Spatial spillover effects in determining China's regional CO2 emission growth : 2007-2010

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Abstract: This paper proposes an alternative input-output based spatial-structural decomposition analysis to elucidate the role of domestic-regional heterogeneity and interregional spillover effects in determining China's regional CO_2 emission growth. Our empirical results based on the 2007 and 2010 Chinese interregional input-output tables show that the changes in most regions' final demand scale, final expenditure structure and export scale give positive spatial spillover effects on other regions' CO_2 emission growth, the changes in most regions' consumption and export preference help the reduction of other regions' CO_2 emissions, the changes in production technology, and investment preference may give positive or negative impacts on other region's CO_2 emission growth through domestic supply chains. For some regions, the aggregate spillover effect from other regions may be larger than the intra-regional effect in determining regional emission growth. All these facts can significantly help better and deeper understanding on the driving forces of China's regional CO_2 emission growth, thus can enrich the policy implication concerning a narrow definition of "carbon leakage" through domestic-interregional trade, and relevant political consensus about the responsibility sharing between developed and developing regions inside China.

Keywords: regional heterogeneity, spillover effect, CO_2 emissions, input-output, supply chain

JEL classification: R15; C65; Q56

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Abstract

This study proposes an alternative input–output based spatial structural decomposition analysis to elucidate the importance of domestic regional heterogeneity and inter-regional spillover effects in determining China's regional CO_2 emissions growth. Our empirical results, based on the 2007 and 2010 Chinese inter-regional input–output tables, show that (1) changes in most regions' final demand scale, final expenditure structure, and export scale have positive spatial spillover effects on other regions' CO_2 emissions growth, (2) changes in most regions' consumption and export preferences help reduce other regions' CO_2 emissions, and (3) changes in production technology and investment preferences may exert positive or negative effects on other region's CO_2 emissions growth through domestic supply chains. For some regions, the aggregate spillover effect from other regions may be larger than the intra-regional effect in determining regional emission growth. All these facts can significantly help provide a better, deeper understanding, via domestic supply chains, of the driving forces behind the growth of regional CO_2 emissions and can thus enrich the policy implications concerning a narrow definition of "carbon leakage" through domestic inter-regional trade as well as a relevant political consensus about responsibility sharing between developed and developing regions inside China.

Keywords: regional heterogeneity, spillover effects, CO_2 emissions, input–output, supply chain

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1 Introduction

As the second-largest economy in the world, China surpassed the United States as the world's leading CO_2 emitter in 2006, and it has recently become responsible for about 30% of the world's total CO_2 emissions (BP, 2015). Furthermore, China's CO_2 emissions per head surpassed those of the EU for the first time in 2014.[1] This undoubtedly poses an urgent challenge to achieve global climate-change mitigation targets, such as limiting the average global surface temperature increase to 2°C (3.6°F) over the pre-industrial average (Rogelj et al., 2009).

China's current high levels of CO_2 emissions come from its accumulatively rapid growth (the average annual growth rate of China's CO_2 emissions was about 6% between 1990 and 2012 (BP, 2015), whereas its national emissions level is simply the aggregation of domestic regional emissions. However, the growth pattern of China's CO_2 emissions at the regional level exhibits a large variation, as shown in Figure 1, due to the regional heterogeneity in terms of initial resource endowment, economic size, industry structure, development stage, foreign dependency, etc. It is clear from this figure that emissions of some Chinese provinces (e.g., Shangdong [SD]) increased very rapidly since 1990 and that they were larger than those of some G20 countries (e.g., Mexico [MEX]) in 2012. The figure also shows that for per capita GDP and CO_2 emissions, very large differentials exist across China's domestic regions. Given these facts, understanding the determinants of China's regional emissions growth can be considered crucial for achieving its national emissions-reduction targets as regional governments are the direct executive body in charge of emission reduction. Additionally, to achieve a balanced environmental governance system for dealing with "carbon leakage" through domestic inter-regional trade and for obtaining relevant consensus about responsibility sharing between developed and developing regions within China, a better understanding of the role of spatial spillover effects in generating regional CO_2 emissions through domestic supply chains is required.

