Sweet spots are in the food system: structural adjustments to co-control regional pollutants and national GHG emissions in China

Liua, L.J.; Lianga, Q.M.; Creutzig, F.; Ward, H.; Zhang, K.

Citation

Liua, L. J., Lianga, Q. M., Creutzig, F., Ward, H., & Zhang, K. (2020). Sweet spots are in the food system: structural adjustments to co-control regional pollutants and national GHG emissions in China. *Ecological Economics*, *171*. doi:10.1016/j.ecolecon.2020.106590

Ecological Economics 171 (2020) 106590

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

Sweet spots are in the food system: Structural adjustments to co-control regional pollutants and national GHG emissions in China

Li-Jing Liu[a,b,d,e], Qiao-Mei Liang[a,b,c,*,1], Felix Creutzig[d,e], Hauke Ward[f,d,g], Kun Zhang[a,b]

[a] Center for Energy and Environmental Policy Research, Beijing Institute of Technology, Beijing 100081, China
[b] School of Management and Economics, Beijing Institute of Technology, Beijing 100081, China
[c] Sustainable Development Research Institute for Economy and Society of Beijing, Beijing 100081, China
[d] Mercator Research Institute on Global Commons and Climate Change, Berlin 10829, Germany
[e] Sustainability Economics of Human Settlements, Technical University Berlin, Berlin 10623, Germany
[f] Institute of Environmental Sciences (CML), Department of Industrial Ecology, Leiden University, the Netherlands
[g] Potsdam Institute for Climate Impact Research, Leibniz Association, Potsdam 14412, Germany

ARTICLE INFO

Keywords:
Greenhouse gas
Pollutant
Multi-regional input-output
China
Co-benefits
Elasticity analysis

ABSTRACT

The Chinese government aims to mitigate climate change while also reducing local air pollution; this requires co-control of greenhouse gases and pollutants. Here, we develop a method combining an elasticity analysis and a multi-regional input–output model, to measure changes in the emissions of greenhouse gases and pollutants and corresponding socio-economic costs caused by the adjustments in intermediate input, inter-regional trade, and final demand transactions for 30 provinces in China. A filter framework is proposed to identify the key structural transactions that can significantly co-control both emission types with small socio-economic impacts. The results show that 13 effective co-control spots can simultaneously reduce greenhouse gases and pollutants. Among these, eight co-controls are associated with low economic costs, which we refer to as 'sweet spots'. Sweet spots cover agricultural inputs in the food and tobacco sectors of Inner Mongolia, Sichuan, Liaoning, and Hubei; self-inputs in the agriculture of Henan; self-inputs in the food and tobacco sector of Shandong; fixed capital formation of agriculture in Hebei; and urban household consumption of agricultural products in Guangdong. This finding is important, as climate measures mostly side-line the agricultural sector so far, both in China and in other parts of the world.

1. Introduction

The threat of climate collapse and health-endangering local air pollution, especially in developing countries, have gained increasing attention and require urgent policy responses (Edenhofer et al., 2014; Fotourehchi, 2016). Both challenges are closely related, as most atmospheric pollutant and greenhouse gas (GHG) emissions stem from the same sources. For example, the burning of fossil fuels generates carbon dioxide (CO_2), sulphur dioxide (SO_2), and nitrogen oxides (NOx) emissions. As a result, there could be significant co-benefits between GHG emissions mitigation and pollutant emissions reduction (Altemeyer-Bartscher et al., 2013; Buchholz et al., 2020). Policies or measures to reduce environmental pollution often produce ancillary effects for climate change mitigation and vice versa (Markandya and Rübbelke, 2012; Nemet et al., 2010). Both at the local level, where they are often focused on the transport sector (Bongardt et al., 2013; Creutzig and He, 2009; Zusman et al., 2012), and at the national level, where all sectors are typically considered (Krook Riekkola et al., 2011; Longo et al., 2011). Therefore, the co-control of GHGs and local pollutants is conducive to reducing the cost of emission reduction, which is especially important and attractive for developing or underdeveloped countries (Bain et al., 2015; Markandya et al., 2018; Rive and Rübbelke, 2010). Such analyses, however, are rarely performed.

An analysis at the multi-regional scale is essential for the co-control of pollutants and GHG emissions. Regions are usually different in terms of climatic conditions, geographical location, resource endowment, economic base, industrial structure, environmental pollution situation etc. (Cadarso et al., 2018; Christis et al., 2017; Zhang and Zhang, 2018). Therefore, pollution reduction policies should be formulated according to a region's specific environmental pollution conditions and development. However, considering the global scope of climate change, a synergistically effective emission control that allows for synergies should

---

[*] Corresponding author at: Center for Energy and Environmental Policy Research, Beijing Institute of Technology (BIT), China.
E-mail address: liangqiaomei@bit.edu.cn (Q.-M. Liang).
[1] School of Management and Economics, Beijing Institute of Technology, 5 South Zhongguancun Street, Haidian District, Beijing 100,081, China

https://doi.org/10.1016/j.ecolecon.2020.106590
Received 22 April 2019; Received in revised form 25 November 2019; Accepted 8 January 2020

consider a multi-regional or multi-national perspective. Moreover, given the close economic ties among the regions within a country, a significant portion of emissions occurring in one region is triggered by demand in other regions, that is, there are obvious emissions due to inter-regional trade (Hong et al., 2016; Zhang et al., 2013). Due to inter-regional trade, the environmental impact caused by policies in one region can be transferred to other regions in a country (Guo et al., 2012). Therefore, examining the impact of regional environmental governance decisions is crucial to identify collaborative emission reduction policies for different emissions and regions.

Hitherto, some studies have focused on multi-regional environmental emission reduction, namely, emission accounting (Prell et al., 2015; Wang et al., 2018), emission reduction potential evaluation (Ward et al., 2017; Zhang et al., 2016), emission reduction policy design (Rocchi et al., 2018), regional responsibility allocation (Zhang et al., 2016; Zhao et al., 2016), and regional trade-related emissions assessment (Tsagkari et al., 2018; Wang and Ang, 2018; Zhang et al., 2018). However, most of these studies have focused on single emissions (the most frequently analysed gases include CO_2, SO_2, and $PM_{2.5}$), only a few having had examined both GHG and air pollution (Huang et al., 2018; Roca and Serrano, 2007; Serrano and Dietzenbacher, 2010) and even fewer have shed light on the effects of structural adjustment.

Structural adjustment is one of the most influential factors of environmental quality (Carvalho and Almeida, 2009; Grossman and Krueger, 1995; Verbeke and Clercq, 2002) and expected to be the main contributor to future emission reduction (Kofi Adom et al., 2012; Liao et al., 2007). Unlike technical measures, which often control for only one pollutant, structural adjustments can simultaneously address different forms of environmental discharges. However, over the past decades, the improvement in the environment of most countries is attributed mainly to technological change (Voigt et al., 2014). Moreover, international trade might also contribute to the change in emissions; for example, China's exports for developed countries' consumption are an important driver of the increase in emissions (Guan et al., 2009; Weber et al., 2008). Therefore, the mitigation potential of structural adjustment, especially that to achieve emission reduction co-benefits, needs to be further explored.

Taking China as an example, this study performs a multi-regional (30 provinces) analysis on the effects of structural adjustment on co-controlling multiple GHGs (CO_2, CH_4, and N_2O) at the national level and multiple pollutants (SO_2, NOx, CO, NH_3, BC, OC, $PM_{2.5}$, and NMVOCs) at the provincial level. This study contributes to the literature by proposing an input–output-based method for calculating the impacts of the adjustments of intra-regional supply-side (production) and demand-side (final demand including consumption, investment, and exports) structures and inter-regional trade structure on multiple emissions, economic growth, and employment. Within this computational framework, not only the environmental impacts of structural adjustment, but also its socio-economic impacts, which are seldom discussed in the literature, are analysed. As a main result, by combining the calculation results and various regional characteristics (e.g. emission characteristics, economic development level, regional development goals, and national overall plan), this study can provide a tailored structural adjustment strategy for China's environmental emission reduction.

China is the world's largest emitter of carbon dioxide (main GHG) (IEA, 2017) with hazardous and severe local environmental pollution (Shao et al., 2018; Zheng et al., 2009). Hence, a study on China can provide a basic reference for other countries with multiple regions that also face similar, dual challenges of climate change and local pollution. The findings could be transferred to a global multi-regional perspective. More importantly, China has an urgent need for solutions to these problems. As a country with a vast territory, there are obvious differences in natural geography, resource endowment, economic development, infrastructure, and population scale among regions in China. Besides the environmental problems, narrowing the regional economic gaps and promoting a balanced regional development is a current major concern (CE50, 2019). As consequence, China has adopted a series of strategic measures to alleviate regional imbalances and uncoordinated problems, such as ‘Western Development’, ‘Rise of Central China’, ‘East Takes the Lead in Development’ strategies. Policies to address regional environmental problems require special attention to ensure they do not contradict coordinated regional economic development goals. In this context, the Chinese government has been attaching increasingly higher importance to the economic structure, especially supply-side structural adjustment. For example, the ‘blue sky defence battle’ of 2018 motivates future improvement of air as induced by supply-side structural emission reductions, while the in-depth structural adjustments of industry, energy, and transportation should be accelerated as well (NDRC, 2018). This motivates our focus on structural adjustment.

