discharged outside China; (b) allocate the downstream emissions embodied in imports to the RoW; and (c) allocate the emissions from final demand to the region where the final consumption occurs.

Mathematically, the income-based SO_2 emissions (IBE) of region s are:

$$IBE^s = \sum_{i=1}^{n} d_i^s \, v_i^s + S_h^r \tag{8}$$

The new term $d_i^s$is the downstream intensity, calculated as:

$$d = (I - G)^{-1} b \tag{9}$$

where b is the column vector of direct intensities as in Eq. (5), $(I - G)^{-1}$ is the Ghosh inverse matrix, and G is the matrix of fixed sales coefficients whose entries are $G_{ij}^{rs} = Z_{ij}^{rs}/x_i^r$. The income-based responsibility of the RoW for the emissions discharged within China is $\sum_{s=1}^{m} \sum_{i=1}^{n} d_i^s \, imp_i^s$.

To calculate the shared responsibility of SO_2 emissions, we apply the indicator proposed by Rodrigues et al. (2006), whereby the environmental responsibility of a region is the average of its consumption-based and income-based emissions:

$$\frac{1}{2}(CBE^r + IBE^r) \tag{10}$$

Note that the current SO_2 reduction targets are assigned to provinces based on their total SO_2 emissions (a production-based approach).

2.5 Data Sources

We used the 30-province, 30-sector Chinese MRIO tables of 2007 (Liu et al., 2012), 2010 (Liu et al., 2014), and 2012 (Mi et al., 2017b). These tables are in the non-competitive form and deflated at 2012 constant prices. Furthermore, since the sectoral SO_2 emissions data are not available at the provincial level, they are estimated using the method proposed by Liu & Wang (2015) as $S_i^r = Q_i^r \cdot \beta_i^r \cdot (1 - \eta_i^r)$, where S_i^r is the sectoral SO_2 emissions (kg), Q_i^r is the coal consumption (kg), β_i^r is the sulfur content (%), and η_i^r is the SO_2 removal rate (%) of sector *i* for region *r*. The industrial and non-industrial SO_2 emissions for 30 provinces can be calculated by assuming that the sulfur content is constant across sectors but differs among provinces ($\beta_i^r = \beta_j^r = \beta^r$), and that the SO_2 removal rate is constant across provinces but differs among sectors ($\eta_i^r = \eta_i^s = \eta_i$, implying that the technology diffusion is equal across provinces). Note that the SO_2 removal rates might actually differ among provinces beyond differences in the industrial structure, as assumed here. The SO_2 scrubbers might be preferentially deployed in developed provinces or at large power plants. However, the necessary data to support these assumptions and include the differences in our analysis are not available.

China Emission Accounts and Datasets (CEADs) provides the coal consumption data (Shan et al., 2016, 2018). The data on SO_2 emissions, industrial SO_2 removal, population, and provincial GDP are obtained from the China Statistical Yearbook on Environment. Since the industrial SO_2 removal data in 2012 are not released yet, they are forecasted based on the data of 2001-2010 using exponential smoothing (Appendix A.3).

To maintain consistency in the classification of sectors, the 44 sectors with SO_2 emissions data and the 30 sectors in the MRIO tables are aggregated to 27 sectors, including 5 non-industrial sectors and 22 industrial sectors. The details on the sector aggregation are documented in Table S1, and the abbreviations for the 30 provinces are shown in Table S2.

3. Results

3.1 Production- and consumption-based SO_2 emissions

During the study period, the total SO_2 emissions increased from 25.8 Mt (million tons) in 2007 to 26.4 Mt in 2010 and then decreased to 22.5 Mt in 2012, consistent with the results obtained by Yang et al. (2018a). Figure S24 illustrates the production- and consumption-based

SO_2 emissions in 2007, 2010, and 2012, and also shows that the production-based emissions were higher than the consumption-based emissions in most provinces since a large part of emissions embodied in consumption leaked to the RoW. During 2007-2012, ~17.1-23.9% of the emissions can be attributed to the RoW. Furthermore, ~64% of the emissions embodied in the RoW occurred in five coastal provinces, namely, Guangdong, Jiangsu, Zhejiang, Shandong, and Shanghai.

Figure S24 also shows that the intra-provincial and inter-provincial consumption varied among different provinces. It is worth noting that the intra-provincial consumption in developed provinces accounted for only a small part of the total consumption-based emissions. For example, the intra-provincial consumption in Beijing, Tianjin, and Shanghai only accounted for 18.8%-39.1% of the total consumption-based emissions. However, in some developing provinces with energy-intensive industries (e.g., Inner Mongolia, Shanxi, and Guizhou), the intra-provincial consumption contributed most to the total consumption-based emissions. Besides, the proportion of intra-provincial consumption showed different trends in some neighboring provinces. For example, the proportion of intra-provincial consumption in Beijing indicated a decreasing trend, from 31.1% in 2007 to 21.7% in 2010, and then to 14.1% in 2012. However, the proportions of intra-provincial consumption in nearby Tianjin and Hebei kept rising during the same time period. Such a pattern among Beijing-Tianjin-Hebei area might be due to the provincial transfer of industries after 2007, when some heavily polluting industries in Beijing were relocated to Tianjin and Hebei (Zheng et al., 2018).

3.2 Inflows and outflows of SO_2 emissions

Figure S25 shows the provincial inflow and outflow of SO_2 emissions through the inter-provincial trade within China in 2007, 2010, and 2012. During the study period, ~37.3%-38.8% of the emissions were generated by the consumption of other provinces. Furthermore, for some developed provinces, e.g., Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, and Guangdong, the inflows were much larger than the outflows. For example, the inflows of SO_2 emissions in Beijing were ~9.9-, 18.2-, and 10.3-fold the outflows in 2007, 2010, and 2012, respectively. On the contrary, for some developing provinces, e.g., Shanxi, Inner Mongolia, Henan, Anhui, and Guizhou, the outflows were much larger than the inflows. For example, the outflows of SO_2 emissions in Inner Mongolia were ~6.5-, 2.3-, and 2.7-times the inflows in those years.

3.3 SO_2 emissions embodied in interregional trade

From the analysis above, there are evident spatial differences between inflows and outflows of SO_2 emissions. To facilitate the visualization of these flows, the 30 provinces are aggregated into eight regions (Feng et al., 2013; Wang et al., 2017, see Figure S1 for details). The SO_2 emissions embodied in interregional trade in 2007, 2010, and 2012 are documented in Figure S26, Figure S27, and Figure S28, respectively.

Figure 1 shows that the Northwest, Southwest, and Central regions had the largest emissions during the study period. However, a considerable proportion of the emissions of these three regions were generated by the consumption in other regions. Besides, the developed Jing-Jin, East Coast, and South Coast regions were the main net importers of emissions, while the less developed Northwest, Southwest, and Central regions were net exporters of emissions. In 2007, the Jing-Jin, East Coast, and South Coast regions outsourced between 0.60 and 1.54 Mt to other regions, which slightly increased in 2010. Although the inflows of these three regions decreased in 2012, they were still much higher than the respective outflows, ~2.1-5.9 times. In 2007, between 1.19 and 1.69 Mt of SO_2 emissions generated in the Central, Northwest, and Southwest regions were embodied in products traded to other regions, accounting for ~21.7-36.3% of the total production-based emissions. The outflows of these three regions slightly fluctuated in 2010 and 2012.

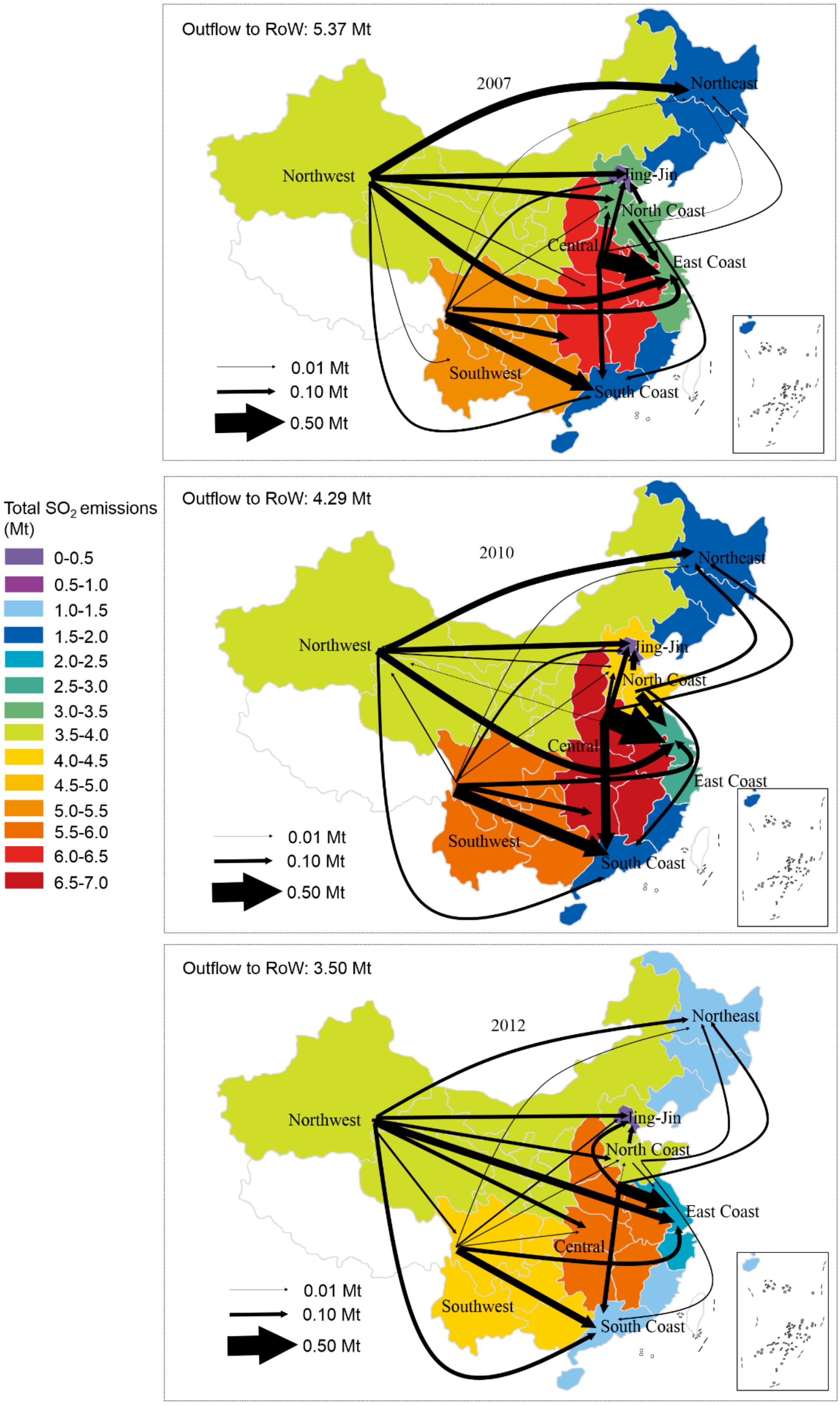


Figure 1. Net transfers of SO_2 emissions of eight regions in China

Figure 1 also illustrates that the largest flow of SO_2 emissions was from the Central region to the East Coast region, followed by the flow from the Southwest to the South Coast, and that from the Northwest to the East Coast. During the study period, ~59-71% of emissions in the Central region can be attributed to the consumption of East Coast. The South Coast region predominately outsourced the emissions to the Southwest region, and ~39-53% of the inflows to the South Coast were from the Southwest region. At the provincial level, Guangdong was the main province in the South Coastal region outsourcing SO_2 emissions to the Southwest. Besides the Central region, the Northwest region, particularly Gansu, Shaanxi, and Inner Mongolia, was also another main destination to which the East Coast outsourced SO_2 emissions. Figure 1 also demonstrates that the outflows from the Central region to the South Coast region increased significantly in 2010, mainly due to the outflows from Jiangxi to Guangdong. More details about the net transfers are documented in Table S4, Table S5, and Table S6, respectively.

It is also worth noting that most provinces outsourced SO_2 emissions to their neighboring provinces. For example, Beijing and Tianjin mainly outsourced the emissions to Hebei and Inner Mongolia. Shanghai, Jiangsu, and Zhejiang, the three developed provinces in the east, mainly outsourced the emissions to nearby regions like Shandong, Henan, and Anhui. In the south, Guangdong mainly outsourced the emissions to Guizhou and Yunnan.

3.4 Biodiversity impacts at provincial level

Figure 2 demonstrates the biodiversity impacts caused by SO_2 emissions for each province. During the study period, the three provinces, Xinjiang, Sichuan, and Fujian, suffered most from the biodiversity loss indicated by the high values of the characterization factors in these provinces, which can be attributed mainly to the atmospheric fate and soil sensitivity factors (Roy et al., 2014). Therefore, the severe biodiversity loss in these three provinces might be due to the proximity of the receptor and the source of SO_2 emissions and the high levels of soil acidification in these three provinces. Furthermore, the biodiversity losses of Sichuan and Fujian reduced during 2010-2012, while the biodiversity loss of Xinjiang increased rapidly during the same period. Besides, the biodiversity loss due to terrestrial acidification in China showed an obvious spatial disparity, with the most severe loss occurred mainly in the western and central regions, and much lower loss occurred in the eastern regions.

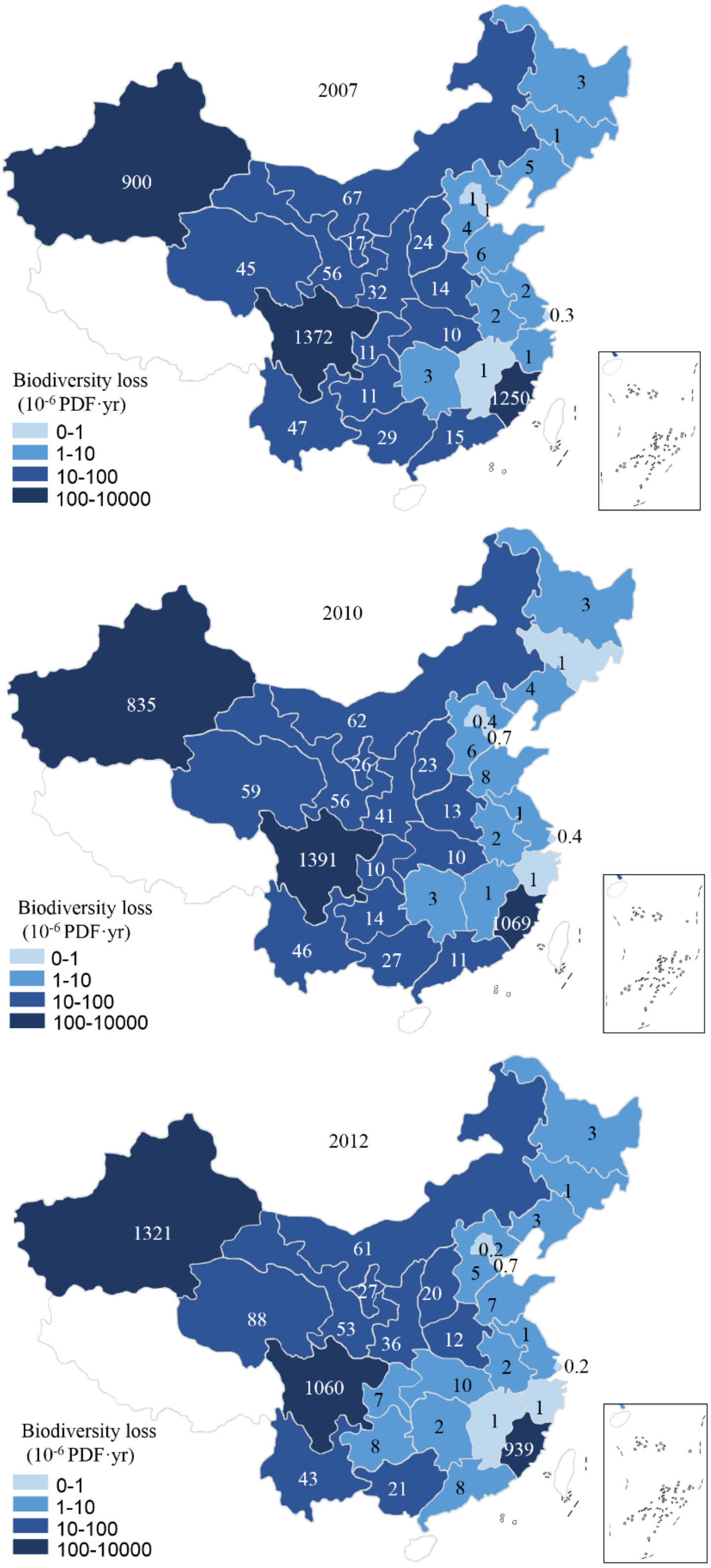


Figure 2. Biodiversity loss due to terrestrial acidification at provincial level (PDF in the legend means "potentially disappeared fraction of species" and the numeric values on the maps indicate

the biodiversity loss of each province).