Many studies concerning the determinants of China's CO_2 emissions growth have used various approaches and databases. The most frequently used approaches include the Index Decomposition Analysis (IDA) and Structural Decomposition Analysis (SDA). The IDA directly decomposes CO_2 emissions from a production-based perspective based on an arithmetical derivation, i.e., decomposition of national emissions (Xu et al., 2014; Xu, et al., 2014; Ouyang and Lin, 2015; Wu, et al., 2016), inter-regional emissions flows (Jiang et al., 2015), provincial emissions (Feng et al., 2009; Chen and Yang, 2015). One drawback of IDA is that this approach solely focuses on the production side[2], meaning that other factors, such as how changes in one region's final demand affect other regions' emissions via international or

[1] BBC news: http://www.bbc.com/news/science-environment-29239194.[2] One exception is Zhang and Tang (2015) who uses the revised LMDI-MRIO method, quantifies the determinants of carbon emissions embodied in Chinese exports.

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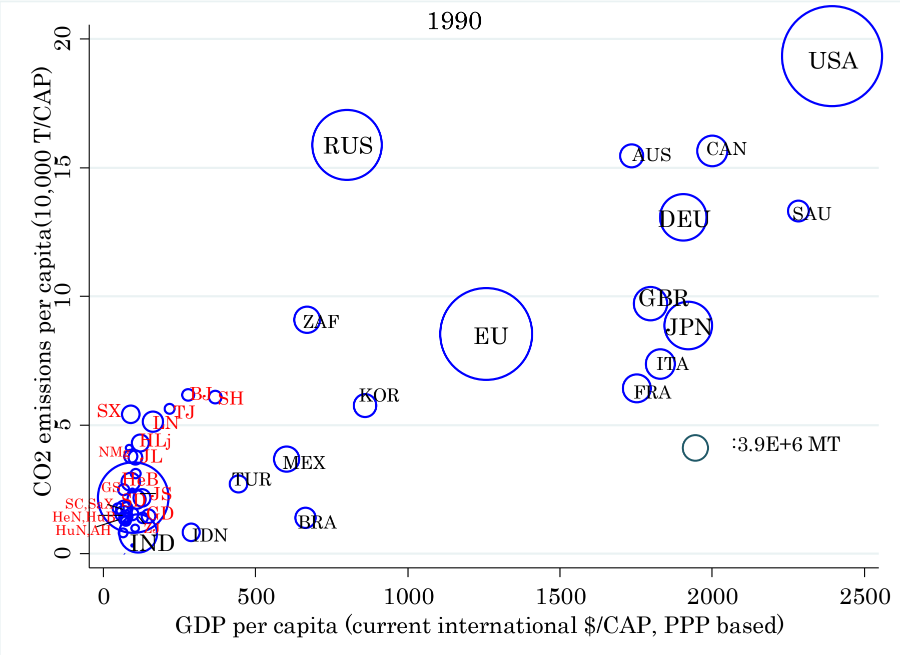
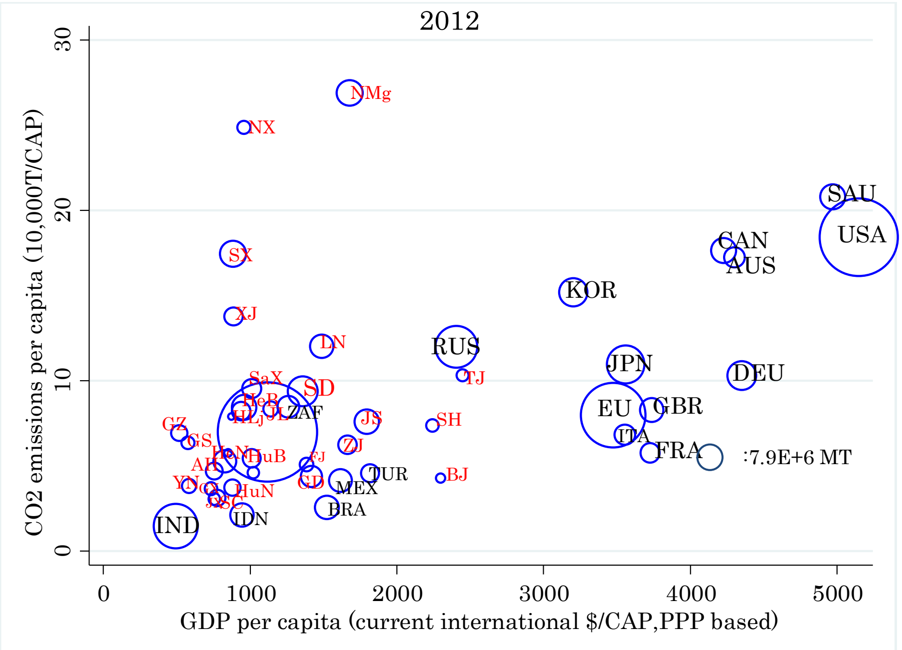
inter-regional production networks, cannot be captured explicitly.