By considering multiple dimensions in addition to GHG emissions, such as air pollution, GDP and employment, this study investigates climate mitigation as part of a broader wellbeing framework. Air quality is a factor shaping the quality of life and thus a major concern in many Chinese provinces, also being included in sustainable development goal (SDG) 3 (United Nations, 2015) on good health and wellbeing and specifically targeted in SDG 3.9, to ‘substantially reduce the number of deaths and illnesses from hazardous chemicals and air …’ by 2030. Similarly, employment is identified as a target in SDG 8 on decent work and economic growth, specifically aimed towards decent work for all women and men by 2030.

Our study uses detailed data on physical goods, pollution, and monetary value across spatial scales (multi-regional input output [MRIO] analysis). Thus it enables the identification of specific components of the economic systems at which adjustments would have the highest benefits regarding wellbeing for the studied categories considered. In this way, we contribute to linking an industrial ecology perspective with that of ecological economics (wellbeing in terms of air quality and decent work (Pirgmaier and Steinberger, 2019)) and economics of climate change mitigation (reducing GHG emissions while considering GDP effects (Stern, 2007)).

2. Method

The adopted method is an elasticity analysis based on a MRIO model. On one hand, this multi-regional model allows for a systematic and comprehensive analysis of the quantitative relationship among regional economies, industries products, industrial structure, and technological differences, and analysing the correlation and influence of industries in different regions. On the other hand, an elasticity analysis allows measuring the relative change in the dependent variables caused by a marginal change in the independent variables. By combining the MRIO model with elasticity analysis, we can thus analyse the impact of the changes in industrial links or products' input–output links on the various regions and the entire country.

2.1. Multi-regional input–output model

Chenery (1953) and Moses (1955) independently proposed the MRIO model, being also known as the Chenery–Moses or column coefficient model and widely used in the literature. In this paper, the basic MRIO model is as follows:

$$\sum_{s=1}^{z} c_i^{rs}\left(\sum_{j=1}^{n} x_{ij}^{s} + \sum_{k=1}^{m} y_{ik}^{s}\right) + y_{ik}^{r} = X_i^{r},$$
$$(i,j \in \{1,2,...,n\})\,(k \in \{1,2,...,m\})\,(r,s \in \{1,2,...,z\})\ n,\ m,\ z \in N \tag{1}$$

where X_i^r represents total output of sector i in region r; c_i^{rs} is the supply coefficient from sector i in region r to region S, namely, the *trade coefficient* among different regions $\left(c_i^{rs} = \frac{t_i^{rs}}{t_i^{s}},\ \ t_i^{s} = \sum_r t_i^{rs}\right)$, where t_i^{rs} is the supply of product i from region r to region S (including production consumption and final demand); $x_{ij}{}^{s}$ the consumption of product *i* by sector *j* in region *S*; $y_{ik}{}^{s}$ the final use *k* for product *i* in region *S*; and $y_{ik}{}^{r}$ the national final use *k* of product *i*, which denotes export to other countries.

Eq. (1) can be rewritten as:

$$\sum_{s=1}^{z} c_i^{rs}\left(\sum_{j=1}^{n} a_{ij}^{s}X_j^{s} + \sum_{k=1}^{m} h_{ik}^{s}g_k^{s}\right) + h_{ik}^{r}g_k^{r} = X_i^{r} \tag{2}$$

where $a_{ij}{}^{s}$ represents the amount of input from sector *i* per unit worth of output of sector *j* in region $s\left(a_{ij}^{s} = \frac{x_{ij}^{s}}{X_j^{s}}\right)$, and can reflect the input structure of sector *j*, called *intermediate input coefficient*; $g_k{}^{s}$ represents total final use *k* of all products in region $s\left(g_k^{s} = \sum_{i=1}^{n} y_{ik}^{s}\right)$; $h_{ik}{}^{s}$ represents the proportion of final use *k* of product *i* in region *S* to the total amount of that final use $\left(h_{ik}^{s} = \frac{y_{ik}^{s}}{g_k^{s}}\right)$ and can reflect the proportion of various sectors' final use in region *S*, known as *final demand coefficient*. In the following, $c_i{}^{rs}$, $a_{ij}{}^{s}$, and $h_{ik}{}^{s}$ are uniformly referred to as *structural coefficients*.

Eq. (2) can expressed in matrix form as in Eqs. (3) and (4):

$$C(AX + HG) + H^{e}G^{e} = X \tag{3}$$

$$\begin{aligned} X &= (I - CA)^{-1}(CHG + H^{e}G^{e}) = (I - M)^{-1}(CHG + H^{e}G^{e}) \\ &= L(CHG + H^{e}G^{e}) \\ (L &= (I - CA)^{-1} = (I - M)^{-1}) \end{aligned} \tag{4}$$

The environmental emission coefficient is introduced to obtain the environmentally extended input–output model:

$$\begin{aligned} E &= B(I - CA)^{-1}(CHG + H^{e}G^{e}) = B(I - M)^{-1}(CHG + H^{e}G^{e}) \\ &= BL(CHG + H^{e}G^{e}) \end{aligned} \tag{5}$$

where *L* is the Leontief-like inverse; H^{e} the export coefficient matrix; *B* the emission coefficient matrix, where $b_{pi}{}^{r}$ is the emission of type *p* caused by per unit output of sector *i* in region *r*; and *E* the emission matrix, where $e_{pi}{}^{r}$ is the emission of type *p* of sector *i* in region *r* (thus, $e_p{}^{r}$ represents total emissions *p* in region *r* and e_p represents national total emissions of *p*).

This study analyses the relative change in various environmental emission of each region and the entire country when a certain element of one of the structural coefficients *A*, *C*, or *H* changes by 1%.

2.2. Elasticity of intermediate input coefficient A and inter-regional trade coefficient C

From Eqs. (4) and (5), changes of elements of the intermediate input coefficient *A* and the inter-regional trade coefficient *C* are closely related to changes in *M* and *L*, respectively. The complication is that when one of the elements in *A* or *C* changes, there will be multiple changes in matrix *M*. Specifically, when $a_{uv}{}^{w}$ changes, $\Delta m_{uv}{}^{qw} = c_u{}^{qw}\Delta a_{uv}{}^{w}$ $(q = 1,2,\ldots,z)$, the corresponding elements of product *u* in *all* regions flowing into sector *v* in region *w* will change in matrix *M*, and these changing elements belong to column (*n* (*w* − 1) + *v*). When $c_u{}^{qw}$changes, $\Delta m_{uv}{}^{qw} = \Delta c_u{}^{qw}a_{uv}{}^{w}$ $(v = 1,2,\ldots,n)$, the corresponding elements of product *u* in region *q* flowing into *all* sectors in region *w* will change in matrix *M*, and these changing elements belong to row (*n*(*q* − 1) + *u*).

Furthermore, the Sherman–Morrison–Woodbury formula (Sherman and Morrison, 1949, 1950; Woodbury, 1950) describes the change in the inverse of a matrix when a row or column changes. This study makes use of this point to obtain Eq. (6) by derivation and transformation:

$$\Delta L = \frac{-LKP^{T}L}{1 + P^{T}LK} \tag{6}$$

where $\Delta M = KP^{T}$, *K* and *P*are two *nz* × 1 vectors with the following properties:

(1) If $a_{uv}{}^{w}$ changes,

$$K = -\begin{bmatrix} \Delta m_{1v}^{1w} \\ \vdots \\ \Delta m_{uv}^{1w} \\ \vdots \\ \Delta m_{nv}^{1w} \\ \vdots \\ \Delta m_{1v}^{qw} \\ \vdots \\ \Delta m_{uv}^{qw} \\ \vdots \\ \Delta m_{nv}^{qw} \\ \vdots \\ \Delta m_{1v}^{zw} \\ \vdots \\ \Delta m_{uv}^{zw} \\ \vdots \\ \Delta m_{nv}^{zw} \end{bmatrix} (\Delta m_{iv}^{qw} = 0, \forall\ i \neq u)\ ,\ P = \begin{bmatrix} 0 \\ \vdots \\ 1(Row(n(w-1)+v)) \\ \vdots \\ 0 \end{bmatrix}$$

The matrix *K* is corresponding with the *column* (n(w – 1) + *v*) of the negative matrix *M*, and in the matrix *P*, only the value in the *row* (n (w – 1) + *v*)is 1.

The corresponding change in the environmental emission matrix is expressed as:

$$\Delta E = B\Delta L(CHG + H^{e}G^{e}) = \frac{-BLKP^{T}L(CHG + H^{e}G^{e})}{1 + P^{T}LK} \tag{7}$$

The elasticity of regional and national environmental emissions due to the change in the direct consumption coefficient $a_{uv}{}^{w}$ is expressed as:

$$\begin{aligned} \varepsilon_{e_p^{r}, a_{uv}^{w}} &= \frac{\Delta e_p^{r}/e_p^{r}}{\Delta a_{uv}^{w}/a_{uv}^{w}} \\ \varepsilon_{e_p, a_{uv}^{w}} &= \frac{\Delta e_p/e_p}{\Delta a_{uv}^{w}/a_{uv}^{w}} \end{aligned} \tag{8}$$

where $\Delta a_{uv}{}^{w}/a_{uv}{}^{w} = 0.01$, that is $a_{uv}{}^{w}$ changes by 1%; structure coefficients *C* and *H* are similar as per the following.