3.5 Regional environmental inequality

From Figure 1 and Figure 2, we find that both the SO_2 emissions and the biodiversity loss displayed regional disparities during the study period. Considering that the embodied emission flows were mainly from developing regions to developed regions, the economic inequalities were likely reflected in environmental inequalities. Hence, the Lorenz curves and Gini indices of GDP, SO_2 emissions, and biodiversity loss are illustrated in Figure 3. During 2007-2010, the inequality of SO_2 emissions remained more or less static, but slightly increased during 2010-2012. Furthermore, the inequality of SO_2 emissions was larger than that of GDP. The changing pattern of SO_2 emissions inequality was in contrast to that of GDP inequality, consistent with Clarke-Sather et al. (2011) who found that carbon inequality and income inequality in China showed inverse trends during 1997-2007. Compared to SO_2 emissions and GDP, the biodiversity loss in 2007, 2010, and 2012 showed the largest degrees of inequality, with Gini coefficients of ~0.9.

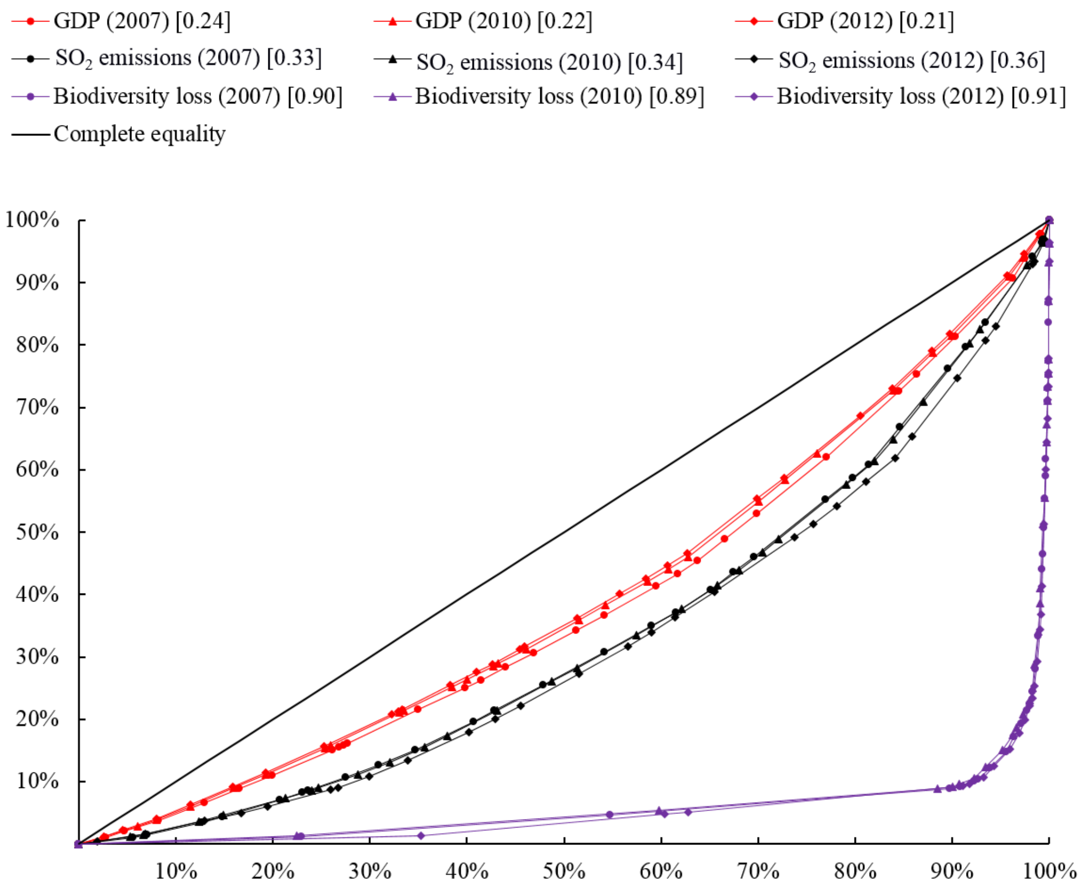


Figure 3. Lorenz curves of population, SO_2 emissions, and biodiversity loss relative to GDP

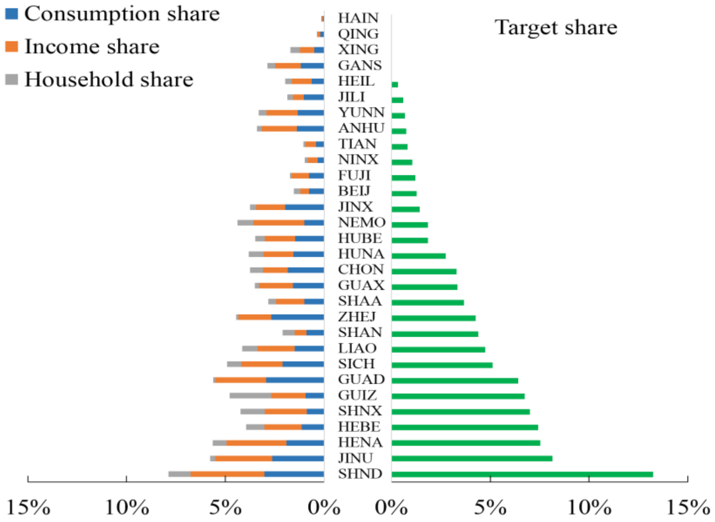
(The numbers in brackets indicate the respective Gini values)

3.6 Shared income and consumer responsibility

We now investigate the shared environmental responsibilities of SO_2 emissions and associated biodiversity loss at the provincial level. When the income-generating provinces share the responsibility with the consuming provinces, we find a similar pattern of provincial allocation of environmental responsibility as that under the consumption-based accounting. Under the shared responsibility approach, the RoW would bear ~15% responsibility of the total SO_2 emissions and only 7 out of 30 provinces would bear more responsibility than the production-based emissions discharged in their own territory. Furthermore, these 7 provinces are mainly developed Jing-Jin regions and developing northeastern regions (e.g., Heilongjiang, Jilin). When concerning the biodiversity loss caused by SO_2 emissions, only a few provinces would bear less responsibility, e.g., Sichuan, Fujian, Xinjiang, and Qinghai. Further details about the shared environmental responsibility of SO_2 emissions and associated biodiversity loss are documented in Table S7 and Table S8.

Figure 4 and Figure 5 show the contribution of consumption, income, and household consumption to the environmental responsibility of SO_2 emissions and biodiversity loss. As illustrated in Figure 4, the consumption contributed most to the environmental responsibility for developed regions, e.g., Beijing, Shanghai, and Zhejiang. However, for developing regions, the income contributed most to the shared responsibility, e.g., Shanxi, Yunnan, and Heilongjiang. These regions showed a similar pattern when assessing the environmental responsibility for biodiversity loss. In contrast to other provinces that would bear less responsibility, the household consumption in Xinjiang contributed a relatively large part to the final responsibility for biodiversity loss (Figure 5).

The current pollution control targets in China are designed by the national government and then assigned to each province. We may assess the fairness of the current allocation scheme of SO_2 reduction targets among provinces under the shared responsibility principle by comparing the provincial share in the allocation of environmental responsibility with the pollution reduction target. The latest reduction targets for SO_2 emissions on the provincial level were designed for 2010 according to the 2005 levels. The provincial shares of SO_2 reduction in the policy are calculated based on the provincial reduction targets for SO_2 emissions, as shown in Table S9. The comparison between the provincial shares of environmental responsibility and the reduction targets is conducted in Figure 4. The results indicate that the reduction targets of some provinces fall behind their estimated environmental responsibility for SO_2 emissions, e.g., Beijing, Tianjin, and Inner Mongolia. For some other provinces, e.g., Shanxi, Shanghai, and Jiangsu, the reduction targets exceeded the environmental responsibility.



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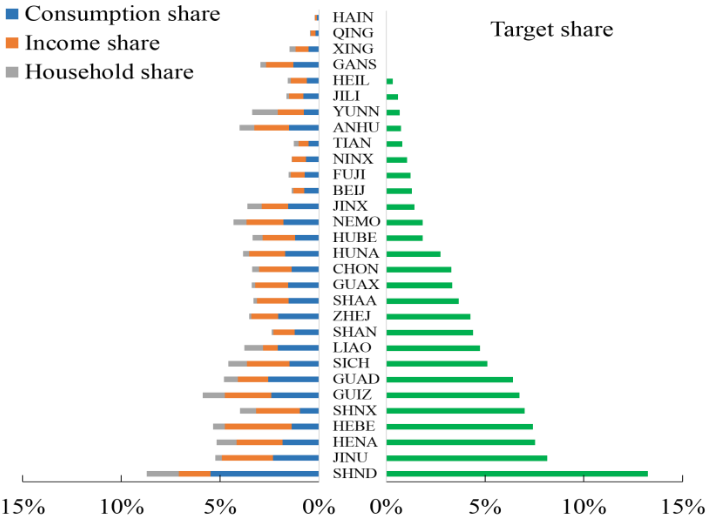

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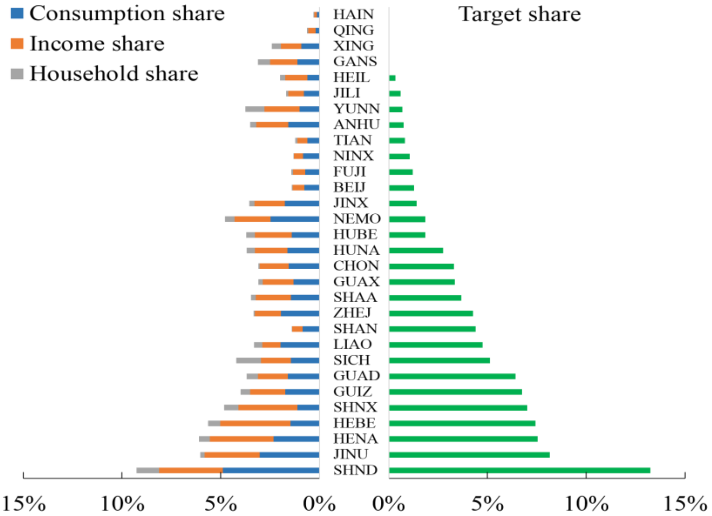
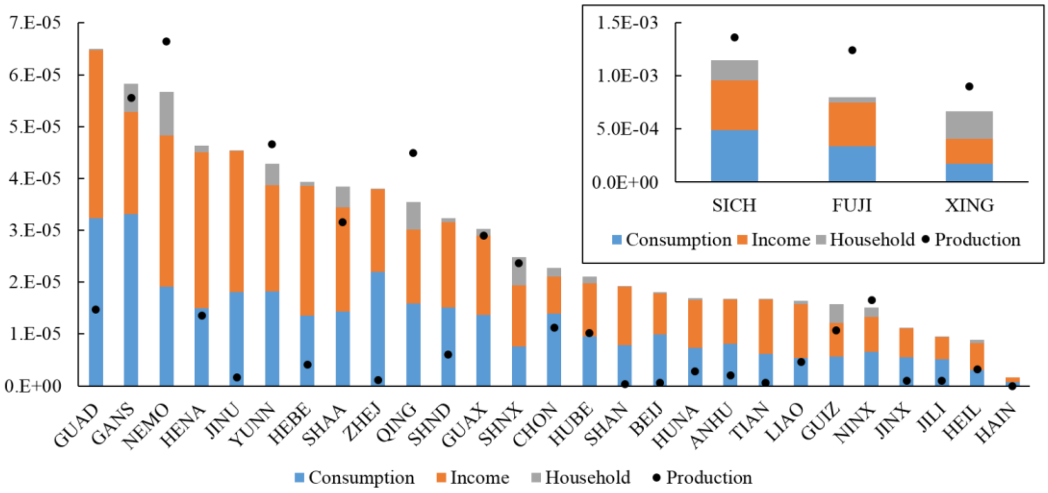


2012

Figure 4. Comparison of provincial responsibility shares and reduction shares in 2010



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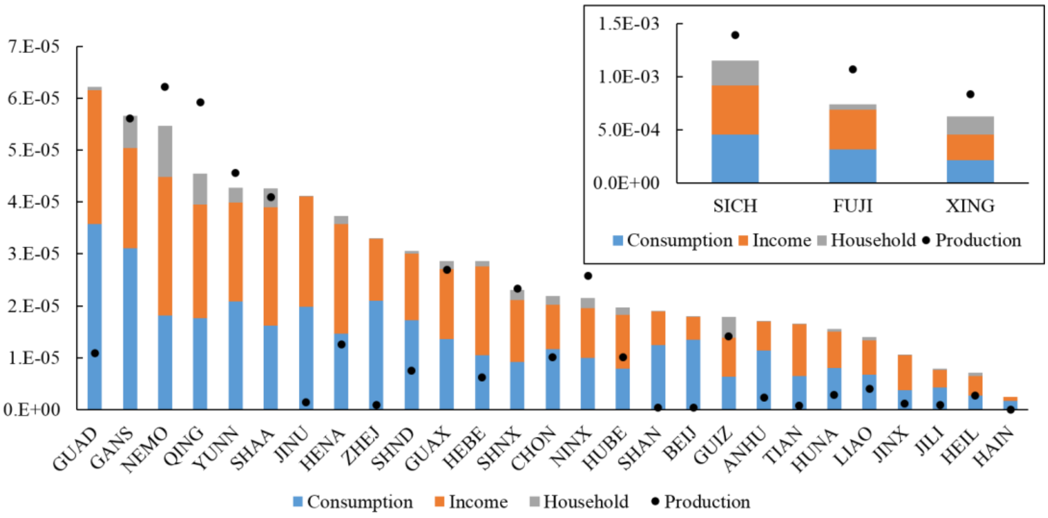
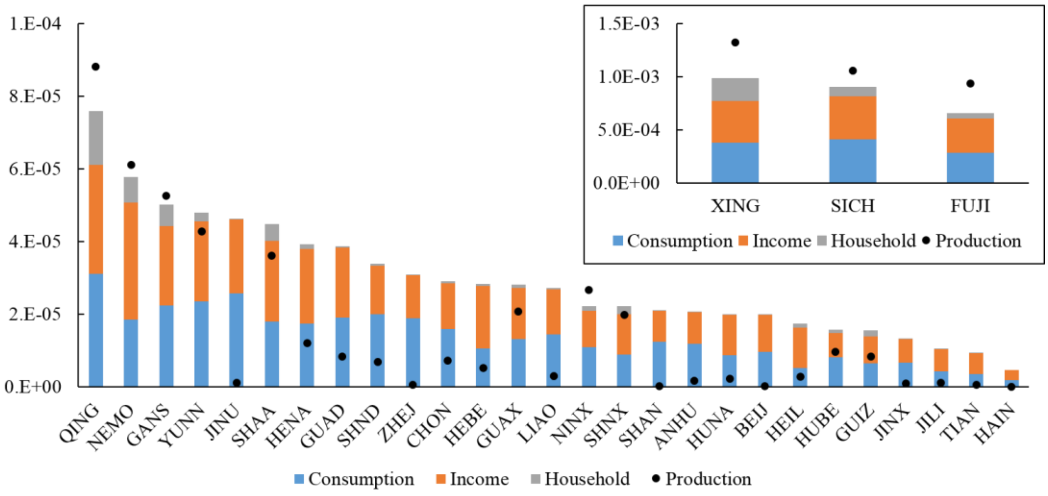


2010



2012

Figure 5. Provincial responsibility for the biodiversity loss caused by terrestrial acidification (Unit: PDF·yr)

4. Discussion

Our results showed that the developed provinces had larger outflows than inflows of SO_2 emissions and mainly outsourced emissions to those developing provinces with energy-intensive industries, especially to their neighboring developing provinces. Under a shared income- and consumption-based responsibility approach, some developed provinces would bear more emission responsibility than that under the production-based accounting method. Furthermore, the developing provinces mainly acted as resource suppliers in the domestic supply chain, especially in the energy intensive sectors (e.g., coal mining, chemistry, metallurgy, and electricity). The developed provinces, however, mainly acted as final consumers rather than resources suppliers, especially in the construction and service sectors (Figure S29, Figure S30).