Note: Bubble size represents the absolute level of CO_2 emissions; detailed names for China's domestic regions (provinces) are shown in Appendix 1. The source data used to make calculations for this figure come from BP and IMF databases

Figure 1 China's regional CO_2 emissions growth

In contrast, SDA can trace changes in carbon emissions driven by final demand with the application of Leontief's Input–Output (IO) model, which combines production-based and consumption-based measures in a consistent framework.[3] This approach is generally adopted for analyzing how changes in carbon intensity, production technology, and final demand affect a country's or region's carbon emissions growth. However, most SDA-based studies on China's CO_2 emissions are at national or single-region levels (Peters et al., 2007; Guan and Peters, 2009; Minx and Baiocchi, 2011; Peng and Shi, 2011; Xu et al., 2011; Feng et al., 2012; Liao and Yoshida, 2013; Su and Ang, 2013; Tian et al., 2014; Wang et al., 2015), and they do not fully consider spillover effects across regions via domestic supply chains[4]. As far as we know, only a few recent studies (Zhang and Lahr, 2014; Xu and Dietzenbacher, 2014) applied the SDA to China's inter-regional IO (IRIO) data to identify sources of regional energy-use growth or emission growth. However, these studies gave no detailed indication regarding how changes in one region's production technology, expenditure structure, and demand preference affect other regions' carbon emissions growth via various spatial spillover routes in domestic supply chains.

This study proposes an alternative SDA, based on Chinese 2007 and 2010 IRIO tables to identify the determinants of regional CO_2 emissions growth with a specific focus on spatial spillover effects of various channels through domestic supply chains. The rest of this study is organized as follows. Section 2 introduces the spatial structural decomposition method and data used. Section 3 first shows the overall situation of production-based CO_2 emissions at the regional level and then presents the decomposition results for the driving forces of regional emissions growth at the aggregate level, followed by detailed decomposition results for the inter-regional level. Section 4 offers conclusions and a policy discussion.

2 Model and data

2.1 Spatial structural decomposition analysis based on the Chinese IRIO table

Input–output analysis (IOA) is an accounting procedure and modeling approach that relies on national or regional input–output tables. A country's IO tables show the flows of goods and services and thus the interdependencies between suppliers and consumers along the production chain within an economy (Miller and Blair, 2009; Murray and Wood, 2010). Due to its ability to provide a lifecycle perspective from "cradle to grave" by accounting for the effects of the full upstream supply chain, IOA

[3] Production-based emissions take place "within national territory and offshore areas over which the country has jurisdiction" (see IPCC, 2006). Consumption-based emissions encompass those emissions from domestic final consumption and those caused by the production of its imports (see Peters and Hertwich, 2008). More relevant discussion can be found in Peters (2008), Pan et al. (2008), Davis and Caldeira (2010) and Meng et al. (2014).