(2) If $c_u{}^{qw}$ changes,

$$K = \begin{bmatrix} 0 \\ \vdots \\ 1(Row(n(q-1)+u)) \\ \vdots \\ 0 \end{bmatrix},\ P = -\begin{bmatrix} \Delta m_{u1}^{q1} \\ \vdots \\ \Delta m_{u1}^{qw} \\ \vdots \\ \Delta m_{u1}^{qz} \\ \vdots \\ \Delta m_{uv}^{q1} \\ \vdots \\ \Delta m_{uv}^{qw} \\ \vdots \\ \Delta m_{uv}^{qz} \\ \vdots \\ \Delta m_{un}^{q1} \\ \vdots \\ \Delta m_{un}^{qw} \\ \vdots \\ \Delta m_{un}^{qz} \end{bmatrix} (\Delta m_{uv}^{qs} = 0, \forall\ s \neq w)$$

The matrix *P* is corresponding with the ***row*** (*n*(*q* − 1) + *u*) of the negative matrix *M*, and in the matrix *K*, only the value in the ***column*** (*n* (*q* − 1) + *u*) is 1.

In this case, the change in *E* is expressed as:

$$\Delta E = B\Delta L(\Delta CHG + H^e G^e) = \frac{-BLKP^T L(\Delta CHG + H^e G^e)}{1 + P^T LK} \tag{9}$$

Consequentially, the elasticity of environmental emissions of each region and the entire country caused by the change in the inter-regional trade coefficient $c_u{}^{qw}$ can be expressed as:

$$\begin{aligned} \varepsilon_{e_p^r, c_u^{qw}} &= \frac{\Delta e_p^r / e_p^r}{\Delta c_u^{qw} / c_u^{qw}} \\ \varepsilon_{e_p, c_u^{qw}} &= \frac{\Delta e_p / e_p}{\Delta c_u^{qw} / c_u^{qw}} \end{aligned} \tag{10}$$

2.3. Elasticity of final demand coefficient H

If $h_{uv}{}^{w}$ (the export coefficient is expressed as $h_u{}^{w}$) changes, the change in the environmental emission matrix is:

$$\begin{aligned} \Delta E &= BLC\Delta HG \\ \Delta E &= BL\Delta H^e G^e \end{aligned} \tag{11}$$

Then, the elasticity of environmental emissions in each region and the entire country to the change in the final demand coefficient $h_{uv}{}^{w}$ can be expressed as:

$$\begin{aligned} \varepsilon_{e_p^r, h_{uv}^w} &= \frac{\Delta e_p^r / e_p^r}{\Delta h_{uv}^w / h_{uv}^w} & & \varepsilon_{e_p^r, h_{uv}^w} = \frac{\Delta e_p^r / e_p^r}{\Delta h_u^w / h_u^w} \\ & & \text{or} & \\ \varepsilon_{e_p, h_{uv}^w} &= \frac{\Delta e_p / e_p}{\Delta h_{uv}^w / h_{uv}^w} & & \varepsilon_{e_p, h_{uv}^w} = \frac{\Delta e_p / e_p}{\Delta h_u^w / h_u^w} \end{aligned} \tag{12}$$

2.4. Data source

The data used in this study include input–output and environmental emission data. Input–output data are from the Chinese MRIO table for 2012, obtained from the China Emission Accounts and Datasets (Mi et al., 2017). The MRIO table is compiled according to the input–output tables of 30 provinces and municipalities (except for Tibet, Taiwan, Hong Kong, and Macao), published by the National Bureau of Statistics of China (Mi et al., 2017) and reports monetary flows. The national economy is divided into 30 sectors and six categories of final demand (rural household consumption, urban household consumption, government consumption, fixed capital formation, inventory changes, and exports) (see Supplementary material 2 for details). The underlying dataset accounts for all imports and exports with the rest of the world. Additionally, this study analyses three major GHGs (CO_2, CH_4 and N_2O) and eight atmospheric pollutants (SO_2, NOx, NH_3, CO, BC, OC, $PM_{2.5}$, and NMVOCs). The relevant environmental emission data are derived from the database of Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS, 2012).

3. Results and discussion

3.1. Basic principles and overall framework for selecting key structural adjustment coefficients

This study selected 30 provinces (municipalities), 30 sectors, and six final-use categories, so the structural adjustment included 27,000 intermediate input transactions, 5400 final demand transactions, and 26,100 inter-regional trade transactions. For the 11 gas types, 643,500 elasticity coefficients at the national level and 19,305,000 elasticity coefficients at the regional level, were calculated.[2] Considering the large set of elasticity coefficients, to determine whether there is a key adjustable structural transaction, the overall framework shown in Fig. 1 was used for multiple rounds of screening. The screening process is according to the following three principles: (1) it has significant GHG emission reduction effect at the national level; (2) it has a relevant emission reduction effect on pollutants in various regions, and matches the regional distribution pattern of pollution degree with emission reduction effects as much as possible; and (3) on the basis of the first two steps, the socio-economic impact at the national and provincial levels should be minimized as much as possible and the balanced regional development strategy taken into consideration.

In accordance with principles (1) and (2) 'with obvious effect of interprovincial pollution reduction', this study takes 0.01 as cut-off point. All flows that were not filtered out are regarded as *Basic Options*. These transactions have the following two characteristics: (1) any national GHG elasticity coefficient is greater than 0.01 and (2) the elasticity coefficient of any one type of air pollutant in any region is greater than 0.01. After this, 76 groups of *Basic Options* transactions were selected, including 45 intermediate input transactions, nine inter-regional trade transactions, and 22 final demand transactions, involving a total of 20 provinces, as shown in Supplementary material 2.

The warming potentials of different GHGs are converted into carbon dioxide equivalent for direct comparison. We consider their Global Warming Potential (GWP). This is because ultimately their joint contribution to climate change is relevant for the overall greenhouse effect. The structural adjustments whose elasticity coefficient causes a comprehensive GHGs reduction of more than 0.01 at the national level are classified as *Advanced Options I*. The empirical results are shown in Section 3.2.1. According to the condition of 'the effect of emission reduction matches the regional distribution of pollution status' in principle (2), this study adopts a weight grade method to sum up the pollution reduction effects in all regions. This weight is the proportion of the per capita emissions of each province in the national per capita emissions. Moreover, the union set of these structural transactions whose reduction effect for each pollutant ranked in the first 20% is classified as *Advanced Options II*. The empirical results are shown in Section 3.2.2. The subset where *Advanced Options I* and *Advanced Options II* intersect are the effective co-control spots (ECCs), which can simultaneously control national GHG and local pollutant emissions. The empirical results are shown in Section 3.2.3.

If the ECCs set is empty, the filtering process ends. If the ECCs set is non-empty, the socio-economic impact of each ECC needs to be further evaluated according to principle (3). The 'national and provincial socio-economic shocks' in principle (3) are represented by the elasticity values of GDP loss and employment loss at the national and provincial levels. According to the condition of 'taking into account the balanced development of different regions' in principle (3), this study uses the weight grade method to synthesize the provincial GDP loss, where the weight is the ratio of national GDP to provincial GDP. Finally, *Advanced Options III* was obtained according to the criterion that both the national GDP loss and national employment loss are below 0.01%, when the structural transactions that caused the provincial comprehensive GDP loss ranked in the top 20% were excluded. When *Advanced Options III* is intersected with the ECCs set, the new subset is represented by the structural adjustment synergy points with obvious environmental emission reduction effects and limited economic impact, called the sweet spots (Ss). The empirical results are shown in Section 3.3.

3.2. Identify effective co-control spots

3.2.1. Structural transactions with significant national GHG emission reduction effects

In this study, 22 structural transactions were selected as *Advanced Options I*, as shown in Fig. 2, which mainly correspond to intermediate inputs (18 transactions).

The results show that the structural transactions with the most significant impact on GHGs are those for the agricultural inputs of food and tobacco sector in Shandong, for which a 1% cut would result in a 0.029% reduction of national GHG emissions. Further, the N_2O

---

[2] See formulas (8), (10) and (12), and all elasticity results can be obtained from the first author.