However, the responsibility of SO_2 emissions and associated biodiversity loss showed different patterns. Only a few provinces would bear more responsibility for SO_2 emissions, while most provinces would bear more responsibility for biodiversity loss. The large differences of biodiversity effects among regions were mainly due to the variations in the distances between emissions and deposition, the buffer capacity, and the plant species sensitivity.

When comparing biodiversity loss to SO_2 emissions, Xinjiang, Sichuan, and Fujian suffered most as indicated by the high values of the characterization factors in these provinces. Furthermore, the household consumption in Xinjiang accounted for ~38.9%, 26.8%, and 22.2% of the total responsibility in 2007, 2010, and 2012, larger than the corresponding proportions in other provinces, indicating that improving the energy efficiency in household consumption could be an efficient way to lower the SO_2-related biodiversity loss in Xinjiang.

Our analysis also showed that the Gini indices of GDP and SO_2 emissions have the opposite temporal trends during the period 2007-2012, consistent with the research by Clarke-Sather et al. (2011) investigating the relationship between income and carbon emissions. However, our analysis revealed that the inequality of SO_2 emissions exceeded GDP inequality while the inequality of carbon emissions was lower than income inequality as shown in Clarke-Sather et al. (2011). According to Chen et al. (2016), the differences of interprovincial carbon emissions from coal in China were greater than that from fossil fuels. Considering that coal combustion accounts for ~72% of the total energy consumption in China and is the main source of SO_2 emissions (Yang et al., 2016), the SO_2 emission differences were greater than the GDP differences. A distinct characteristic in the inequality analysis is that the biodiversity impact inequality was far greater than GDP and SO_2 inequalities, because the biodiversity loss in Xinjiang, Sichuan, and Fujian was much more severe than in other provinces.

The impacts of other acidifying pollutants (NOx and NH_3) and of pollutant interactions on terrestrial biodiversity may be investigated in an analogous manner. In addition, the impacts on aquatic ecosystems and on human health deserve more research attention.

5. Conclusions

Using a MRIO model, this paper conducted a quantification of the shared responsibility for SO_2 emissions and associated biodiversity loss for 30 provinces in China for 2007, 2010, and 2012. The results showed that the developed provinces caused more SO_2 emissions through consumption than through production, while the opposite applied to the developing provinces. Under the shared responsibility principle, the rest of the world would bear ~15% responsibility of the total SO_2

emissions in China. Some developed northern provinces (e.g., Beijing, Tianjin) and developing northeastern provinces (e.g., Heilongjiang, Jilin) would bear more responsibility for SO_2 emissions. Other provinces, especially those with energy-intensive industries, would bear less responsibility for SO_2 emissions. For example, the responsibility for SO_2 emissions in Beijing was ~1.8-, 2.4-, and 3.6-times the actual emissions in 2007, 2010, and 2012. However, the responsibility for SO_2 emissions in Inner Mongolia was only 69.7%, 77.4%, and 75.6% of the actual emissions.

Compared to SO_2 emissions, biodiversity loss was much more unequal within 30 provinces in China, with Gini coefficients of about 0.9. The provinces that suffered from severe biodiversity loss, e.g., Sichuan, Fujian, and Xinjiang, would bear less environmental responsibility. Furthermore, the differences between environmental responsibility and biodiversity loss occurred within the provinces were even larger. For example, in Xinjiang, the environmental responsibility for biodiversity loss was ~73.8%, 74.6%, and 74.9% of the biodiversity loss occurred within the province in 2007, 2010, and 2012. However, in Shanghai, the responsibility for biodiversity loss was ~58-, 54-, and 93-fold the biodiversity loss occurred within the province.

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Appendix

A.1. Sector classification

Table S1. Sector classification

	Coal consumption (44 sectors)	MRIO (30 sectors)	Aggregates sectors (27 sectors)
1	Farming, Forestry, Animal Husbandry, Fishery & Water Conservancy	Agriculture	Agriculture
2	Coal Mining and Dressing	Coal mining	Coal mining
3	Petroleum and Natural Gas Extraction	Petroleum and Gas	Petroleum and Gas
4	Ferrous Metals Mining and Dressing Nonferrous Metals Mining and Dressing	Metal Mining	Metal Mining
5	Nonmetal Minerals Mining and Dressing Other Minerals Mining and Dressing	Nonmetal Mining	Nonmetal Mining
6	Food Processing Food Production Beverage Production Tobacco Processing	Food Processing and Tobaccos	Food Processing and Tobaccos

7	Textile Industry	Textile	Textile
8	Garments and Other Fiber Products Leather, Furs, Down and Related Products	Clothing, Leather, Fur, etc.	Clothing, Leather, Fur, etc.
9	Timber Processing, Bamboo, Cane, Palm & Straw Products Furniture Manufacturing	Wood Processing and Furnishing	Wood Processing and Furnishing
10	Papermaking and Paper Products Printing and Record Medium Reproduction	Paper Making, Printing, Stationery, etc.	Paper Making, Printing, Stationery, etc.
11	Petroleum Processing and Coking	Petroleum Refining, Coking, etc.	Petroleum Refining, Coking, etc.
12	Raw Chemical Materials and Chemical Products Medical and Pharmaceutical Products Chemical Fiber Rubber Products Plastic Products	Chemical Industry	Chemical Industry
13	Nonmetal Mineral Products	Nonmetal Products	Nonmetal Products
14	Smelting and Pressing of Ferrous Metals Smelting and Pressing of Nonferrous Metals	Metallurgy	Metallurgy
15	Metal Products	Metal Products	Metal Products

16	Ordinary Machinery Equipment for Special Purpose	General and Specialist Machinery	General and Specialist Machinery
17	Transportation Equipment	Transport Equipment	Transport Equipment
18	Electric Equipment and Machinery	Electrical Equipment	Electrical Equipment
19	Electronic and Telecommunications Equipment	Electronic Equipment	Electronic Equipment
20	Instruments, Meters Cultural and Office Machinery	Instrument and meter	Instrument and meter
21	Other Manufacturing Industry Scrap and waste	Other Manufacturing	Other Manufacturing
22	Electric Power, Steam and Hot Water Production and Supply	Electricity and Hot Water Production and Supply	Electricity and Hot Water Production and Supply
23	Gas Production and Supply Tap Water Production and Supply	Gas and Water Production and Supply	Gas and Water Production and Supply
24	Construction	Construction	Construction
25	Transport, Storage, Postal & Telecommunications Services	Transport and Storage	Transport and Storage
26	Wholesale, Retail Trade and Catering Service	Wholesale and Retailing Hotel and Restaurant	Wholesale, Retail Trade and Catering Service
27	Other	Leasing and Commercial Services Scientific Research Other Services	Other Services

A.2. Abbreviation of 30 provinces and classification of eight regions in China

Table S2. Abbreviation of 30 provinces in China

Name	Abb.	Name	Abb.	Name	Abb.
Beijing	BEIJ	**Zhejiang**	ZHEJ	**Hainan**	HAIN
Tianjin	TIAN	**Anhui**	ANHU	**Chongqing**	CHON
Hebei	HEBE	**Fujian**	FUJI	**Sichuan**	SICH
Shanxi	SHNX	**Jiangxi**	JINX	**Guizhou**	GUIZ
Inner Mongolia	NEMO	**Shandong**	SHND	**Yunnan**	YUNN
Liaoning	LIAO	**Henan**	HENA	**Shaanxi**	SHAA
Jilin	JILI	**Hubei**	HUBE	**Gansu**	GANS
Heilongjiang	HEIL	**Hunan**	HUNA	**Qinghai**	QING
Shanghai	SHAN	**Guangdong**	GUAD	**Ningxia**	NINX
Jiangsu	JINU	**Guangxi**	GUAX	**Xinjiang**	XING

Figure S1. Eight regions of China

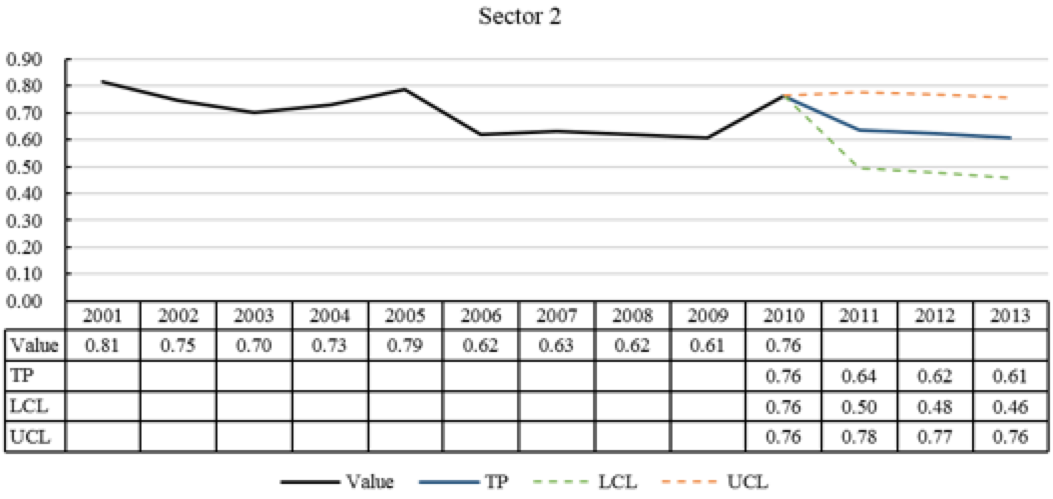
A.3 Prediction of $(1-\eta_i)$ *values in 2012*

The $(1-\eta_i)$ values in 2012 are estimated by exponential smoothing according to the values during 2001-2010 with some obvious outliers excluded by visual inspection. The results are shown in Table S3. Figure S2 to Figure S23 illustrate the values of $(1-\eta_i)$, the trend prediction (TP) values, the lower confidence limits (LCL), and the upper confidence limits (UCL) based on the standard deviation for the 22 industrial sectors (from sector 2 to sector 23 in Table S1) during 2001-2010, respectively.

Table S3. Prediction of $(1-\eta_i)$ values in 2012

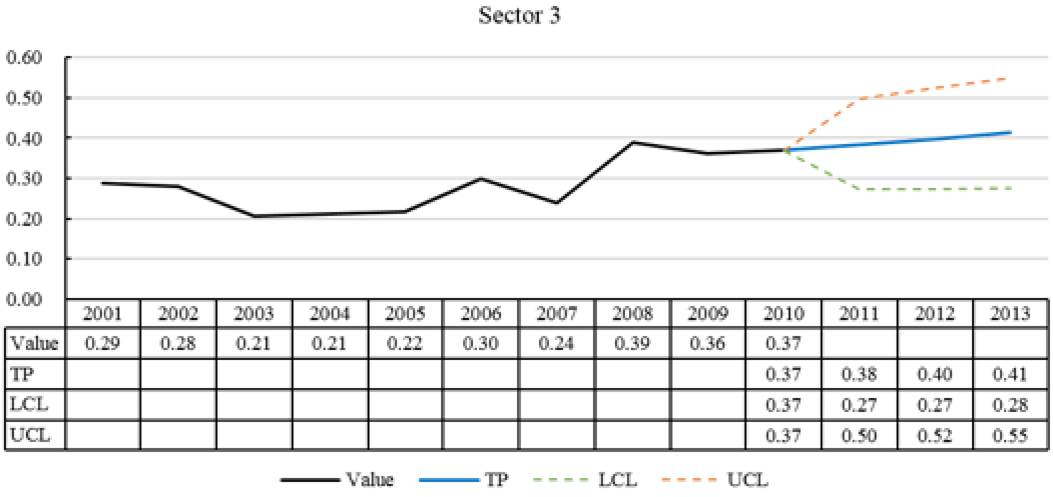
Sector	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2012
2	0.81	0.75	0.70	0.73	0.79	0.62	0.63	0.62	0.61	0.76	0.62
3	0.29	0.28	0.21	0.21	0.22	0.30	0.24	0.39	0.36	0.37	0.40
4	0.72	0.58	0.55	0.65	0.57	0.63	0.57	0.32	0.23	0.22	0.17
5	0.76	0.77	0.74	0.62	0.35	0.87	0.69	0.71	0.64	0.66	0.63
6	0.80	0.80	0.75	0.70	0.72	0.72	0.74	0.73	0.69	0.69	0.67
7	0.81	0.79	0.76	0.80	0.77	0.77	0.77	0.72	0.71	0.71	0.70
8	0.80	0.76	0.78	0.82	0.75	0.78	0.76	0.76	0.75	0.80	0.77
9	0.85	0.77	0.79	0.84	0.82	0.88	0.92	0.83	0.85	0.83	0.87
10	0.85	0.74	0.73	0.74	0.72	0.68	0.71	0.70	0.66	0.69	0.65
11	0.51	0.43	0.42	0.46	0.44	0.33	0.27	0.24	0.21	0.21	0.12
12	0.63	0.61	0.62	0.64	0.54	0.60	0.59	0.54	0.49	0.46	0.45
13	0.90	0.85	0.83	0.82	0.78	0.80	0.81	0.82	0.79	0.81	0.79
14	0.30	0.28	0.79	0.29	0.31	0.27	0.26	0.23	0.21	0.24	0.21
15	0.83	0.80	0.13	0.86	0.82	0.74	0.15	0.85	0.83	0.77	0.79
16	0.79	0.74	0.70	0.74	0.70	0.58	0.71	0.76	0.75	0.65	0.68
17	0.75	0.77	0.72	0.77	0.73	0.67	0.74	0.70	0.69	0.67	0.66

18	0.80	0.76	0.82	0.81	0.76	0.91	0.82	0.71	0.71	0.67	0.70
19	0.69	0.86	0.77	0.74	0.70	0.62	0.77	0.65	0.62	0.63	0.59
20	0.75	0.68	0.71	0.79	0.85	0.94	0.81	0.77	0.71	0.56	0.54
21	0.80	0.81	0.75	0.85	0.81	0.83	0.88	0.84	0.77	0.67	0.69
22	0.90	0.89	0.89	0.85	0.82	0.74	0.58	0.50	0.39	0.32	0.15
23	0.73	0.77	0.77	0.80	0.71	0.74	0.78	0.68	0.72	0.58	0.61