[4] Research on Chinese inter-regional or inter-provincial carbon emission transfer include Feng et al. (2013), Guo et al. (2012), Su and Ang (2014), Meng et al. (2013), Liu, H. et al. (2015), Liu, L.C. et al. (2015)

has become an important approach for estimating embodied emissions in trade (e.g., Peters et al., 2007; Guan et al., 2008, 2009; Feng et al., 2012). Following the format used in the official Chinese IRIO table, an open and non-competitive type of environmentally extended inter-regional IO model with G domestic regions, N sectors, and M types of domestic final demand can be given in the following form:

$$\mathbf{C} = \mathrm{diag}(\mathbf{c}) \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{F} \cdot \mathbf{u}_1 = \mathrm{diag}(\mathbf{c}) \cdot \mathbf{B} \cdot \mathbf{F} \cdot \mathbf{u}_1, \tag{1}$$

where

$$\mathbf{c} = [\mathbf{c}^1 \quad \cdots \quad \mathbf{c}^G] = [\mathbf{C}^1 \quad \cdots \quad \mathbf{C}^G]//[\mathbf{X}^1 \quad \cdots \quad \mathbf{X}^G],$$

$$\mathbf{X} = \begin{pmatrix} \mathbf{X}^1 \\ \vdots \\ \mathbf{X}^G \end{pmatrix},\ \mathrm{A} = \begin{pmatrix} \mathbf{A}^{11} & \cdots & \mathbf{A}^{1G} \\ \vdots & \ddots & \vdots \\ \mathbf{A}^{G1} & \cdots & \mathbf{A}^{GG} \end{pmatrix},\ \mathrm{F} = \begin{pmatrix} \mathbf{F}^{11} & \cdots & \mathbf{F}^{1G} \mathbf{F}^{1E} \\ \vdots & \ddots & \vdots \quad \vdots \\ \mathbf{F}^{G1} & \cdots & \mathbf{F}^{GG} \mathbf{F}^{GE} \end{pmatrix},\ \mathbf{B} = \begin{pmatrix} \mathbf{B}^{11} & \cdots & \mathbf{B}^{1G} \\ \vdots & \ddots & \vdots \\ \mathbf{B}^{G1} & \cdots & \mathbf{B}^{GG} \end{pmatrix}.$$

In the above equations, $\mathbf{C}$ is the $\mathrm{GN} \times 1$ column vector representing the induced emissions by total final demand via domestic inter-regional and inter-industrial supply chains (by definition, it equals the production-based emissions by sector and region); $\mathbf{c}$ is the $\mathrm{GN} \times 1$ column vector of emission coefficients representing the emissions per economic output by sector and region (we define "//" as an element-wise vector division operator); $\mathbf{X}$ is the $\mathrm{GN} \times 1$ output vector; $\mathbf{A}$ is the $\mathrm{GN} \times \mathrm{GN}$ inter-regional input coefficient matrix, defined as the share of intermediate input in output; $\mathbf{F}$ is the $\mathrm{GN} \times (\mathrm{GM} + 1)$ inter-regional final demand matrix with one $\mathrm{GN} \times 1$ column vector for exports included; $\mathbf{B}$ is the $\mathrm{GN} \times \mathrm{GN}$ inter-regional Leontief inverse representing the induced output by one unit of final demand; and $\mathbf{u}_1$ is the $(\mathrm{GM} + 1) \times 1$ column vector with 1s. Considering the representative domestic regions S and R $(S, R \in G)$, the above elements with sectoral details can be given as follows:

$$\mathbf{X}^S = \begin{pmatrix} X_1^S \\ \vdots \\ X_N^S \end{pmatrix},\ \mathbf{A}^{SR} = \begin{pmatrix} a_{11}^{SR} & \cdots & a_{1N}^{SR} \\ \vdots & \ddots & \vdots \\ a_{N1}^{SR} & \cdots & a_{NN}^{SR} \end{pmatrix},\ \mathbf{F}^{SR} = \begin{pmatrix} f_{11}^{SR} & \cdots & f_{1M}^{SR} \\ \vdots & \ddots & \vdots \\ f_{N1}^{SR} & \cdots & f_{NM}^{SR} \end{pmatrix},$$

$$\mathbf{F}^{SE} = \begin{pmatrix} f_1^{SE} \\ \vdots \\ f_N^{SE} \end{pmatrix},\mathbf{B}^{SR} = \begin{pmatrix} b_{11}^{SR} & \cdots & b_{1N}^{SR} \\ \vdots & \ddots & \vdots \\ b_{N1}^{SR} & \cdots & b_{NN}^{SR} \end{pmatrix}.$$

With the representative sectors i and j $(i, j \in N)$, X_j^S represents region S's output for sector j, a_{ij}^{SR} represents the amount of region S's good i used as input to produce one unit of output of sector j in region R, f_{ik}^{SR} represents region R's kth final demand for good i produced in region S, f_i^{SE} represents region S's export of good i, and b_{ij}^{SR} represents the induced output of region S's good i by a one-unit increase of final demand for region R's good j in the IRIO system.