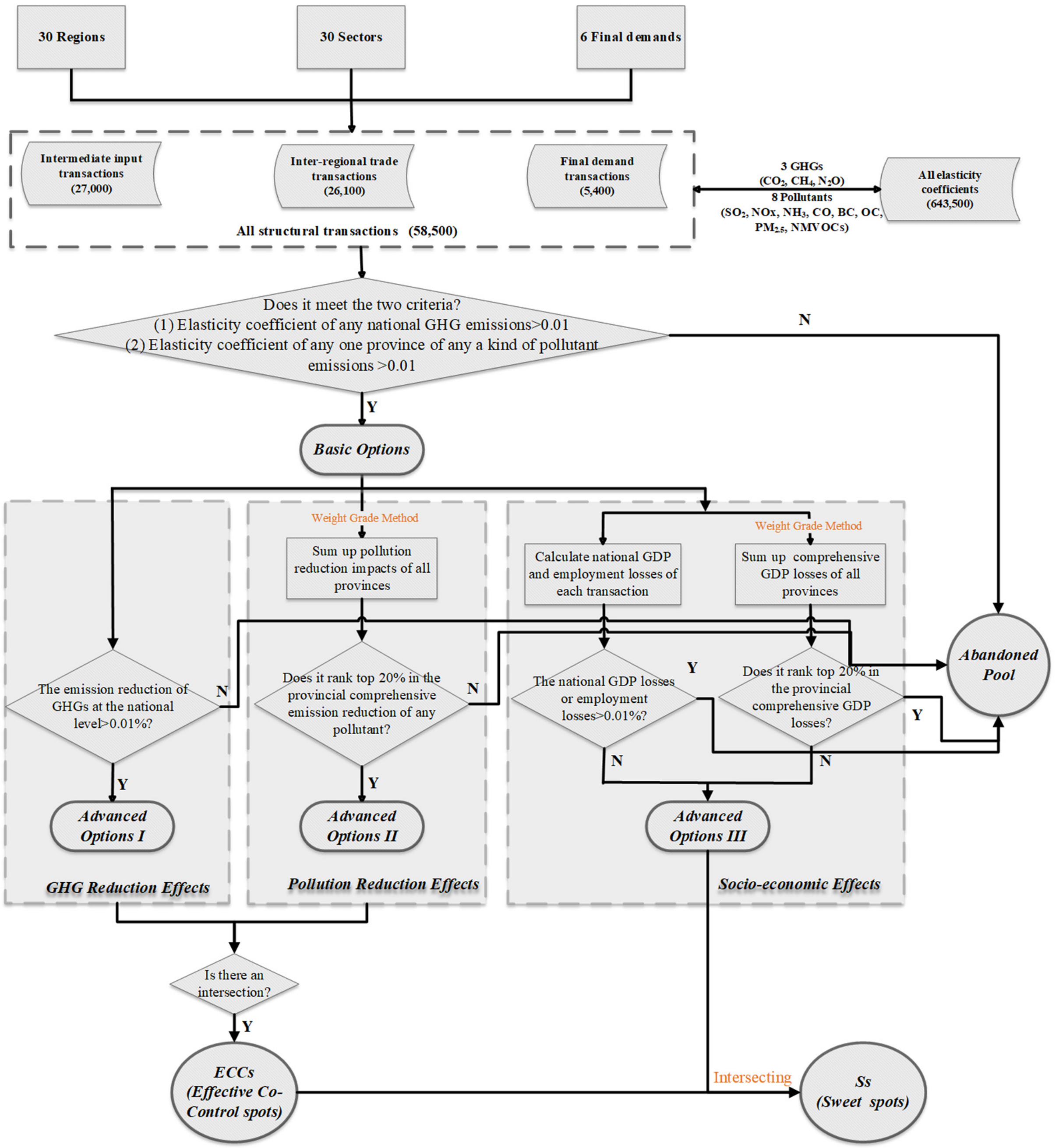

Fig. 1. Overall filter framework.

emission reduction brought by this structural adjustment is also the largest (0.052%), while the CH_4 emission reduction ranks seventh (0.016%). The agricultural inputs in the production process of food and tobacco in Henan rank second in terms of the reduction effects on GHG emissions. An input reduction of 1% can reduce the GHG emission by 0.021%, of which the N_2O emission reduction effect is the most significant, ranking second (0.036%). A 1% decrease in the coal input of the electricity production process in Henan can reduce GHG emissions by 0.019% (ranking third) and also lead to the maximum CH_4 emission reduction (0.031%), but its effect on the national CO_2 and N_2O emission reduction is no more than 0.01%. Additionally, the structural transactions that could significantly control GHG emissions also include self-inputs in the food and tobacco sector in Shandong; agricultural inputs in the food and tobacco sectors of Sichuan, Hubei, Inner Mongolia, Jiangsu, and Liaoning; self-inputs for coal mining in Inner Mongolia; coal inputs in the petroleum refining and coking of Hebei; coal inputs in the electricity sectors of Hebei, Jiangsu, Guangdong, and Zhejiang; self-inputs for the chemical industries of Shandong and Jiangsu; self-inputs in the agricultural sector of Henan; self-supply of agricultural products within Shandong; fixed capital formation in agriculture and construction of Hebei; and urban household consumption of agricultural products in Guangdong.

Generally, the self-inputs in the chemical industry of Jiangsu had a significant impact on the emission reduction of the three GHGs, with the reduction ratios being 0.012% (CO_2), 0.010% (CH_4), and 0.010% (N_2O). The GHG emission reduction effect caused by the coal input in the mining industry of Inner Mongolia, the petroleum refining and coking of Hebei, and the electricity industries of Henan, Jiangsu, Guangdong, Zhejiang and Hebei is driven mainly by the CH_4 emission reduction, of 0.024%, 0.025%, 0.031%, 0.024%, 0.018%, 0.017% and 0.016%, respectively. It is worth noting that the self-inputs in the production process of chemical products in Shandong province and

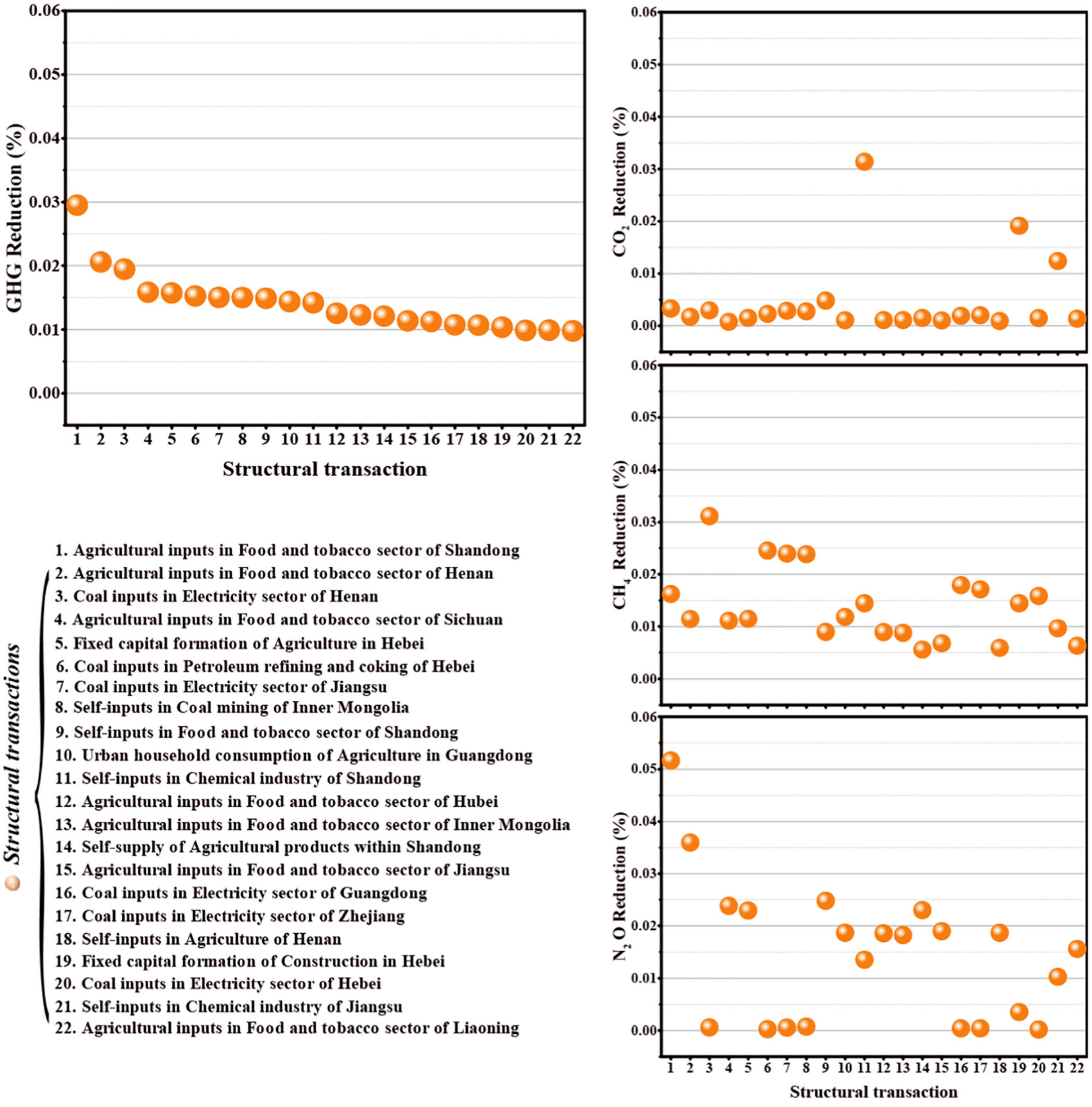

Fig. 2. Percentage change in CO_2, CH_4, and N_2O and the sum of GHGs at the national level caused by a 1% reduction in the structural transactions in *Advanced Options I*.

fixed capital formation in construction of Hebei, are two of the few structural transactions that significantly reduce CO_2 emissions. This former's adjustment contributed to the largest reduction in CO_2 emissions (0.031%) in all 76 structural transactions and also reduced CH_4 emissions by 0.014% (ranking ninth) and N_2O emissions by 0.014% (ranking 18th). The latter's adjustment can reduce CO_2 emissions by 0.019% (ranking ninth), CH_4 emissions by 0.014% (ranking tenth) and N_2O emissions by 0.004% (ranking 38th). The adjustment of the remaining 12 structural transactions reduced mainly the national N_2O emission by 0.016%–0.052%.