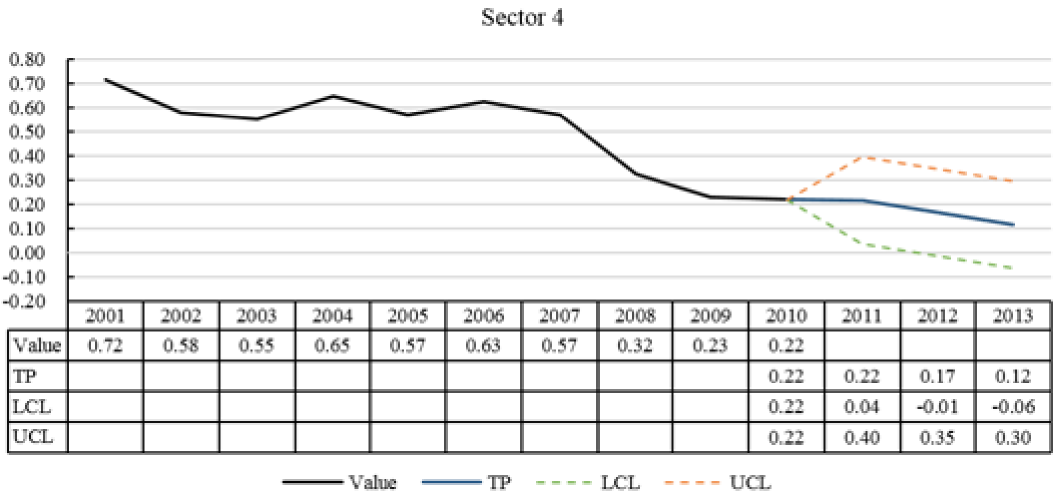
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Value	0.81	0.75	0.70	0.73	0.79	0.62	0.63	0.62	0.61	0.76			
TP										0.76	0.64	0.62	0.61
LCL										0.76	0.50	0.48	0.46
UCL										0.76	0.78	0.77	0.76

Figure S2. Prediction of $(1-\eta_i)$ value for Sector 2 in 2012



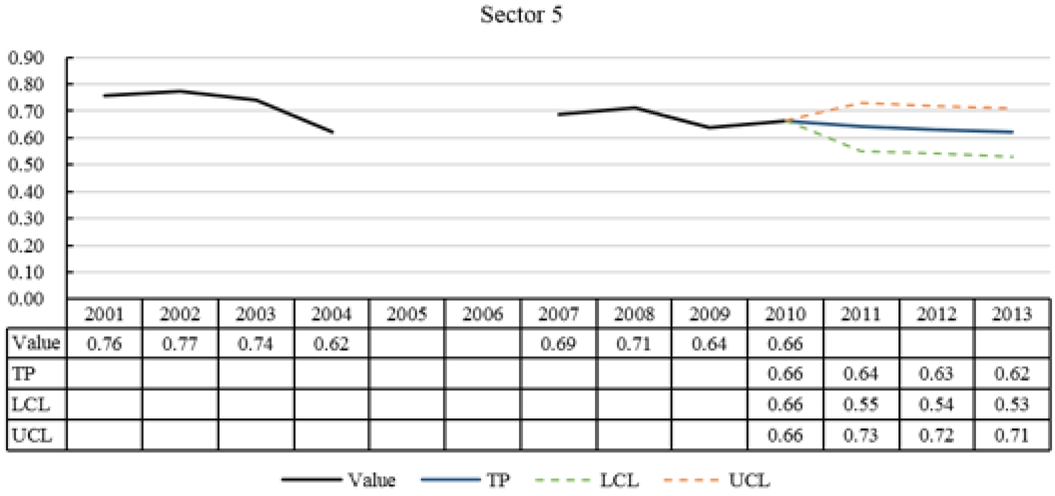
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Value	0.29	0.28	0.21	0.21	0.22	0.30	0.24	0.39	0.36	0.37			
TP										0.37	0.38	0.40	0.41
LCL										0.37	0.27	0.27	0.28
UCL										0.37	0.50	0.52	0.55

Figure S3. Prediction of $(1-\eta_i)$ value for Sector 3 in 2012



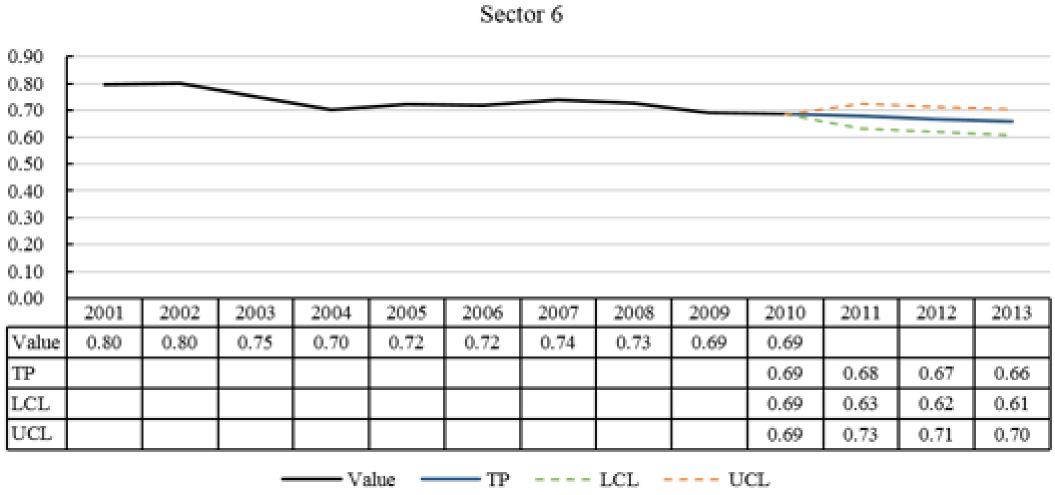
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Value	0.72	0.58	0.55	0.65	0.57	0.63	0.57	0.32	0.23	0.22			
TP										0.22	0.22	0.17	0.12
LCL										0.22	0.04	-0.01	-0.06
UCL										0.22	0.40	0.35	0.30

Figure S4. Prediction of $(1-\eta_i)$ value for Sector 4 in 2012



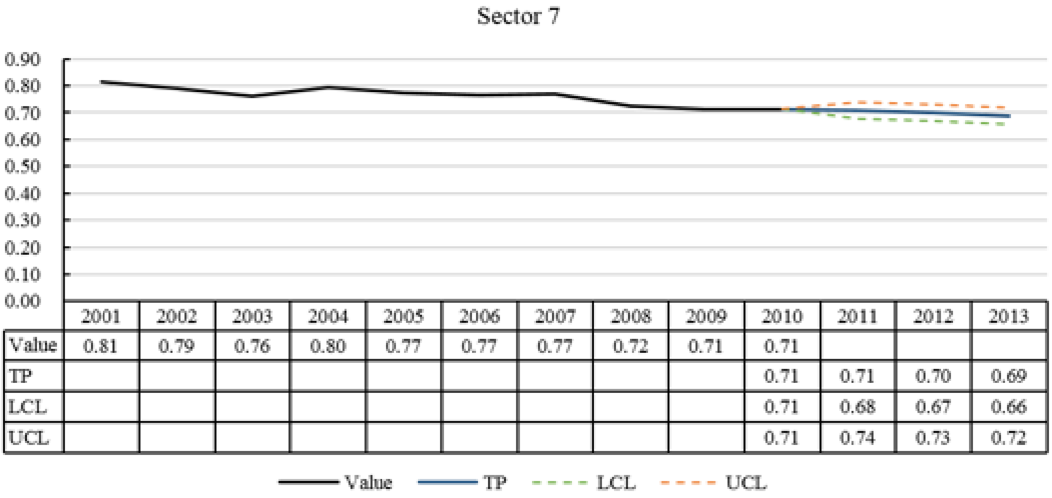
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Value	0.76	0.77	0.74	0.62			0.69	0.71	0.64	0.66			
TP										0.66	0.64	0.63	0.62
LCL										0.66	0.55	0.54	0.53
UCL										0.66	0.73	0.72	0.71

Figure S5. Prediction of $(1-\eta_i)$ value for Sector 5 in 2012



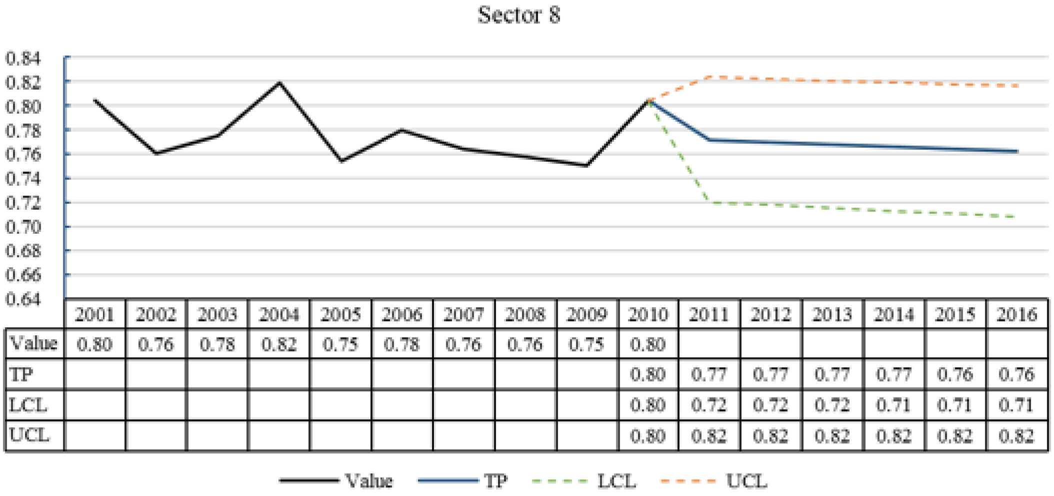
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Value	0.80	0.80	0.75	0.70	0.72	0.72	0.74	0.73	0.69	0.69			
TP										0.69	0.68	0.67	0.66
LCL										0.69	0.63	0.62	0.61
UCL										0.69	0.73	0.71	0.70

Figure S6. Prediction of $(1-\eta_i)$ value for Sector 6 in 2012



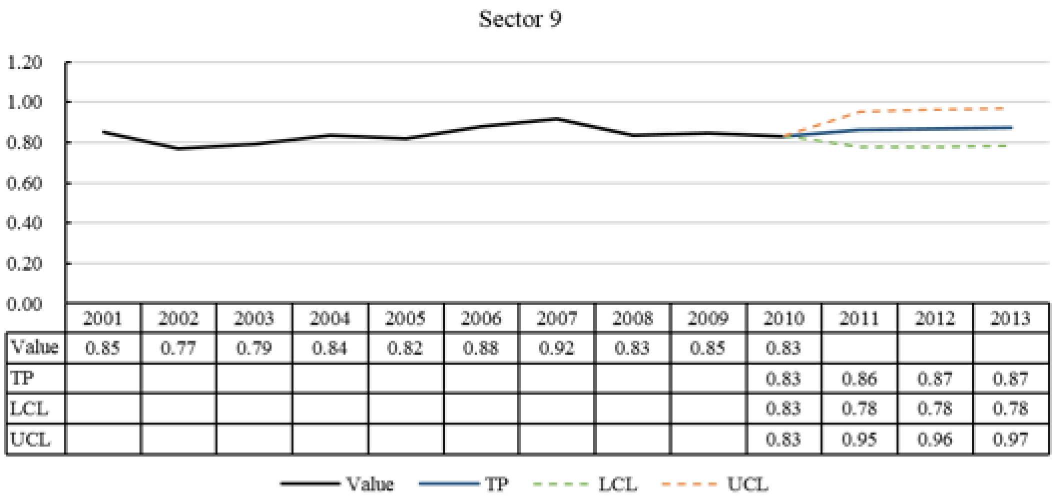
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Value	0.81	0.79	0.76	0.80	0.77	0.77	0.77	0.72	0.71	0.71			
TP										0.71	0.71	0.70	0.69
LCL										0.71	0.68	0.67	0.66
UCL										0.71	0.74	0.73	0.72

Figure S7. Prediction of $(1-\eta_i)$ value for Sector 7 in 2012



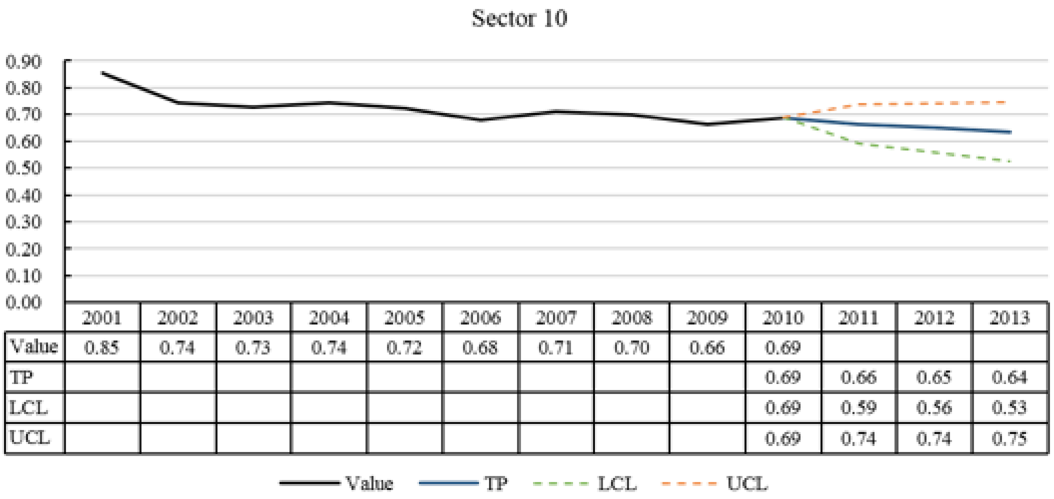
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Value	0.80	0.76	0.78	0.82	0.75	0.78	0.76	0.76	0.75	0.80						
TP										0.80	0.77	0.77	0.77	0.77	0.76	0.76
LCL										0.80	0.72	0.72	0.72	0.71	0.71	0.71
UCL										0.80	0.82	0.82	0.82	0.82	0.82	0.82

Figure S8. Prediction of $(1-\eta_i)$ value for Sector 8 in 2012



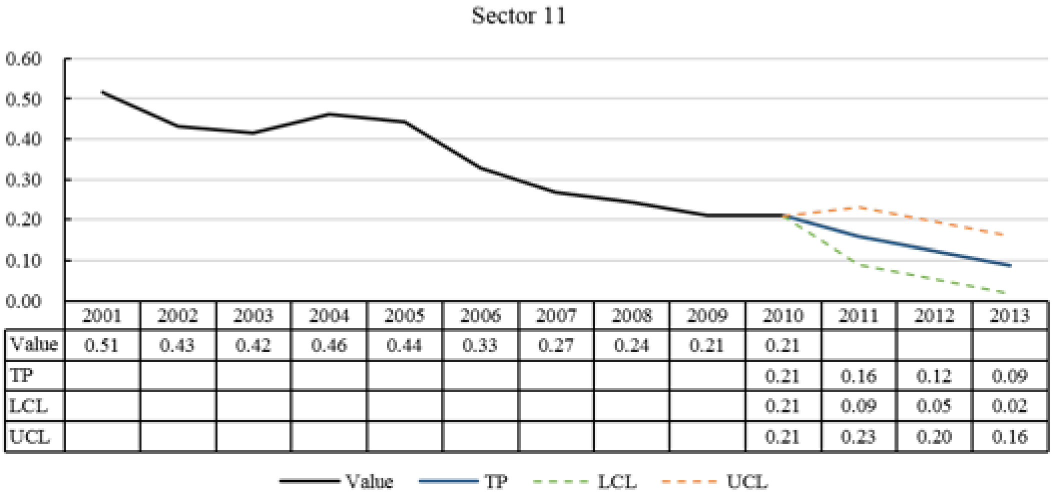
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Value	0.85	0.77	0.79	0.84	0.82	0.88	0.92	0.83	0.85	0.83			
TP										0.83	0.86	0.87	0.87
LCL										0.83	0.78	0.78	0.78
UCL										0.83	0.95	0.96	0.97