For a representative region S, Eq. (1) can be rewritten as follows:

$$\mathrm{diag}(\mathbf{C}^{S}) = \mathrm{diag}(\mathbf{c}^{S})\left[\sum_{R}^{G}\left(\sum_{T}^{G}\mathbf{B}^{SR}\cdot\mathbf{F}^{RT}\cdot\mathbf{u}_2 + \mathbf{B}^{SR}\cdot\mathbf{F}^{RE}\right)\right], \tag{2}$$

where $\mathbf{u}_2$ is a $M \times 1$ column vector with 1s. This equation reflects the fact that a region's emissions depend on its own carbon intensity, its own and other regions' final demand, and exports via domestic supply chains.

Following Dietzenbacher and Los (1988), we adopt the average of the two so-called polar decomposition forms because it is remarkably close to the average of the full set of structural decompositions.

$$\begin{aligned}
&\begin{bmatrix} 0 & \cdots & 0 \\ \vdots & \mathrm{diag}(\Delta\mathbf{C}^{S}) & \vdots \\ 0 & \cdots & 0 \end{bmatrix} = \begin{bmatrix} 0 & \cdots & 0 \\ \vdots & \mathrm{diag}\left(\mathbf{C}_{t1}^{S} - \mathbf{C}_{t0}^{S}\right) & \vdots \\ 0 & \cdots & 0 \end{bmatrix} \\
&= \hat{\mathbf{c}}_{t1}^{S}\cdot\mathbf{B}_{t1}\cdot\mathbf{F}_{t1}\cdot\mathbf{u}_1 - \hat{\mathbf{c}}_{t0}^{S}\cdot\mathbf{B}_{t0}\cdot\mathbf{F}_{t0}\cdot\mathbf{u}_1 \\
&= 1/2\cdot[\Delta\hat{\mathbf{c}}^{S}\cdot(\mathbf{B}_{t0}\cdot\mathbf{F}_{t0} + \mathbf{B}_{t1}\cdot\mathbf{F}_{t1})]\cdot\mathbf{u}_1 \\
&+\ 1/2\cdot\left[\hat{\mathbf{c}}_{t0}^{S}\cdot\Delta\mathbf{B}\cdot\mathbf{F}_{t1} + \hat{\mathbf{c}}_{t1}^{S}\cdot\Delta\mathbf{B}\cdot\mathbf{F}_{t0}\right]\cdot\mathbf{u}_1 \\
&+\ 1/2\cdot\left[\hat{\mathbf{c}}_{t0}^{S}\cdot\mathbf{B}_{t0}\cdot\Delta\mathbf{F} + \hat{\mathbf{c}}_{t1}^{S}\cdot\mathbf{B}_{t1}\cdot\Delta\mathbf{F}\right]\cdot\mathbf{u}_1,
\end{aligned} \tag{3}$$

where $\hat{\mathbf{c}}^{S}$ is the $GN \times GN$ matrix expressing regional carbon intensity as shown below:

$$\hat{\mathbf{c}}^{S} = \begin{bmatrix} 0 & \cdots & 0 \\ \vdots & \mathrm{diag}(\mathbf{c}^{S}) & \vdots \\ 0 & \cdots & 0 \end{bmatrix}.$$

Clearly, the change of a representative region S's emissions ($\Delta\mathbf{C}^{S}$) between the benchmark year (t0) and the target year (t1) can be first decomposed into three factors, which are related to the change of region S's carbon intensity ($\Delta\hat{\mathbf{c}}^{S}$), the change of Leontief inverse ($\Delta\mathbf{B}$), and the change of final demand ($\Delta\mathbf{F}$).