3.2.2. Structural transactions with significant provincial comprehensive pollutant reduction effect

In this study, 40 structural transactions meeting the condition *Advanced Options II* were selected (see Figs. 3 and 4). Among them, adjusting fixed capital formation of construction in Hebei province can simultaneously reduce the provincial comprehensive emissions of various pollutants, and the control effect of $PM_{2.5}$, BC, and OC emissions ranks second, while that of SO_2, NOx, CO, and NMVOCs also ranks in the top 10. Adjusting the fixed capital formation of the construction sector in Zhejiang has a significant provincial comprehensive emission reduction effect on $PM_{2.5}$ (ranking third), SO_2 (ranking ninth), NOx (ranking third), BC (ranking third), CO (ranking fifth), OC (ranking sixth) and NMVOCs (ranking eighth).

From Fig. 3, the provincial comprehensive emission reduction effect of adjusting the fixed capital formation of the construction sector in Shanxi ranks first for $PM_{2.5}$, BC, and OC, second for SO_2 and forth for CO, but only 40th and 21st for NH_3 and NMVOCs, respectively. The structural transaction with the most significant provincial comprehensive reduction for SO_2 and NOx are the self-inputs in the electricity sector of Beijing, and its adjustment ranking twelfth in the reduction effect of comprehensive $PM_{2.5}$ in all provinces. For CO, the structural transaction with the largest provincial comprehensive emission reduction is the self-inputs in the metallurgy sector of Jiangsu, its reduction effects ranking in the top five for $PM_{2.5}$, SO_2 and NMVOCs. For NH_3, the adjustment of the agricultural inputs in the food and tobacco sector of

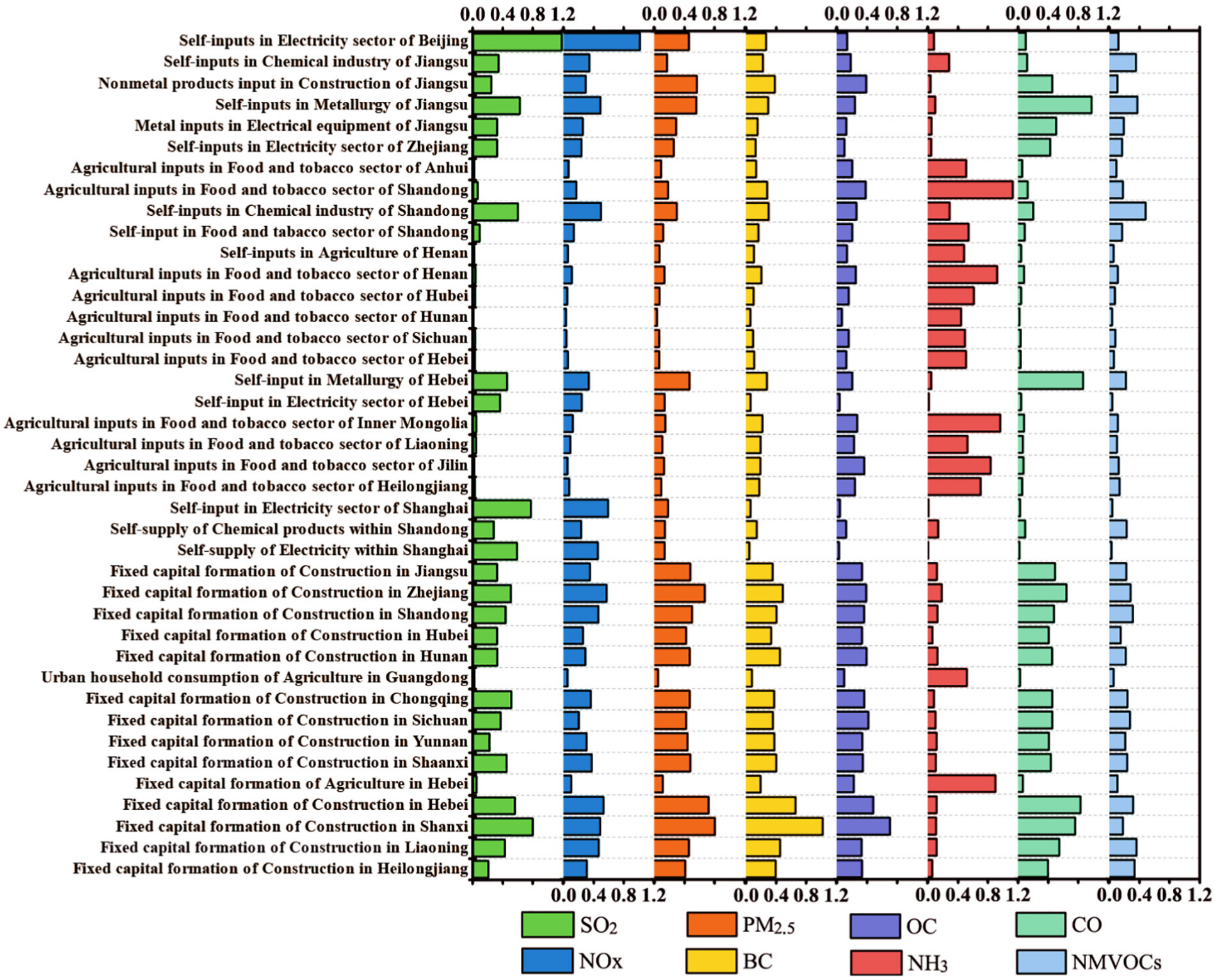

Fig. 3. Percentage of provincial comprehensive pollutant emission reduction caused by the 1% reduction of the structural transactions in *Advanced Options II* (i.e. the sum result with the proportion of per capita emissions of each province in the national per capita emissions as the weight, which is not applicable to the threshold range of 0.01).

Shandong has the strongest provincial comprehensive emission reduction effect, and its emission reduction effect on OC also ranks seventh. For NMVOCs, the self-inputs in the chemical industry of Shandong have the most significant provincial comprehensive emission reduction effect, its reduction ranking in the top five for SO_2 and NOx. In addition, the structural transactions that can significantly reduce multiple pollutants also include the self-inputs in the metal smelting industries of Hebei; non-metal products inputs in construction of Jiangsu; self-inputs in the chemical industry of Jiangsu; and fixed capital formation of construction in Shandong, Jiangsu, Liaoning, Shaanxi, Chongqing, Hunan, Sichuan, Heilongjiang and Yunnan.

3.2.3. *Effective co-control spots*

From the intersection of *Advanced Options I* in Section 3.2.1 and *Advanced Options II* in Section 3.2.2, there are 13 structural transactions that can simultaneously control GHGs and pollutants (i.e. ECCs). They include self-inputs in the chemical industries of Shandong and Jiangsu; agricultural inputs in the food and tobacco sectors of Shandong, Sichuan, Inner Mongolia, Liaoning, Henan, and Hubei; self-inputs in the agricultural sector of Henan; self-inputs in the food and tobacco sector of Shandong; fixed capital formation of agriculture and construction in Hebei, and urban agricultural household consumption in Guangdong. For example, a 1% reduction in the fixed capital formation in the construction sector of Hebei would result in a 0.010% reduction in national GHG emissions. Additionally, its adjustment has not only a significant effect on all pollutants in Hebei with percentages from 0.02% (NH_3) to 0.35% (CO), but also a reduction effect of more than 0.01% for a variety of pollutants in other nine provinces. The regional matching degree of most pollutants' emission reduction is relatively high, as shown in Fig. 4.

Therefore, the coordinated emission reduction of GHGs and local pollutants can start with a focus on four components of supply chains. First, it is important to decrease the consumption of the chemical industry for its own sectoral products (e.g. demand for rubber in the manufacture of tires) in Shandong and Jiangsu and improving the utilization rate; second, reduce the agricultural products input demand of the food processing industries in Shandong, Sichuan, Inner Mongolia, Liaoning, Henan and Hubei, and the input demand of the food processing industry in Shandong province for its own sectoral products (e.g. demand for fresh meat in the production of meat products and for processed rice and flour in the production of instant noodles and other convenience foods); third, shift the fixed capital formation in Hebei from agriculture and construction to other sectors; and fourth, promote the rational consumption of agricultural products, especially meat and meat products[3] by urban residents in Guangdong, while reducing food

---

[3] According to the statistics, the urban household consumption of agricultural products in Guangdong ranked first in China in 2017 and meat consumption accounted for 22% of total consumption (according to the Guangdong Statistical Yearbook Accounting Data (http://www.gdstats.gov.cn/tjsj/gdtjnj/)). This result shows that reducing the urban residents' consumption of agricultural products in Guangdong contributes to the reduction of national