Figure S9. Prediction of $(1-\eta_i)$ value for Sector 9 in 2012



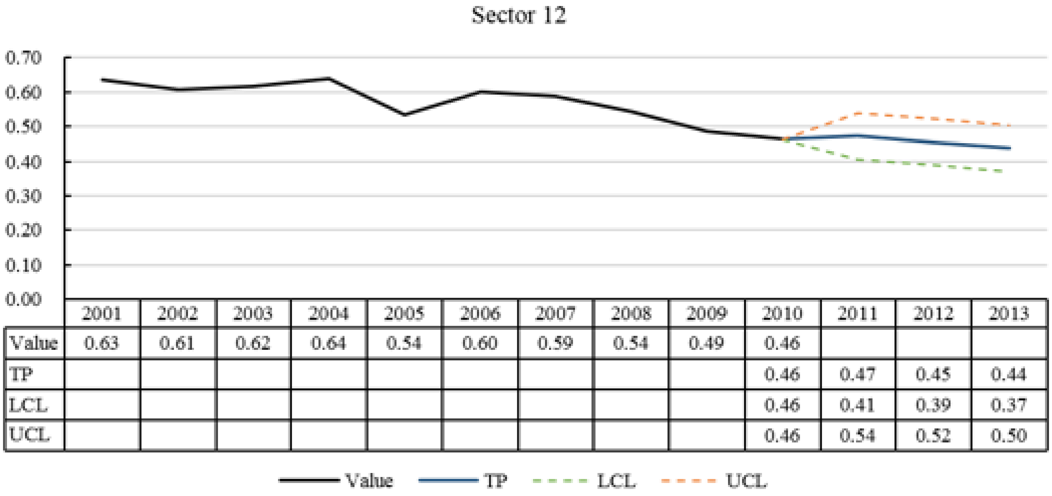
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Value	0.85	0.74	0.73	0.74	0.72	0.68	0.71	0.70	0.66	0.69			
TP										0.69	0.66	0.65	0.64
LCL										0.69	0.59	0.56	0.53
UCL										0.69	0.74	0.74	0.75

Figure S10. Prediction of $(1-\eta_i)$ value for Sector 10 in 2012



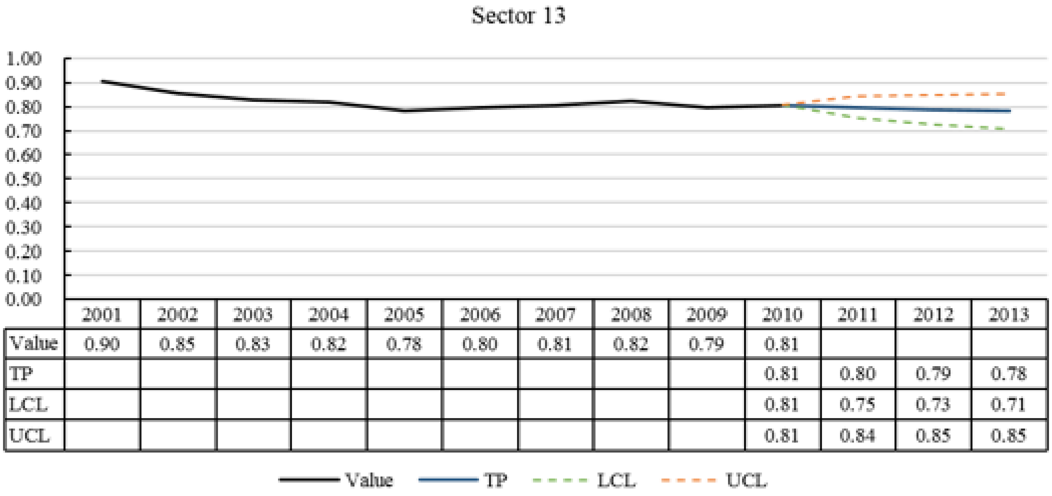
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Value	0.51	0.43	0.42	0.46	0.44	0.33	0.27	0.24	0.21	0.21			
TP										0.21	0.16	0.12	0.09
LCL										0.21	0.09	0.05	0.02
UCL										0.21	0.23	0.20	0.16

Figure S11. Prediction of $(1-\eta_i)$ value for Sector 11 in 2012



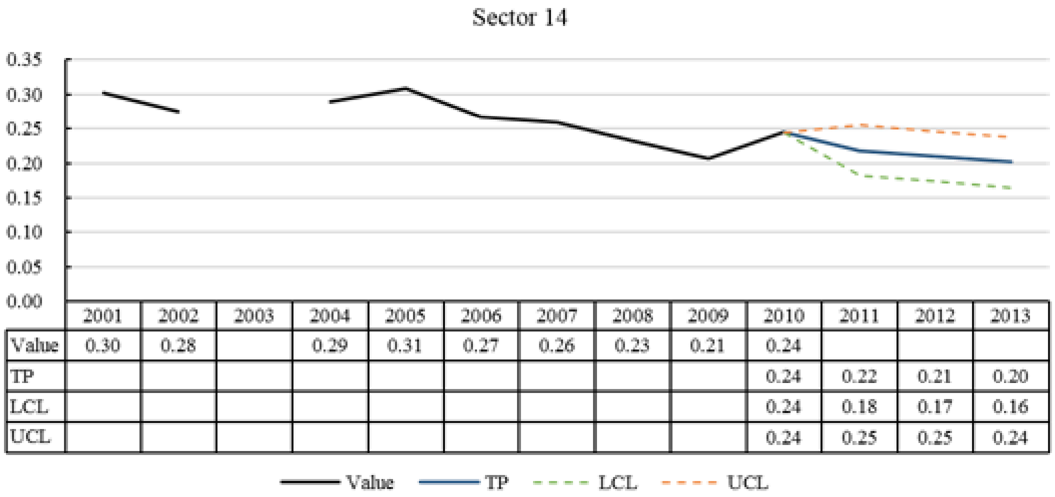
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Value	0.63	0.61	0.62	0.64	0.54	0.60	0.59	0.54	0.49	0.46			
TP										0.46	0.47	0.45	0.44
LCL										0.46	0.41	0.39	0.37
UCL										0.46	0.54	0.52	0.50

Figure S12. Prediction of $(1-\eta_i)$ value for Sector 12 in 2012



	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Value	0.90	0.85	0.83	0.82	0.78	0.80	0.81	0.82	0.79	0.81			
TP										0.81	0.80	0.79	0.78
LCL										0.81	0.75	0.73	0.71
UCL										0.81	0.84	0.85	0.85

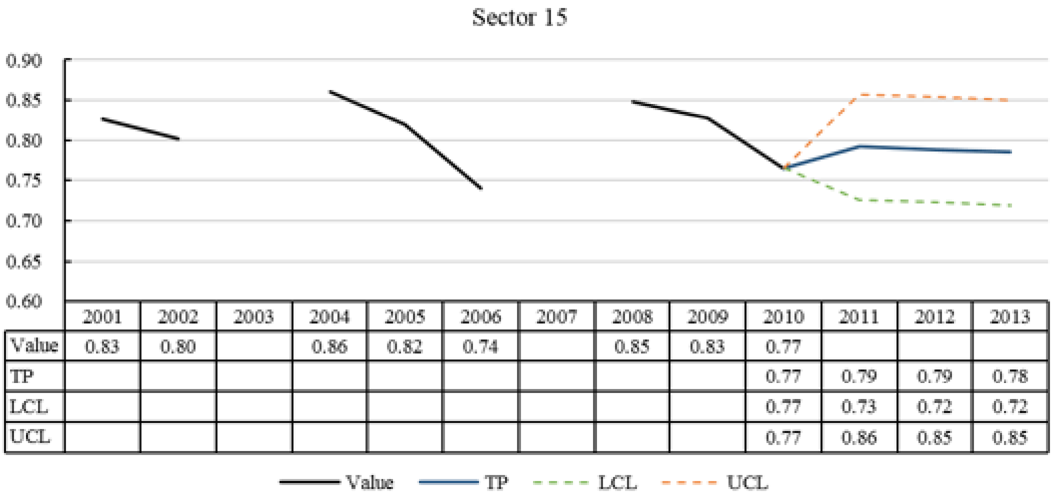
Figure S13. Prediction of $(1-\eta_i)$ value for Sector 13 in 2012



Sector 14

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Value	0.30	0.28		0.29	0.31	0.27	0.26	0.23	0.21	0.24			
TP										0.24	0.22	0.21	0.20
LCL										0.24	0.18	0.17	0.16
UCL										0.24	0.25	0.25	0.24

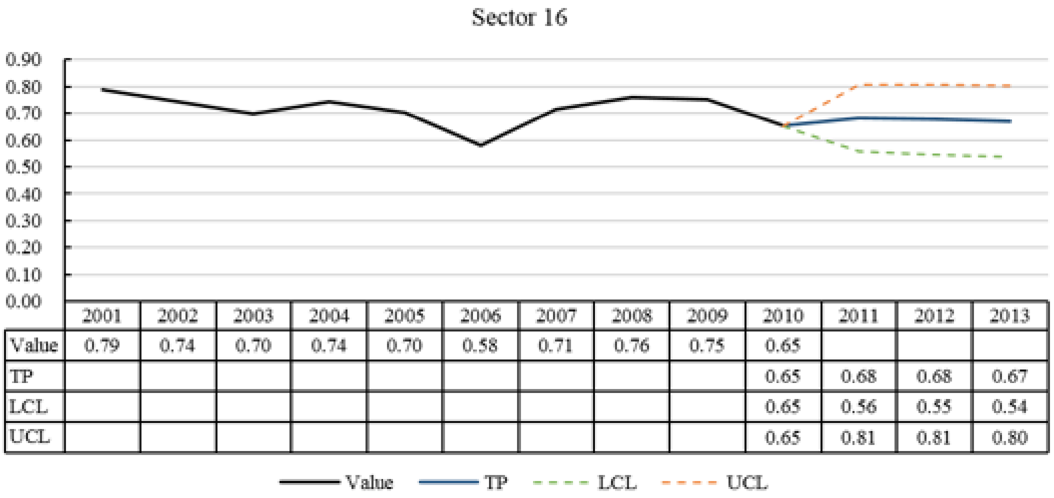
Figure S14. Prediction of $(1-\eta_i)$ value for Sector 14 in 2012



Sector 15

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Value	0.83	0.80		0.86	0.82	0.74		0.85	0.83	0.77			
TP										0.77	0.79	0.79	0.78
LCL										0.77	0.73	0.72	0.72
UCL										0.77	0.86	0.85	0.85

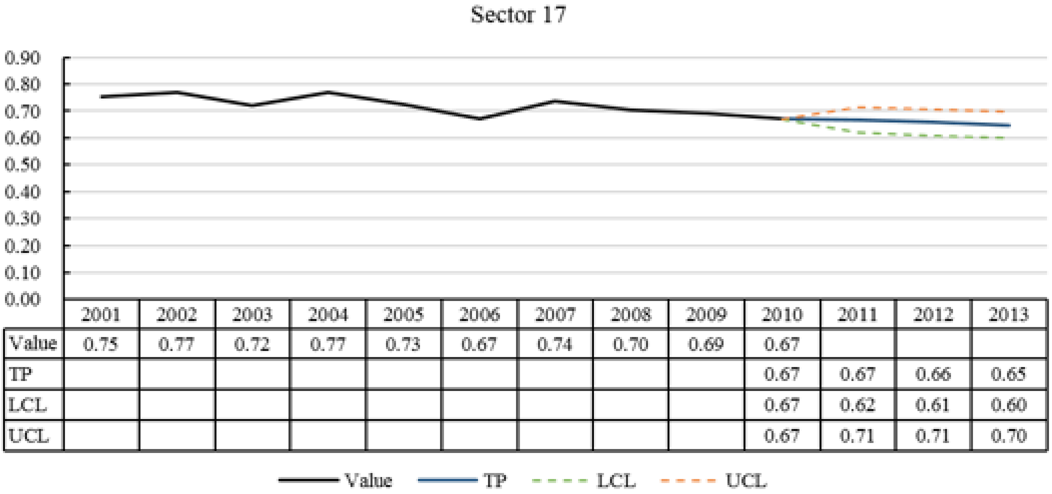
Figure S15. Prediction of $(1-\eta_i)$ value for Sector 15 in 2012



Sector 16

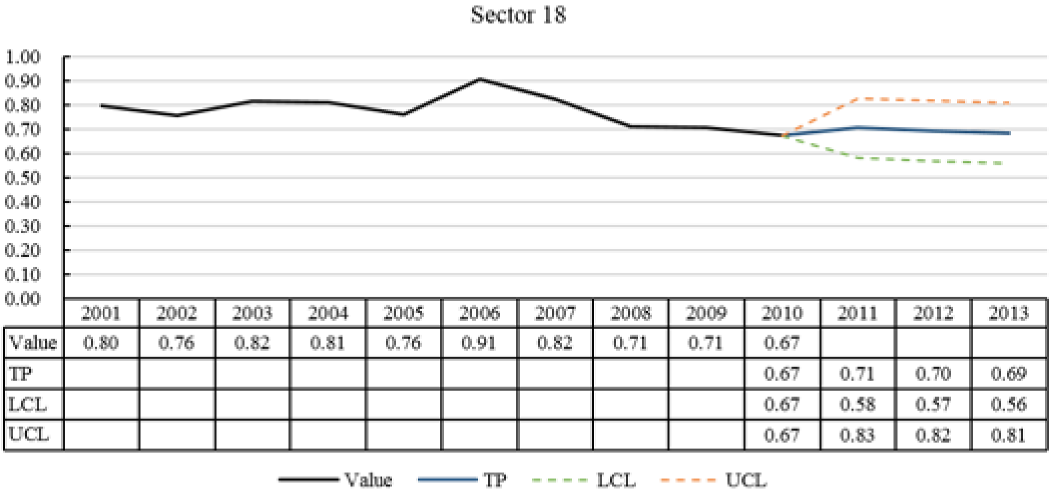
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Value	0.79	0.74	0.70	0.74	0.70	0.58	0.71	0.76	0.75	0.65			
TP										0.65	0.68	0.68	0.67
LCL										0.65	0.56	0.55	0.54
UCL										0.65	0.81	0.81	0.80