Because the following equation always holds, the change of Leontief inverse can be re-expressed by the change of input coefficients that directly represents a region's production function (intermediate input structure).

$$\begin{aligned}
\Delta\mathbf{B} &= \mathbf{B}_{t1} - \mathbf{B}_{t0} \\
&= [(\mathbf{I} - \mathbf{A}_{t1})^{-1}\cdot(\mathbf{I} - \mathbf{A}_{t0}) - \mathbf{I}]\cdot(\mathbf{I} - \mathbf{A}_{t0})^{-1} \\
&= [(\mathbf{I} - \mathbf{A}_{t1})^{-1} - (\mathbf{I} - \mathbf{A}_{t1})^{-1}\cdot\mathbf{A}_{t0} - \mathbf{I}]\cdot(\mathbf{I} - \mathbf{A}_{t0})^{-1} \\
&= (\mathbf{I} - \mathbf{A}_{t1})^{-1}\cdot[(\mathbf{I} - \mathbf{A}_{t0}) - (\mathbf{I} - \mathbf{A}_{t1})]\cdot(\mathbf{I} - \mathbf{A}_{t0})^{-1} \\
&= (\mathbf{B}_{t1}\cdot\Delta\mathbf{A}\cdot\mathbf{B}_{t0}) \\
&= \left(\mathbf{B}_{t1}\cdot\sum_{R=1}^{G}\Delta\mathbf{A}^{R}\cdot\mathbf{B}_{t0}\right),
\end{aligned} \tag{4}$$

where

$$\Delta\mathbf{A} = \Delta\mathbf{A}^{1} + \cdots + \Delta\mathbf{A}^{G} = \sum_{R}^{G}\Delta\mathbf{A}^{R},$$

$$\Delta\mathbf{A}^{\mathrm{R}} = \begin{bmatrix} 0\cdots\Delta\mathbf{A}^{1\mathrm{R}}\cdots 0 \\ \vdots\cdots \quad \vdots \quad \cdots\vdots \\ 0\cdots\Delta\mathbf{A}^{\mathrm{GR}}\cdots 0 \end{bmatrix}.$$

In addition, a change in overall final demand $(\Delta\mathbf{F}\cdot \mathrm{u1})$ can be rewritten as the summation of changes in regional final demand $(\Delta\mathbf{F}^{\mathrm{R}}\cdot\mathbf{u}_2)$ and exports $(\Delta\hat{\mathbf{F}}^{\mathrm{RE}})$.

$$\Delta\mathbf{F}\cdot\mathbf{u}_1 = \textstyle\sum_{\mathrm{R}}^{\mathrm{G}}(\Delta\mathbf{F}^{\mathrm{R}}\cdot\mathbf{u}_2 + \Delta\hat{\mathbf{F}}^{\mathrm{RE}}), \tag{5}$$

where

$$\Delta\mathbf{F}^{\mathrm{R}} = \mathbf{F}_{\mathrm{t1}}^{\mathrm{R}} - \mathbf{F}_{\mathrm{t0}}^{\mathrm{R}} = (\mathbf{F}_{\mathrm{t1}}^{1\mathrm{R}} \quad \cdots \quad \mathbf{F}_{\mathrm{t1}}^{\mathrm{GR}})' - (\mathbf{F}_{\mathrm{t0}}^{1\mathrm{R}} \quad \cdots \quad \mathbf{F}_{\mathrm{t0}}^{\mathrm{GR}})' = (\Delta\mathbf{F}^{1\mathrm{R}} \quad \cdots \quad \Delta\mathbf{F}^{\mathrm{GR}})',$$
$$\Delta\hat{\mathbf{F}}^{\mathrm{RE}} = \hat{\mathbf{F}}_{\mathrm{t1}}^{\mathrm{RE}} - \hat{\mathbf{F}}_{\mathrm{t0}}^{\mathrm{RE}} = (0 \quad \cdots \quad \hat{\mathbf{F}}_{\mathrm{t1}}^{\mathrm{RE}}\cdots \quad 0)' - (0 \quad \cdots \quad \hat{\mathbf{F}}_{\mathrm{t0}}^{\mathrm{RE}}\cdots \quad 0)' = (0 \quad \cdots \quad \Delta\mathbf{F}^{\mathrm{RE}}\cdots \quad 0)'.$$

$\Delta\mathbf{F}^{\mathrm{R}}$ is a $\mathrm{GN}\times\mathrm{M}$ matrix and $\Delta\hat{\mathbf{F}}^{\mathrm{RE}}$ is a $\mathrm{GN}\times 1$ vector.