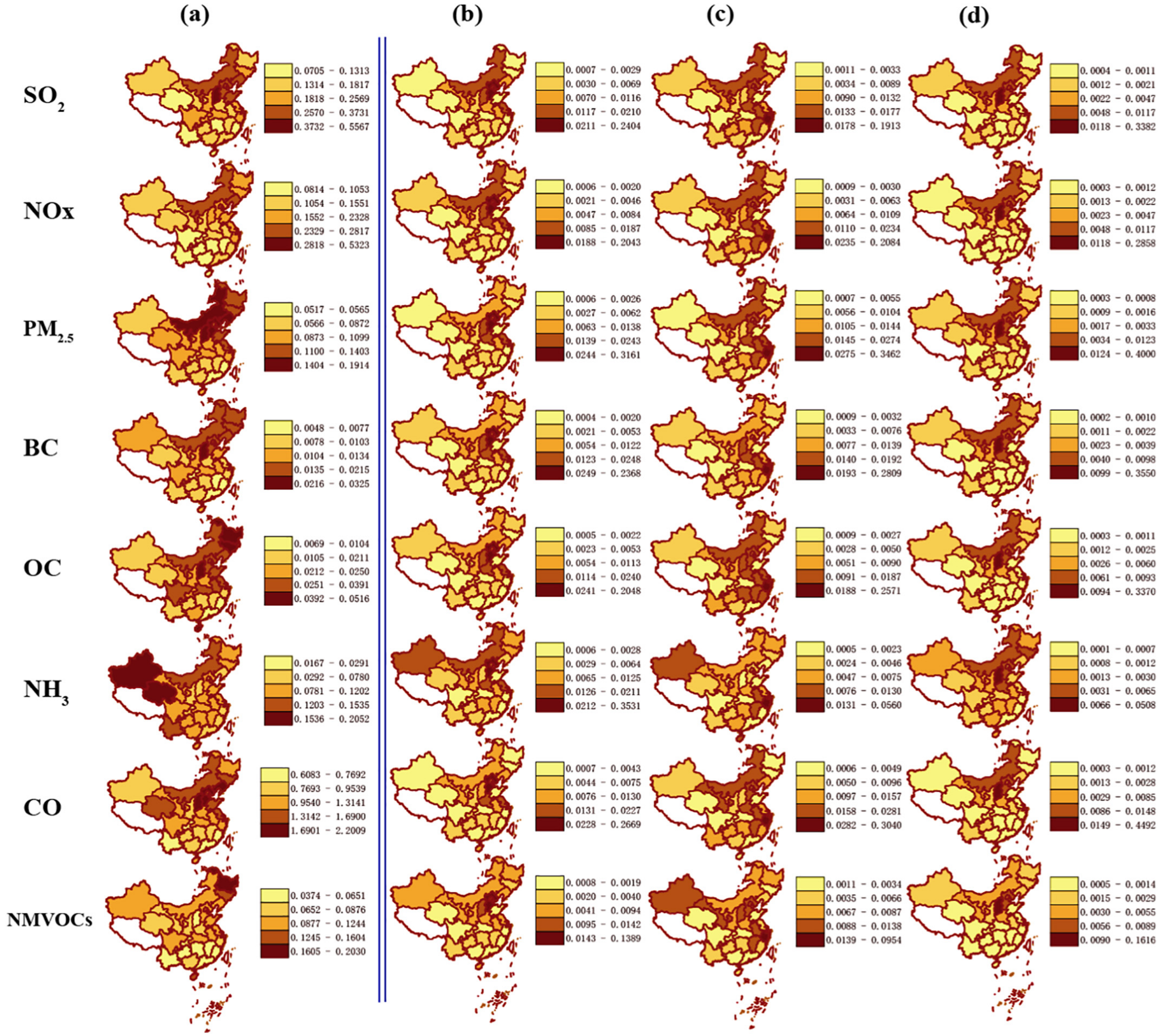

Fig. 4. Matching result of the provincial pollutant emission reduction effect and current provincial pollutant emission distribution. Fig. 4(a) shows the provincial per capita emissions of various pollutants (the units are Mt. for CO_2 and Kt for other pollutants per 10,000 people). Due to space limitations, by ranking the reduction effect of each structural transaction on eight pollutants and taking the average value, this study selected the main structural transactions with the mean ranking in the top three from *Advanced Options II*. The reduction percentage (%) of provincial pollutant emissions caused by the reduction of 1% is shown in Fig. 4(b)–(d). Fig. 4(b) represents the fixed capital formation of construction in Hebei, Fig. 4(c) the fixed capital formation of construction in Zhejiang, and Fig. 4(d) the fixed capital formation of construction in Shanxi.

waste as much as possible.

3.3. Identify sweet spots

According to the condition *Advanced Options III*, there are eight structural transactions that would allow to reduce GHGs and local pollutants cooperatively and only cause a small economic impact (i.e. Ss), as shown in Fig. 5. They include agricultural inputs in the food and tobacco sector of Inner Mongolia, Sichuan, Liaoning, and Hubei; self-inputs in the agriculture of Henan; self-inputs in the food and tobacco sector of Shandong; fixed capital formation of the agricultural sector of Hebei; and urban household consumption of agricultural products in Guangdong. For example, if Hebei reduces its agricultural fixed capital formation by 1%, it could reduce national GHG emission by 0.016% (ranking fifth). Further, the emission reduction of at least two gases in 18 regions exceeded 0.01% and the provincial comprehensive emission reductions of NH_3 ranked in the top 5 of 76 transactions, especially it can reduce the NH_3 emissions of three major provinces by 0.030% (Henan), 0.220% (Hebei) and 0.009% (Jiangsu), respectively. Moreover, the accompany GDP loss and employment loss of reducing fixed capital formation by 1% in Hebei are only 0.003% (ranking 35th) and 0.006% (ranking 19th), and provincial comprehensive GDP loss ranked

---

(*footnote continued*)
methane and nitrous oxide emission and provincial comprehensive ammonia emissions, as meat is the main source of these emissions (e.g. animals themselves emit large amounts of methane, animal husbandry consumes land and leads to deforestation and increases greenhouse gas emissions).

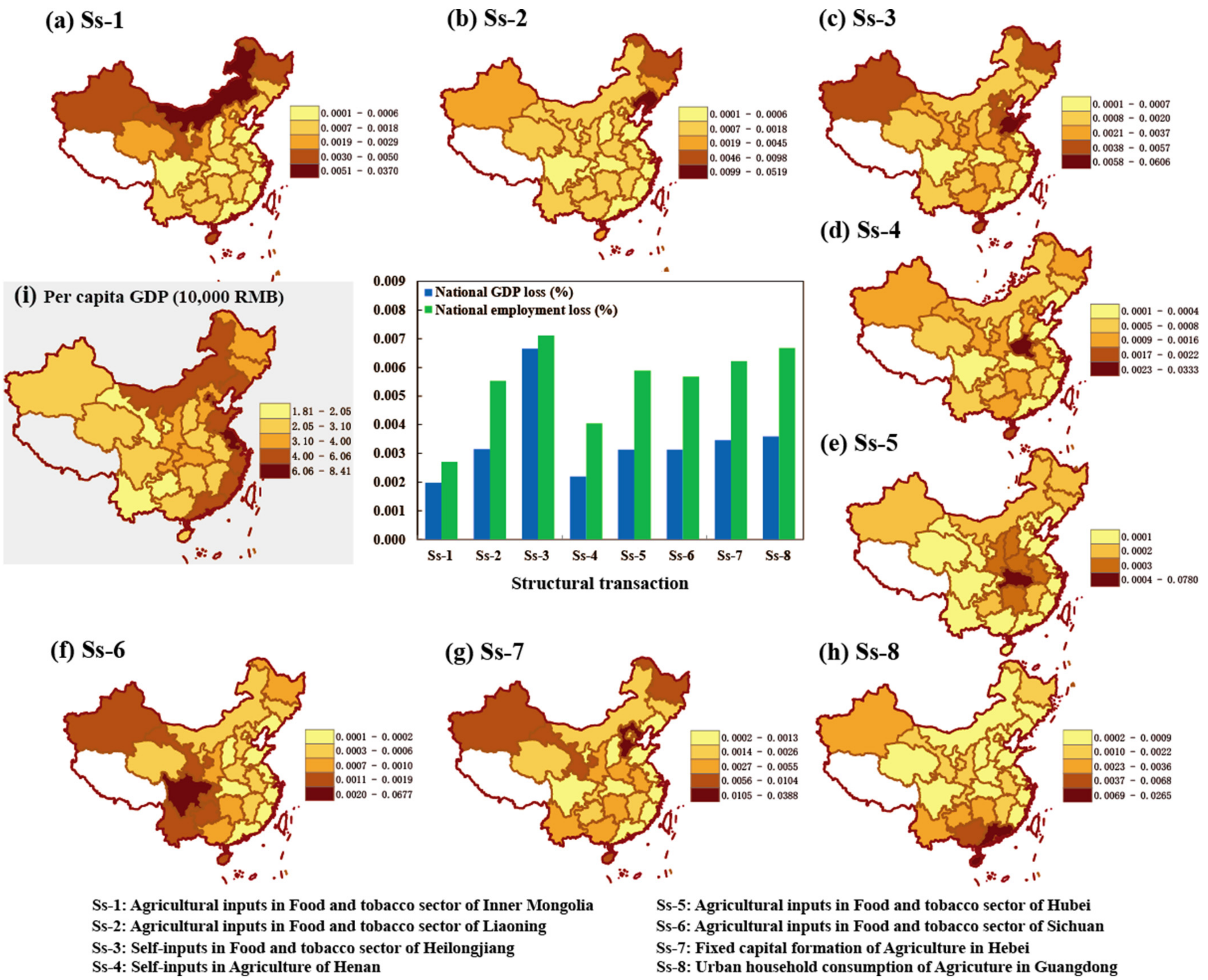

Fig. 5. National GDP, employment, and provincial GDP losses caused by a 1% reduction in Ss. The central bar chart shows national GDP and employment losses, Figs. 5(a)–(h) respectively represent the GDP percentage loss (%) in each region caused by changes in eight SS, and Fig. 5(i) shows the current situation of per capita GDP in each region.