Figure S16. Prediction of $(1-\eta_i)$ value for Sector 16 in 2012



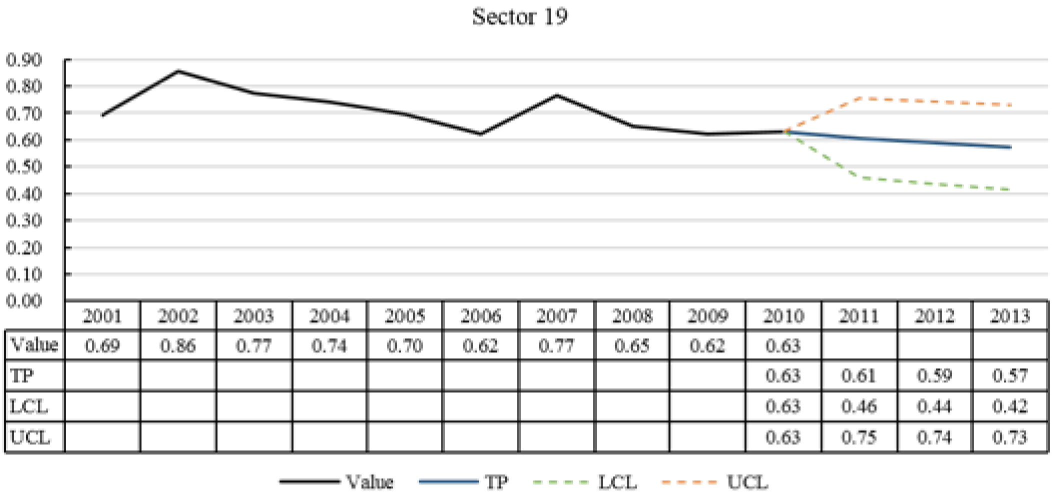
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Value	0.75	0.77	0.72	0.77	0.73	0.67	0.74	0.70	0.69	0.67			
TP										0.67	0.67	0.66	0.65
LCL										0.67	0.62	0.61	0.60
UCL										0.67	0.71	0.71	0.70

Figure S17. Prediction of $(1-\eta_i)$ value for Sector 17 in 2012



	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Value	0.80	0.76	0.82	0.81	0.76	0.91	0.82	0.71	0.71	0.67			
TP										0.67	0.71	0.70	0.69
LCL										0.67	0.58	0.57	0.56
UCL										0.67	0.83	0.82	0.81

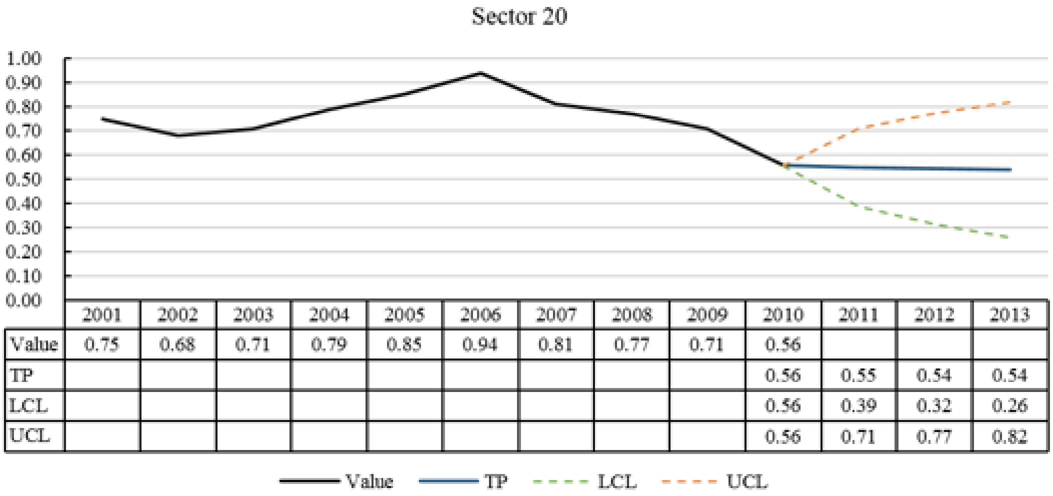
Figure S18. Prediction of $(1-\eta_i)$ value for Sector 18 in 2012



Sector 19

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Value	0.69	0.86	0.77	0.74	0.70	0.62	0.77	0.65	0.62	0.63			
TP										0.63	0.61	0.59	0.57
LCL										0.63	0.46	0.44	0.42
UCL										0.63	0.75	0.74	0.73

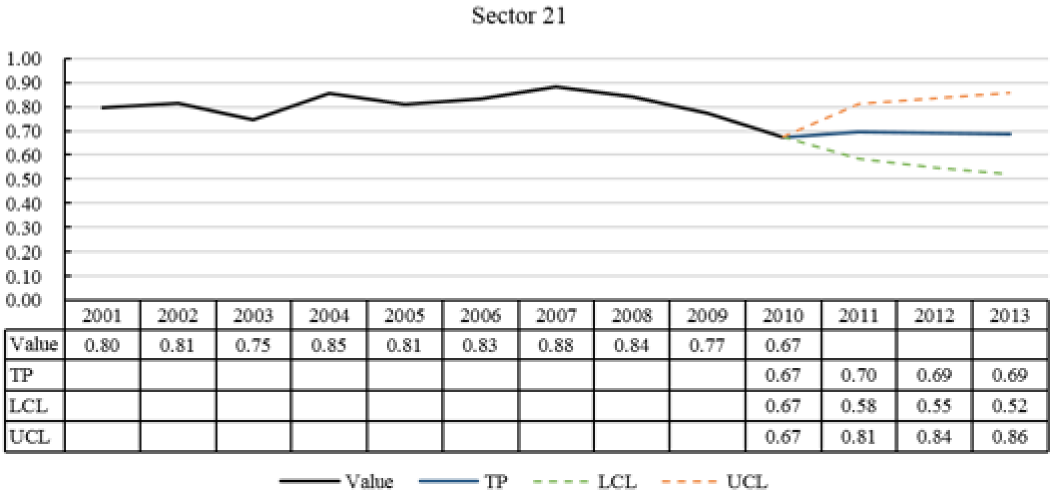
Figure S19. Prediction of $(1-\eta_i)$ value for Sector 19 in 2012



Sector 20

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Value	0.75	0.68	0.71	0.79	0.85	0.94	0.81	0.77	0.71	0.56			
TP										0.56	0.55	0.54	0.54
LCL										0.56	0.39	0.32	0.26
UCL										0.56	0.71	0.77	0.82

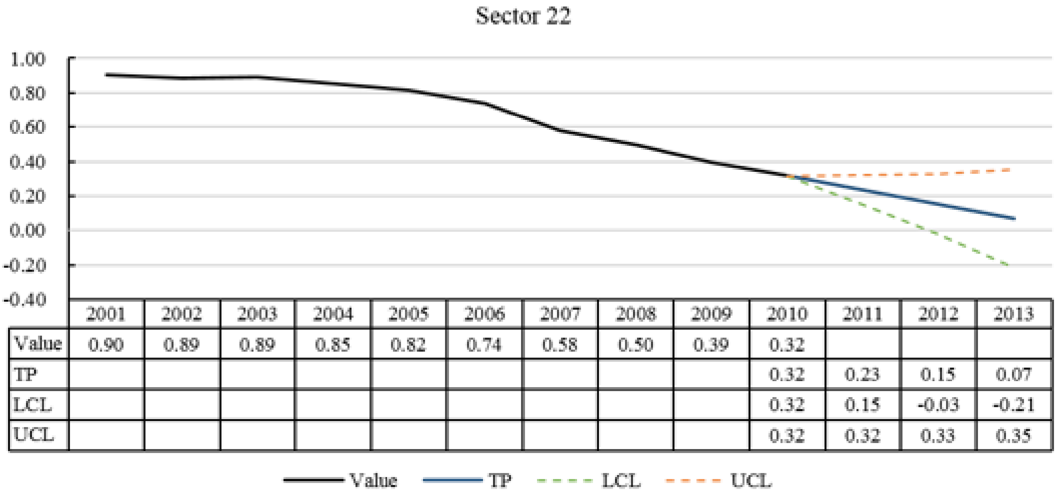
Figure S20. Prediction of $(1-\eta_i)$ value for Sector 20 in 2012



Sector 21

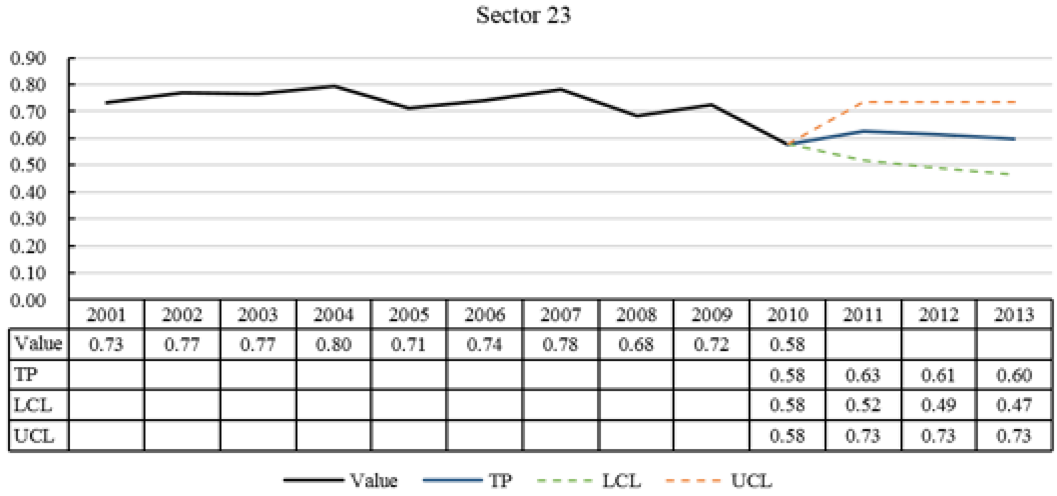
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Value	0.80	0.81	0.75	0.85	0.81	0.83	0.88	0.84	0.77	0.67			
TP										0.67	0.70	0.69	0.69
LCL										0.67	0.58	0.55	0.52
UCL										0.67	0.81	0.84	0.86

Figure S21. Prediction of $(1-\eta_i)$ value for Sector 21 in 2012



	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Value	0.90	0.89	0.89	0.85	0.82	0.74	0.58	0.50	0.39	0.32			
TP										0.32	0.23	0.15	0.07
LCL										0.32	0.15	-0.03	-0.21
UCL										0.32	0.32	0.33	0.35

Figure S22. Prediction of $(1-\eta_i)$ value for Sector 22 in 2012



	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Value	0.73	0.77	0.77	0.80	0.71	0.74	0.78	0.68	0.72	0.58			
TP										0.58	0.63	0.61	0.60
LCL										0.58	0.52	0.49	0.47
UCL										0.58	0.73	0.73	0.73

Figure S23. Prediction of $(1-\eta_i)$ value for Sector 23 in 2012

A.4. Production- and consumption-based SO_2 emissions in 2007, 2010, and 2012

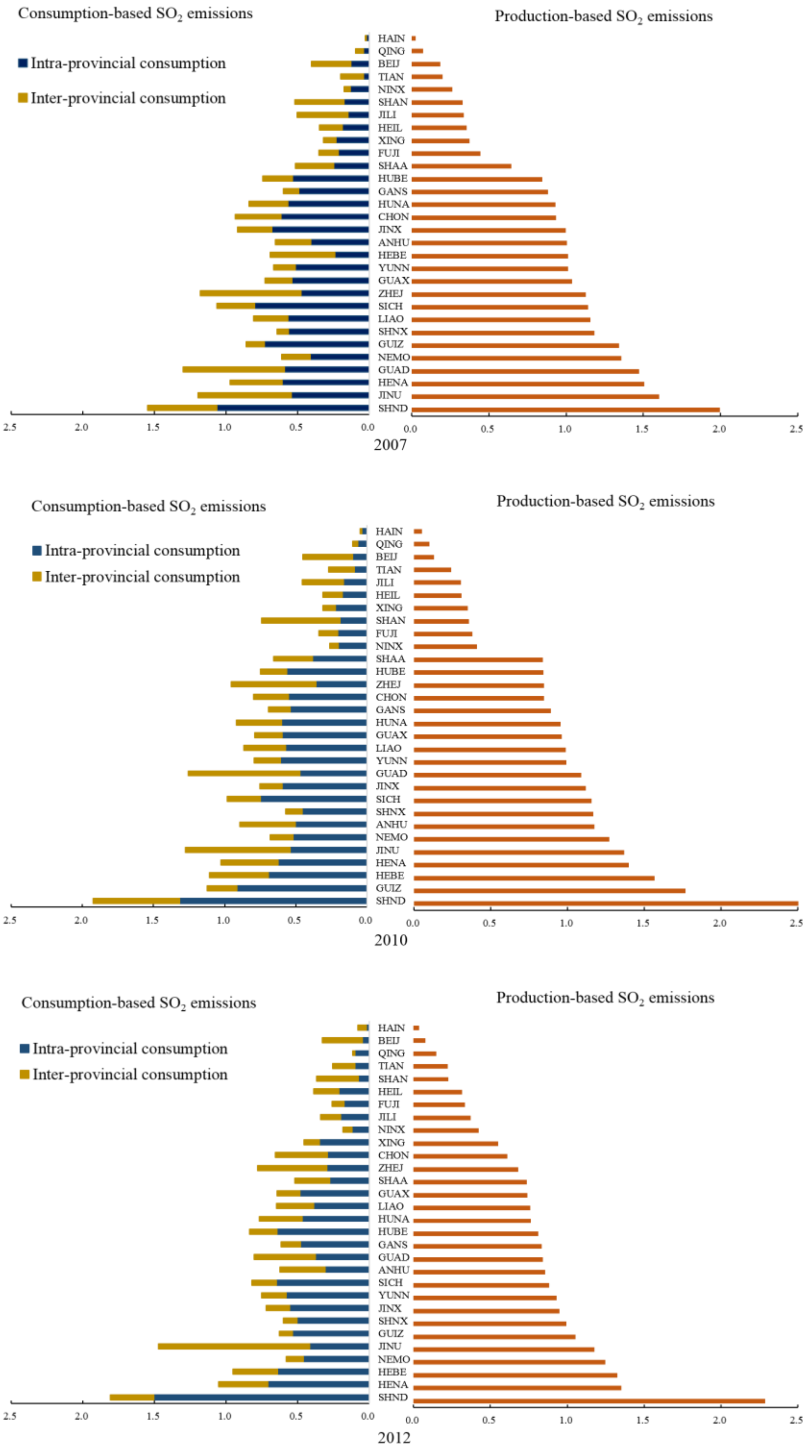


Figure S24. Production- and consumption-based SO_2 emissions in China (Unit: Mt) (There is a mismatch of 20.8%, 16.3%, and 15.5% between production-based and consumption-based SO_2 emissions in 2007, 2010, and 2012 because of the leakage to foreign countries as explained in the method section)