30th.

Therefore, appropriate socio-economic safeguard measures should be taken to reduce the negative impacts on national and provincial GDP and employment. This holds for instance when adjusting other remaining ECCs particularly, including the fixed capital formation in construction of Hebei; the self-inputs in the chemical industries of Shandong and Jiangsu, as well as agricultural inputs in the food and tobacco industries of Shandong and Liaoning. Specifically, when the fixed capital formation of construction in Hebei is reduced, special attention should be given to the adverse impact on the GDP and employment in Hebei, Shanxi and Jiangsu. In the same vein, when the self-inputs in the chemical industry of Shandong are reduced, special attention should be given to the adverse impact on the GDPs of Shanxi, Inner Mongolia, Heilongjiang, Shandong, Shaanxi, and Xinjiang, as well as employment in Shanxi and Shandong. Special attention should be given to the GDP impact on Shanghai, Anhui, and Jiangsu, as well as the employment impact on Anhui and Jiangsu when adjusting the self-inputs in the chemical industry of Jiangsu. When adjusting the agricultural inputs in the food and tobacco industry of Shandong, particular attention should be paid to the GDP impact on Heilongjiang, Shandong, Hainan, and Xinjiang, as well as the employment impact on Hebei, Heilongjiang, Anhui, Shandong, Hainan, and Xinjiang. When adjusting the agricultural products inputs in the food and tobacco industry of Liaoning, politicians should control for the impact on the GDP and employment of the same province, and employment of Heilongjiang. The effects of adjusting ECCs on GDP and employment of each province are shown in Supplementary material 3.

4. Conclusions and policy recommendations

This study proposes an elasticity analysis method based on the MRIO model to measure the changes in all types of GHG and pollutant emissions caused by the changes in intermediate input and inter-regional trade transactions in any region, as well as final demand transactions. The corresponding socio-economic costs (including national and regional GDP and employment losses) are also evaluated. On this basis, this study constructs a filter framework to identify the key structural transactions that can significantly co-control national GHGs and local pollutants with small socio-economic impacts. This study also takes 30 provinces (municipalities) in China as an example and takes a variety of GHGs (CO_2, CH_4, and N_2O) and local pollutants (SO_2, NOx, NH_3, CO, BC, OC, $PM_{2.5}$, and NMVOCs) as objects to demonstrate and verify the effectiveness of this method. The empirical analysis leads to the following conclusions and policy implications.

Most reductions in both GHG emissions and air pollutants at the lowest level of economic losses can be achieved in the agricultural sector, hence environmental emission reduction strategies through structural adjustments should focus here. In detail, the current carbon pricing scheme in China is focusing on only CO_2 and is related to the power sector, and it will probably proposed to cover other key emission industries such as petroleum chemistry, building materials, steel, nonferrous metals, paper making and aviation. The results suggest that most sweet spots mostly reduce non-CO_2 GHGs emissions and that the agricultural sector hold potentials for significant and effective GHG emissions abatement with relatively small economic losses. Thus agriculture could be covered in GHG emissions reduction policies and non-CO_2 GHG should be part of the carbon pricing scheme. Meanwhile, the realization of related structural adjustment through market mechanism instead of command-and-control is also important.

In terms of controlling local pollutants, the selected sweet spots that are related to agricultural products, have the strongest effect on NH_3 emission, followed by $PM_{2.5}$, BC (black carbon) and OC (organic carbon), the CO, SO_2 and NOx emission reduction are the weakest. Therefore, the structural adjustment measures targeted NH_3 emission reduction could be supported in the aspects of agricultural sources. But the results show that there exists an effective co-control spot – fixed capital formation adjustment of the construction sector in Hebei, which reduces significantly the main components of haze ($PM_{2.5}$, SO_2, and NOx) and also BC and OC. Therefore, focusing on the adjustment of this structural transaction can further improve the governance of haze.

Auxiliary measures could compensate for economic losses. For instance, a measure to improve industries' productivity efficiency can be expected to bring positive economic impacts even if some specific resource inputs might be reduced. However, it needs to be carefully designed to avoid the erosion of emission reduction effects brought by structural adjustment, as higher efficiency might increase the scale of industries and lead to higher environmental emissions. At this point, additional supporting means may be necessary, such as taxing fossil fuels to avoid the decline of energy-use cost. In any case, it is important to note that reductions in air pollution will have beneficial repercussions on economic performance, too, as health burdens to the economy will be largely reduced (Matus et al., 2012).

The computational method and analytical framework proposed in this study have a wide range of applications. For instance, as long as corresponding MRIO data can be obtained, it can be used to examine the effect of the changes in the global trade structure on the co-control of multiple emissions (CO_2 vs. non-CO_2 GHGs, global GHG emissions vs. regional pollutant emissions) in various countries. It can also be used to help other countries that face the challenge of dual emission reduction for GHGs and pollutants as to identify the key structural adjustment points in other multi-regional contexts. Thus it could be used to analyse the adjustment and allocation of structural transactions among different cities and towns within a single province or a country. It could also be applied in a multi-country context. Conversely, the empirical accounting results for China in this study provide not only a set of tailored co-control schemes, but also the foundation and basis for a series of other studies on its emission reduction policies. For example, in the application of such tools as computable general equilibrium to analyse the effect of some emission reduction policies, in addition to using the policy environment of 'business as usual', one can also refer to the results of this study to construct a policy environment with structural adjustment and compare the environmental emission reduction effects and socio-economic impacts of reduction policies under structural adjustment or otherwise. Future studies should analyse the interaction between the effects of structural adjustment measures and socio-economic policies and explore how to design supporting policies that are helpful in not only nurturing social and economic growth, but also maintaining the emission reduction effects of structural adjustment.

China has frequently been acknowledged as being the workshop of the world, highlighting its special role for international supply chains in recent decades, while at the same time becoming a major contributor of global GHG emissions and other pollutants. Studies have highlighted the heterogeneity in bilateral trade relationships across the globe (Davis and Caldeira, 2010). Unfortunately, the underlying dataset of our study accounts is not more explicit on the "rest of the world". Future approaches could merge the Chinese MRIO with other multi-regional input-output data to disentangle international relationships of China with different export destinations and vice versa. Such an approach could help identifying international sweets spots of the global trade and production network.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2020.106590.

Funding sources

This work was supported by the National Key Research and Development Program of China [grant number 2016YFA0602600]; and the National Natural Science Foundation of China [grant numbers 71422011, 71461137006, and 71521002]. This work was also supported by the Bundesministerium für Bildung und Forschung (BMBF) grant "Klimapolitische Maßnahmen und Transformationspfade zur Begrenzung der globalen Erwärmung auf 1.5 °C (PEP1p5) [grant number 01LS1610B].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Altemeyer-Bartscher, M., Markandya, A., Rübbelke, D.T.G., 2013. International side-payments to improve global public good provision when transfers are refinanced through a tax on local and global externalities. Int. Econ. J. 28, 71–93.

Bain, P.G., Milfont, T.L., Kashima, Y., Bilewicz, M., Doron, G., Garðarsdóttir, R.B., Gouveia, V.V., Guan, Y., Johansson, L.-O., Pasquali, C., Corral-Verdugo, V., Aragones, J.I., Utsugi, A., Demarque, C., Otto, S., Park, J., Soland, M., Steg, L., González, R., Lebedeva, N., Madsen, O.J., Wagner, C., Akotia, C.S., Kurz, T., Saiz, J.L., Schultz, P.W., Einarsdóttir, G., Saviolidis, N.M., 2015. Co-benefits of addressing climate change can motivate action around the world. Nat. Clim. Chang. 6, 154–157.

Bongardt, D., Creutzig, F., Hüging, H., Sakamoto, K., Bakker, S., Gota, S., Böhler-Baedeker, S., 2013. Low-Carbon Land Transport: Policy Handbook. Routledge.

Buchholz, W., Markandya, A., Rübbelke, D.T.G., Vögele, S., 2020. Co-Benefits under the Market Mechanisms of the Paris Agreement, Ancillary Benefits of Climate Policy - New Theoretical Developments and Empirical Findings. Springer International Publishing.

Cadarso, M.A., Monsalve, F., Arce, G., 2018. Emissions burden shifting in global value chains—winners and losers under multi-regional versus bilateral accounting. Econ. Syst. Res. 30, 439–461.

Carvalho, T., Almeida, E., 2009. The Global Environmental Kuznets Curve and the Kyoto Protocol. (CEP 36036, 330).

Economic Daily, 2019. 2019: regional policies and stable growth, China Regional Economic Forum 50. http://cen.ce.cn/more/201904/01/t20190401_31780321.shtml Beijing.

Chenery, H.B., 1953. The Structure and Growth of the Italian Economy. US Mutual Security Agency, Rome.

Christis, M., Geerken, T., Vercalsteren, A., Vrancken, K.C., 2017. Improving footprint calculations of small open economies: combining local with multi-regional input-output tables. Econ. Syst. Res. 29, 25–47.

Creutzig, F., He, D., 2009. Climate change mitigation and co-benefits of feasible transport demand policies in Beijing. Transp. Res. D 14, 120–131.

Davis, S.J., Caldeira, K.J.P.o.t.N.A.o.S, 2010. Consumption-Based Accounting of CO_2 Emissions. 107. pp. 5687–5692.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Kadner, S., Minx, J.C., Brunner, S., 2014. Technical summary. In: Climate Change 2014: Mitigation of Climate Change. IPCC Working Group III Contribution to AR5. Cambridge University Press.

Fotourehchi, Z., 2016. Health effects of air pollution: an empirical analysis for developing countries. Atmos. Pollut. Res. 7, 201–206.

GAINS, 2012. Mitigation of air pollutants and greenhouse gases program. http://gains.iiasa.ac.at/models/gains_models3.html, Accessed date: 28 March 2012.

Grossman, G.M., Krueger, A.B., 1995. Economic growth and the environment. Quart. J. Econ. 110, 353–377.

Guan, D., Peters, G.P., Weber, C.L., Hubacek, K., 2009. Journey to world top emitter: an analysis of the driving forces of China's recent CO_2 emissions surge. Geophys. Res. Lett. 36, L04709.

Guo, J., Zhang, Z., Meng, L., 2012. China's provincial CO_2 emissions embodied in international and interprovincial trade. Energy Policy 42, 486–497.
Hong, J., Shen, G.Q., Guo, S., Xue, F., Zheng, W., 2016. Energy use embodied in China's construction industry: a multi-regional input–output analysis. Renew. and Sustain. Energy Rev. 53, 1303–1312.
Huang, R., Hubacek, K., Feng, K.S., Li, X.J., Zhang, C., 2018. Re-examining embodied SO_2 and CO_2 emissions in China. Sustainability 10, 1–17.
IEA, 2017. In: h.w.i.o.m.s.C.H.X.a (Ed.), CO_2 Emissions from Fuel Combustion 2017–Highlights., in: 2017.
Kofi Adom, P., Bekoe, W., Amuakwa-Mensah, F., Mensah, J.T., Botchway, E., 2012. Carbon dioxide emissions, economic growth, industrial structure, and technical efficiency: empirical evidence from Ghana, Senegal, and Morocco on the causal dynamics. Energy 47, 314–325.
Krook Riekkola, A., Ahlgren, E.O., Söderholm, P., 2011. Ancillary benefits of climate policy in a small open economy: the case of Sweden. Energy Policy 39, 4985–4998.
Liao, H., Fan, Y., Wei, Y.-M., 2007. What induced China's energy intensity to fluctuate: 1997–2006? Energy Policy 35, 4640–4649.
Longo, A., Hoyos, D., Markandya, A., 2011. Willingness to pay for ancillary benefits of climate change mitigation. Environ. Resour. Econ. 51, 119–140.
Markandya, A., Rübbelke, D.T.G., 2012. Impure public technologies and environmental policy. J. Econ. Stud. 39, 128–143.
Markandya, A., Sampedro, J., Smith, S.J., Van Dingenen, R., Pizarro-Irizar, C., Arto, I., González-Eguino, M., 2018. Health co-benefits from air pollution and mitigation costs of the Paris Agreement: a modelling study. The Lancet Planetary Health 2, e126–e133.
Matus, K., Nam, K.-M., Selin, N.E., Lamsal, L.N., Reilly, J.M., Paltsev, S.J.G., 2012. Health Damages from Air Pollution in China. 22. pp. 55–66.
Mi, Z., Meng, J., Guan, D., Shan, Y., Song, M., Wei, Y.-M., Liu, Z., Hubacek, K., 2017. Chinese CO_2 emission flows have reversed since the global financial crisis. Nat. Commun. 8, 1712.
Moses, L.N., 1955. The stability of interregional trading patterns and input-output analysis. Amer. Econ. Rev. 45, 803–832.
NDRC, 2018. Report on the Work of the Government. www.ndrc.gov.cn.
Nemet, G.F., Holloway, T., Meier, P., 2010. Implications of incorporating air-quality cobenefits into climate change policymaking. Environ. Res. Lett. 5.
Pirgmaier, E., Steinberger, J., 2019. Roots, riots, and radical change—a road less travelled for ecological economics. Sustainability 11, 2001.
Prell, C., Sun, L.X., Feng, K.S., Myroniuk, T.W., 2015. Inequalities in global trade: a cross-country comparison of trade network position, economic wealth, pollution and mortality. PLoS One 10, 1–18.
Rive, N., Rübbelke, D.T.G., 2010. International environmental policy and poverty alleviation. Rev. World Econ. 146, 515–543.
Roca, J., Serrano, M., 2007. Income growth and atmospheric pollution in Spain: an input–output approach. Ecolog. Econ. 63, 230–242.
Rocchi, P., Serrano, M., Roca, J., Arto, I., 2018. Border carbon adjustments based on avoided emissions: addressing the challenge of its design. Ecolog. Econ. 145, 126–136.
Serrano, M., Dietzenbacher, E., 2010. Responsibility and trade emission balances: an evaluation of approaches. Ecolog. Econ. 69, 2224–2232.
Shao, S., Tian, Z., Fan, M., 2018. Do the rich have stronger willingness to pay for environmental protection? New evidence from a survey in China. World Devel 105, 83–94.
Sherman, J., Morrison, W.J., 1949. Adjustment of an inverse matrix corresponding to changes in the elements of a given column or a given row of the original matrix (abstract). Ann. Math. Stat. 20, 621.
Sherman, J., Morrison, W.J., 1950. Adjustment of an inverse matrix corresponding to a change in one element of a given matrix. Ann. Math. Stat. 21, 124–127.
Stern, N., 2007. The Economics of Climate Change: The Stern Review. Cambridge University Press.
Tsagkari, M., Gaona, A., Gonzalez, J.F., Jarvinen, J., 2018. The evolution of carbon dioxide emissions embodied in international trade in Poland: an input-output approach. Environ. Socio-Econ. Stud 6, 36–43.
United Nations, 2015. Sustainable Development Goals. United Nations, New York. http://www.un.org/sustainabledevelopment/summit/.
Verbeke, T., Clercq, M.D., 2002. Environmental quality and economic growth. In: UC Econ.&Bus. Admin. Working Paper, pp. 128.
Voigt, S., De Cian, E., Schymura, M., Verdolini, E., 2014. Energy intensity developments in 40 major economies: structural change or technology improvement? Energy Econ. 41, 47–62.
Wang, H., Ang, B.W., 2018. Assessing the role of international trade in global CO_2 emissions: an index decomposition analysis approach. Appl. Energy 218, 146–158.
Wang, Y., Bi, F.F., Zhang, Z.K., Zuo, J., Zillante, G., Du, H.B., Liu, H.W., Li, J., 2018. Spatial production fragmentation and $PM_{2.5}$ related emissions transfer through three different trade patterns within China. J. Clean. Prod. 195, 703–720.
Ward, H., Radebach, A., Vierhaus, I., Fugenschuh, A., Steckel, J.C., 2017. Reducing global CO_2 emissions with the technologies we have. Resource Energy Econ 49, 201–217.
Weber, C.L., Peters, G.P., Guan, D., Hubacek, K., 2008. The contribution of Chinese exports to climate change. Energy Policy 36, 3572–3577.
Woodbury, M.A., 1950. Inverting Modified Matrices, Memorandum Report No. 42.Statistical Research Group. Princeton University, Princeton, NJ.
Zhang, B., Chen, Z.M., Xia, X.H., Xu, X.Y., Chen, Y.B., 2013. The impact of domestic trade on China's regional energy uses: a multi-regional input–output modeling. Energy Policy 63, 1169–1181.
Zhang, B., Yang, T.R., Chen, B., Sun, X.D., 2016. China's regional CH_4 emissions: characteristics, interregional transfer and mitigation policies. Appl. Energy 184, 1184–1195.
Zhang, Y., Li, Y.G., Liu, G.Y., Hao, Y., 2018. CO_2 metabolic flow analysis in global trade based on ecological network analysis. J. Clean. Prod. 170, 34–41.
Zhang, Y.J., Zhang, K.B., 2018. The linkage of CO_2 emissions for China, EU, and USA: evidence from the regional and sectoral analyses. Environ. Sci. Pollut. Res. 25, 20179–20192.
Zhao, Y.H., Liu, Y., Wang, S., Zhang, Z.H., Li, J.C., 2016. Inter-regional linkage analysis of industrial CO_2 emissions in China: an application of a hypothetical extraction method. Ecol. Indic. 61, 428–437.
Zheng, J., Zhang, L., Che, W., Zheng, Z., Yin, S., 2009. A highly resolved temporal and spatial air pollutant emission inventory for the Pearl River Delta region, China and its uncertainty assessment. Atmos. Environ. 43, 5112–5122.
Zusman, E., Srinivasan, A., Dhakal, S., 2012. Low Carbon Transport in Asia: Strategies for Optimizing co-Benefits. Routledge.