A.5. Inflows and outflows of SO_2 emissions in 2007, 2010, and 2012

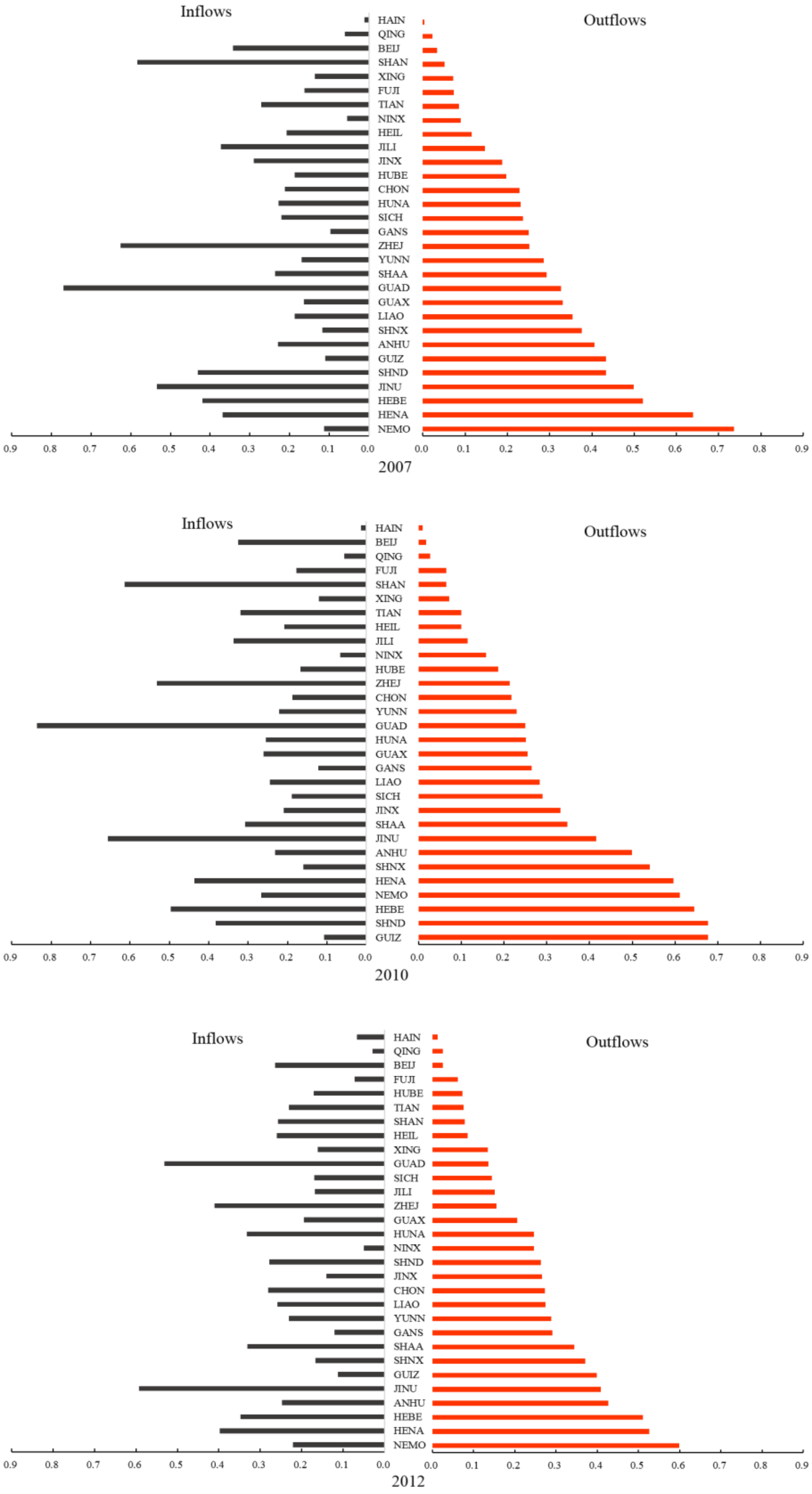


Figure S25. Inflows and outflows of SO_2 emissions in China (Unit: Mt)

A.6. Net transfers of SO_2 emissions of eight regions

Table S4, Table S5, and Table S6 present the net transfers of SO_2 emissions of eight regions in 2007, 2010, and 2012, respectively.

Table S4. Net transfer of SO_2 emissions in 2007 (Unit: kt)

	Northeast	Jing-Jin	North Coast	East Coast	South Coast	Central	Northwest	Southwest
Northeast		43	-2	35	13	-30	-202	-8
Jing-Jin	-43		-111	-18	-11	-104	-142	-65
North Coast	2	111		162	68	-97	-117	-25
East Coast	-35	18	-162		-6	-437	-195	-125
South Coast	-13	11	-68	6		-132	-59	-285
Central	30	104	97	437	132		-34	-149
Northwest	202	142	117	195	59	34		17
Southwest	8	65	25	125	285	149	-17	

Table S5. Net transfer of SO_2 emissions in 2010 (Unit: kt)

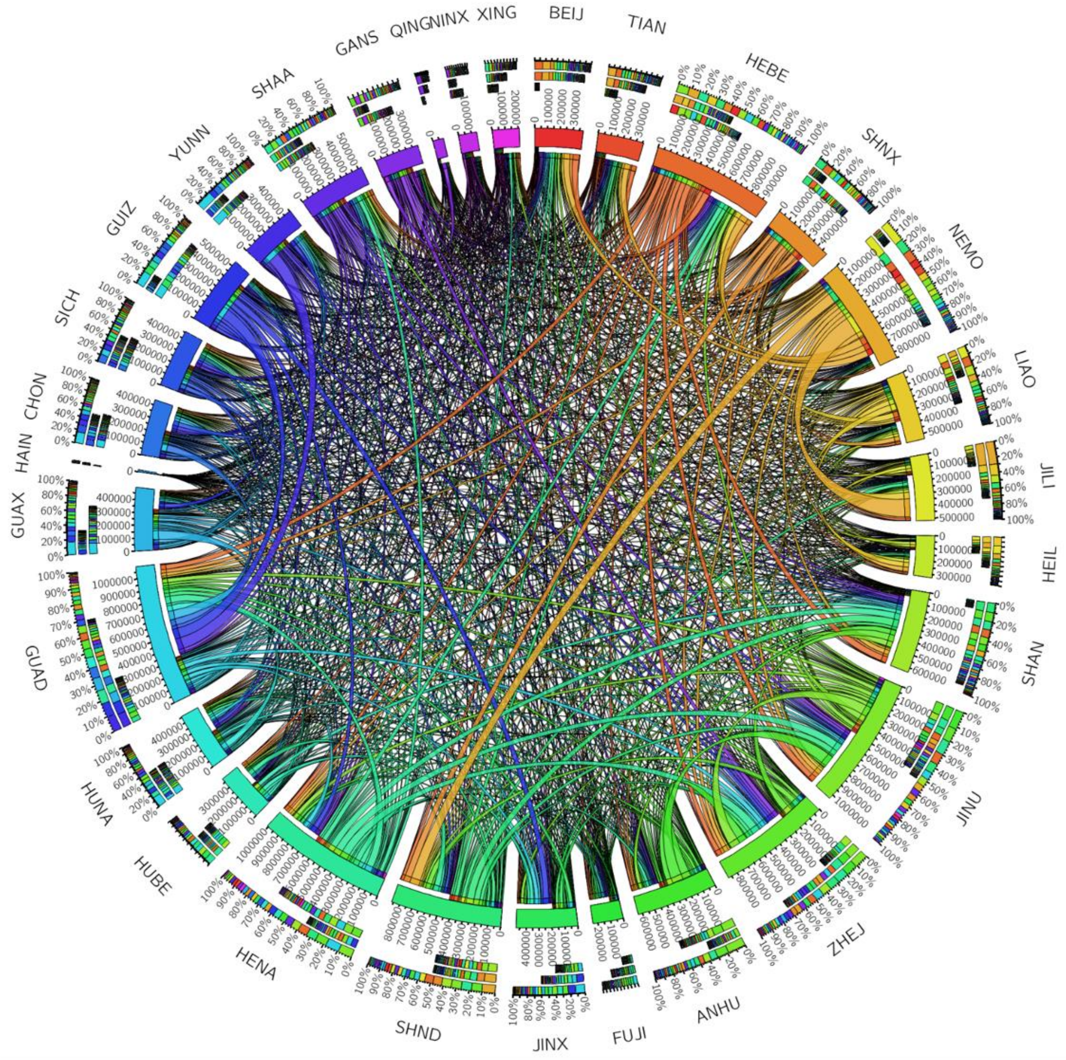
	Northeast	Jing-Jin	North Coast	East Coast	South Coast	Central	Northwest	Southwest
Northeast		26	-80	5	8	-70	-155	-26
Jing-Jin	-26		-151	-19	-8	-124	-140	-59
North Coast	80	151		265	88	-89	-34	-17
East Coast	-5	19	-265		4	-552	-185	-121
South Coast	-8	8	-88	-4		-229	-71	-310
Central	70	124	89	552	229		9	-131
Northwest	155	140	34	185	71	-9		-36
Southwest	26	59	17	121	310	131	36	

Table S6. Net transfer of SO2 emissions in 2012 (Unit: kt)

	Northeast	Jing-Jin	North Coast	East Coast	South Coast	Central	Northwest	Southwest
Northeast		40	-48	1	10	-66	-86	-25
Jing-Jin	-40		-91	-28	-4	-91	-99	-39
North Coast	48	91		70	35	-8	-88	0
East Coast	-1	28	-70		20	-297	-194	-102
South Coast	-10	4	-35	-20		-119	-103	-178
Central	66	91	8	297	119		-106	-25
Northwest	86	99	88	194	103	106		48
Southwest	25	39	0	102	178	25	-48	

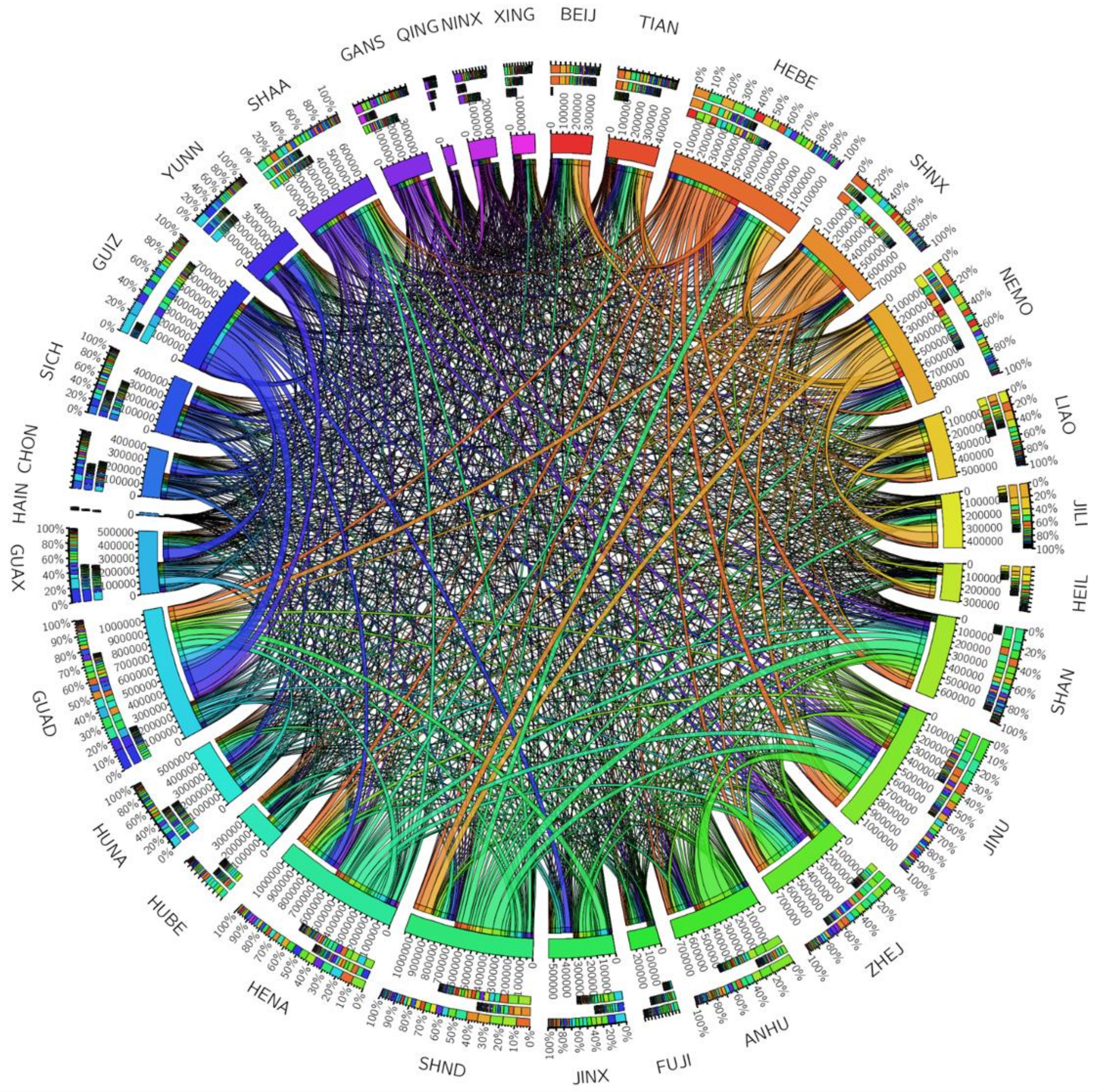
A.7. Embodied SO_2 emissions of 30 provinces in 2007, 2010, and 2012

Figure S26, Figure S27, and Figure S28 present the embodied SO_2 emissions of 30 provinces in 2007, 2010, and 2012, respectively. The flows of SO_2 emissions among 30 provinces are drawn by Circos, an open-source software package for data visualization (Krzywinski, 2009). The three ribbons located outside show, respectively, the sum of inflow and outflow, inflow, and outflow of a province. Furthermore, the sizes of ribbons are proportional to the corresponding values. The innermost ribbon has a direction: it starts with the outflow value which it touches and ends with inflow value where there is a gap.



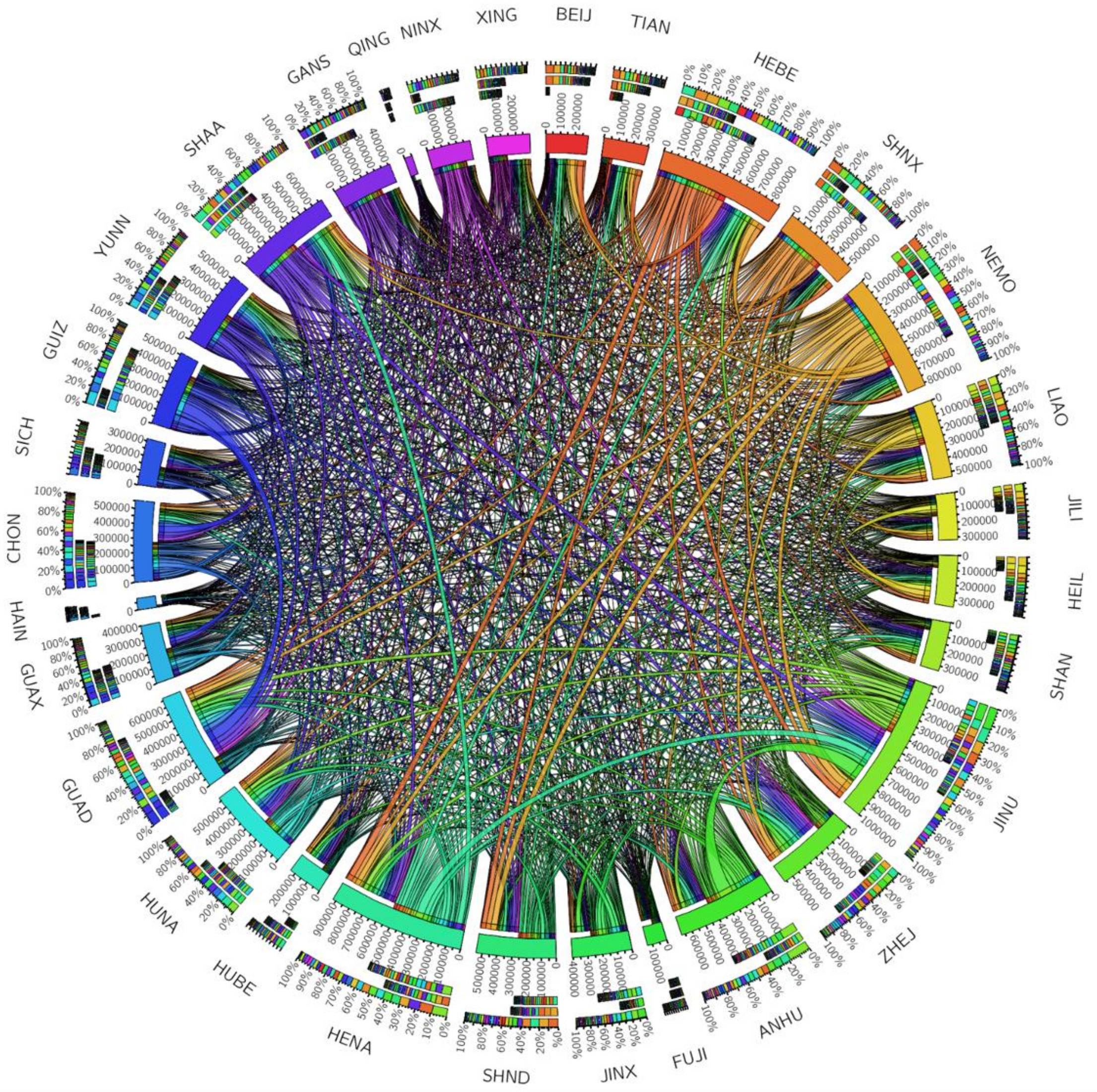
2007

Figure S26. Embodied SO_2 emissions of 30 provinces in 2007 (Unit: t)



2010

Figure S27. Embodied SO_2 emissions of 30 provinces in 2010 (Unit: t)



2012

Figure S28. Embodied SO_2 emissions of 30 provinces in 2012 (Unit: t)

A.8. Regional shares of SO_2 reduction and SO_2 responsibility

This section shows the results of environmental responsibility about SO_2 emissions and acidification, as well as the provincial targets about SO_2 reduction.

Table S7. Regional responsibility of SO_2 emissions in 2007, 2010, and 2012 (Unit: Mt)

	2007		2010		2012	
	Emissions	Responsibility	Emissions	Responsibility	Emissions	Responsibility

BEIJ	0.19	0.33	0.13	0.31	0.08	0.28
TIAN	0.20	0.23	0.24	0.29	0.22	0.24
HEBE	1.01	0.85	1.57	1.22	1.32	1.11
SHNX	1.18	0.92	1.17	0.91	0.99	0.95
NEMO	1.36	0.95	1.27	0.98	1.25	0.94
LIAO	1.16	0.90	0.99	0.86	0.76	0.65
JILI	0.34	0.40	0.31	0.37	0.37	0.33
HEIL	0.35	0.43	0.31	0.36	0.32	0.40
SHAN	0.33	0.45	0.36	0.54	0.23	0.28
JINU	1.60	1.25	1.37	1.19	1.18	1.19
ZHEJ	1.13	0.96	0.84	0.80	0.68	0.66
ANHU	1.01	0.74	1.17	0.91	0.86	0.69
FUJI	0.44	0.37	0.38	0.35	0.33	0.28
JINX	1.00	0.81	1.12	0.82	0.95	0.70
SHND	2.00	1.70	2.52	1.98	2.29	1.83
HENA	1.51	1.22	1.40	1.18	1.35	1.20
HUBE	0.85	0.75	0.84	0.76	0.81	0.73
HUNA	0.93	0.83	0.96	0.87	0.76	0.73
GUAD	1.47	1.21	1.09	1.09	0.84	0.73
GUAX	1.04	0.76	0.96	0.77	0.74	0.61
HAIN	0.03	0.03	0.05	0.05	0.04	0.06
CHON	0.94	0.81	0.85	0.77	0.61	0.61
SICH	1.14	1.06	1.16	1.04	0.88	0.83
GUIZ	1.34	1.03	1.77	1.34	1.05	0.79
YUNN	1.01	0.72	0.99	0.77	0.93	0.74
SHAA	0.64	0.61	0.84	0.75	0.74	0.69
GANS	0.88	0.62	0.89	0.67	0.84	0.62
QING	0.08	0.08	0.10	0.10	0.15	0.12

NINX	0.26	0.21	0.41	0.31	0.43	0.26
XING	0.37	0.37	0.35	0.34	0.55	0.48
RoW		4.19		3.66		2.81
Total	**25.78**	**25.78**	**26.38**	**26.38**	**22.54**	**22.54**

Table S8. Regional responsibility of biodiversity loss in 2007, 2010, and 2012 (Unit: PDF·yr)

	2007		2010		2012	
	Acidification	Responsibility	Acidification	Responsibility	Acidification	Responsibility
BEIJ	5.57E-07	1.80E-05	3.89E-07	1.80E-05	2.34E-07	1.99E-05
TIAN	5.98E-07	1.67E-05	7.29E-07	1.66E-05	6.69E-07	9.30E-06
HEBE	4.05E-06	3.94E-05	6.27E-06	2.86E-05	5.30E-06	2.83E-05
SHNX	2.36E-05	2.48E-05	2.33E-05	2.31E-05	1.99E-05	2.22E-05
NEMO	6.65E-05	5.67E-05	6.22E-05	5.46E-05	6.10E-05	5.78E-05
LIAO	4.63E-06	1.64E-05	3.96E-06	1.40E-05	3.04E-06	2.73E-05
JILI	1.02E-06	9.55E-06	9.17E-07	7.84E-06	1.11E-06	1.06E-05
HEIL	3.19E-06	8.87E-06	2.76E-06	7.12E-06	2.85E-06	1.74E-05
SHAN	3.31E-07	1.93E-05	3.55E-07	1.90E-05	2.26E-07	2.10E-05
JINU	1.60E-06	4.54E-05	1.37E-06	4.11E-05	1.18E-06	4.61E-05
ZHEJ	1.13E-06	3.79E-05	8.44E-07	3.29E-05	6.82E-07	3.07E-05
ANHU	2.01E-06	1.68E-05	2.35E-06	1.71E-05	1.72E-06	2.07E-05
FUJI	1.25E-03	8.03E-04	1.07E-03	7.41E-04	9.39E-04	6.60E-04
JINX	9.97E-07	1.11E-05	1.12E-06	1.06E-05	9.51E-07	1.32E-05
SHND	5.99E-06	3.23E-05	7.55E-06	3.06E-05	6.87E-06	3.39E-05
HEN	1.36E-05	4.64E-05	1.26E-05	3.74E-05	1.22E-05	3.93E-05

A						
HUBE	1.02E-05	2.11E-05	1.01E-05	1.97E-05	9.74E-06	1.58E-05
HUNA	2.80E-06	1.70E-05	2.87E-06	1.56E-05	2.29E-06	1.99E-05
GUAD	1.47E-05	6.50E-05	1.09E-05	6.22E-05	8.43E-06	3.86E-05
GUAX	2.90E-05	3.03E-05	2.70E-05	2.86E-05	2.08E-05	2.82E-05
HAIN	0.00E+00	1.65E-06	0.00E+00	2.41E-06	0.00E+00	4.72E-06
CHON	1.12E-05	2.28E-05	1.01E-05	2.20E-05	7.33E-06	2.92E-05
SICH	1.37E-03	1.15E-03	1.39E-03	1.15E-03	1.06E-03	9.03E-04
GUIZ	1.07E-05	1.57E-05	1.42E-05	1.79E-05	8.44E-06	1.56E-05
YUNN	4.66E-05	4.28E-05	4.57E-05	4.27E-05	4.28E-05	4.79E-05
SHAA	3.16E-05	3.85E-05	4.10E-05	4.26E-05	3.61E-05	4.49E-05
GANS	5.56E-05	5.83E-05	5.61E-05	5.66E-05	5.26E-05	5.01E-05
QING	4.49E-05	3.54E-05	5.92E-05	4.54E-05	8.81E-05	7.59E-05
NINX	1.66E-05	1.51E-05	2.58E-05	2.15E-05	2.68E-05	2.23E-05
XING	9.00E-04	6.64E-04	8.35E-04	6.24E-04	1.32E-03	9.89E-04
RoW	–	5.49E-04	–	4.73E-04	–	3.98E-04
Total	**3.93E-03**	**3.93E-03**	**3.72E-03**	**3.72E-03**	**3.74E-03**	**3.74E-03**

At the beginning of 11th FYP, the Chinese government set the provincial targets of SO_2 emissions based on the 2005 level. Columns 2-4 in Table S9 show the reduction targets set by the Chinese government, from which we can calculate the reduction amount and the corresponding share of each province.

Table S9. Provincial reduction targets of SO_2 emissions in 2010

	2005 (Mt)	2010 (Mt)	Change (%)	Allocation (Mt)	Share (%)
BEIJ	0.19	0.15	-20.40	0.04	1.29
TIAN	0.27	0.24	-9.40	0.03	0.83
HEBE	1.50	1.27	-15.00	0.23	7.43
SHNX	1.52	1.30	-14.00	0.21	7.00
NEMO	1.46	1.40	-3.80	0.06	1.85
LIAO	1.20	1.05	-12.00	0.14	4.76
JILI	0.38	0.36	-4.70	0.02	0.59
HEIL	0.51	0.50	-2.00	0.01	0.33
SHAN	0.51	0.38	-25.90	0.13	4.39
JINU	1.37	1.13	-18.00	0.25	8.16
ZHEJ	0.86	0.73	-15.00	0.13	4.26
ANHU	0.57	0.55	-4.00	0.02	0.76
FUJI	0.46	0.42	-8.00	0.04	1.22
JINX	0.61	0.57	-7.00	0.04	1.42
SHND	2.00	1.60	75.70	0.40	13.25
HENA	1.63	1.40	-14.00	0.23	7.53
HUBE	0.72	0.66	-7.80	0.06	1.85
HUNA	0.92	0.84	-9.00	0.08	2.74
GUAD	1.29	1.10	-15.00	0.19	6.41
GUAX	1.02	0.92	-9.90	0.10	3.34
HAIN	0.02	0.02	0.00	0.00	0.00
CHON	0.84	0.74	-11.90	0.10	3.30

SICH	1.30	1.14	-11.90	0.16	5.12
GUIZ	1.36	1.15	-15.00	0.20	6.74
YUNN	0.52	0.50	-4.00	0.02	0.69
SHAA	0.92	0.81	-12.00	0.11	3.67
GANS	0.56	0.56	0.00	0.00	0.00
QING	0.12	0.12	0.00	0.00	0.00
NINX	0.34	0.31	-9.30	0.03	1.06
XING	0.52	0.52	0.00	0.00	0.00

A.9. Production-, consumption-, and income-based SO_2 emissions in some provinces

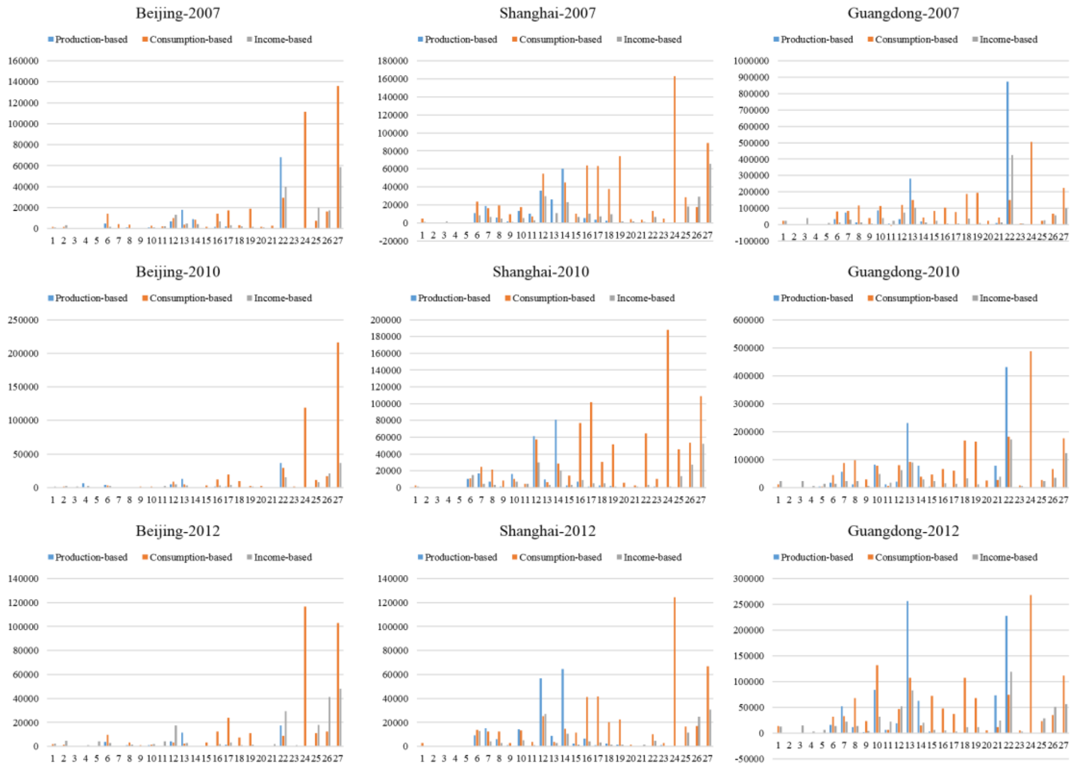


Figure S29. Production-, consumption-, and income-based SO_2 emissions in developed provinces (Unit: t)

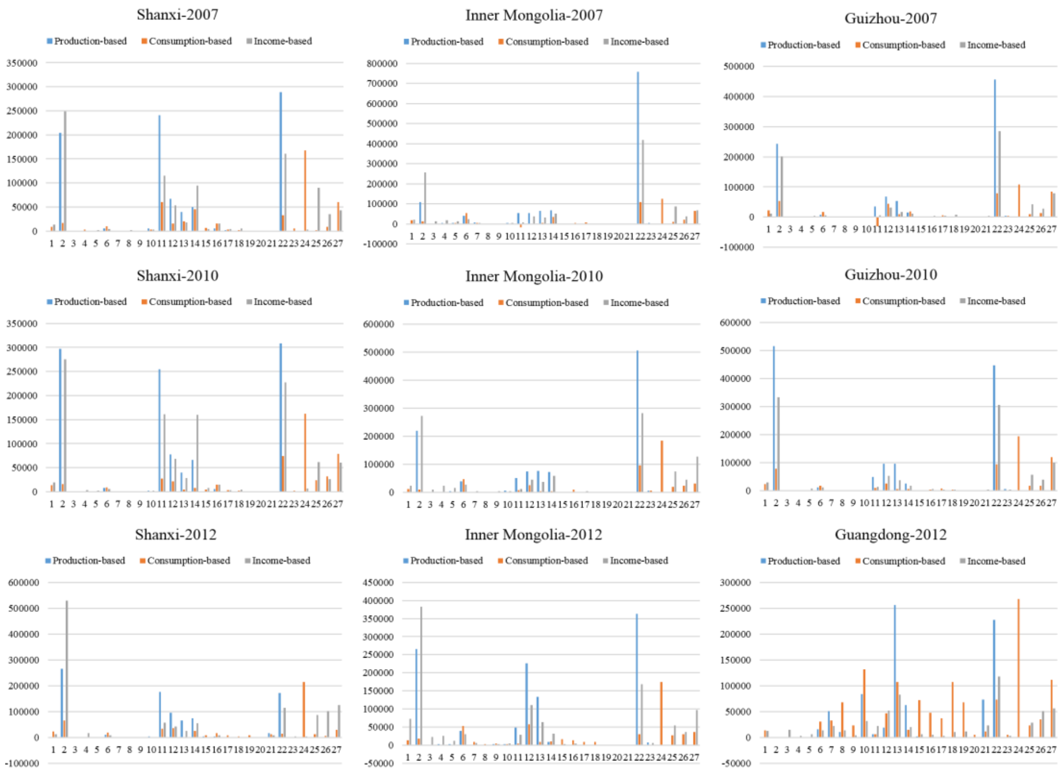


Figure S30. Production-, consumption-, and income-based SO_2 emissions in developing provinces

(Unit: t)