Furthermore, regional final demand in an IRIO system can be re-expressed according to the following formula:

$$\begin{aligned}\mathbf{F}^{\mathrm{R}}\cdot\mathbf{u}_2 &= (\mathbf{u}_3\cdot\mathbf{F}^{\mathrm{R}}\cdot\mathbf{u}_2)\cdot[\mathbf{F}^{\mathrm{R}}\cdot(\mathrm{diag}(\mathbf{u}_3\cdot\mathbf{F}^{\mathrm{R}}))^{-1}]\cdot[\mathrm{diag}(\mathbf{u}_3\cdot\mathbf{F}^{\mathrm{R}})/(\mathbf{u}_3\cdot\mathbf{F}^{\mathrm{R}}\cdot\mathbf{u}_2)]\cdot\mathbf{u}_2 \\ &= \mathrm{S}^{\mathrm{R}}\cdot\mathbf{P}^{\mathrm{R}}\cdot\mathbf{D}^{\mathrm{R}}\cdot\mathbf{u}_2 \\ &= \mathrm{S}^{\mathrm{R}}\cdot\textstyle\sum_{\mathrm{k}=1}^{\mathrm{M}}\mathbf{P}_{\mathrm{k}}^{\mathrm{R}}\cdot\mathbf{D}^{\mathrm{R}}\cdot\mathbf{u}_2,\end{aligned} \tag{6}$$

where

$$\mathbf{P}^{\mathrm{R}} = \mathbf{P}_1^{\mathrm{R}} + \cdots + \mathbf{P}_{\mathrm{k}}^{\mathrm{R}} + \cdots + \mathbf{P}_{\mathrm{M}}^{\mathrm{R}} = \textstyle\sum_{\mathrm{k}=1}^{\mathrm{M}}\mathbf{P}_{\mathrm{k}}^{\mathrm{R}},$$
$$\mathbf{P}_{\mathrm{k}}^{\mathrm{R}} = \begin{bmatrix} 0\cdots\mathbf{P}_{\mathrm{k}}^{1\mathrm{R}}\cdots 0 \\ \vdots\cdots \quad \vdots \quad \cdots\vdots \\ 0\cdots\mathbf{P}_{\mathrm{k}}^{\mathrm{GR}}\cdots 0 \end{bmatrix},$$

and $\mathbf{u}_3$ is a $1\times\mathrm{GN}$ column vector with 1's.

Obviously, S^{R} is a scalar representing the final demand scale. $\mathbf{P}^{\mathrm{R}}$ shows the share of final demand expenditure on an individual good out of total final demand expenditure by a different item k (e.g.,., consumption and investment) and thus can be considered a proxy of a region's final demand preferences. $\mathbf{D}^{\mathrm{R}}$ gives the share of final demand expenditure by different item out of the total final demand expenditure, thus it can reflect the structure of final demand expenditure.

Following the same logic used in Eq. (3), the change of regional final demand can be decomposed into three factors, as shown below:

$$\begin{aligned}\Delta\mathbf{F}^{\mathrm{R}}\cdot\mathbf{u}_2 &= \mathbf{F}_{\mathrm{t1}}^{\mathrm{R}}\cdot\mathbf{u}_2 - \mathbf{F}_{\mathrm{t0}}^{\mathrm{R}}\cdot\mathbf{u}_2 \\ &= \mathrm{S}_{\mathrm{t1}}^{\mathrm{R}}\cdot\mathbf{P}_{\mathrm{t1}}^{\mathrm{R}}\cdot\mathbf{D}_{\mathrm{t1}}^{\mathrm{R}}\cdot\mathbf{u}_2 - \mathrm{S}_{\mathrm{t0}}^{\mathrm{R}}\cdot\mathbf{P}_{\mathrm{t0}}^{\mathrm{R}}\cdot\mathbf{D}_{\mathrm{t0}}^{\mathrm{R}}\cdot\mathbf{u}_2\end{aligned}$$

$$= 1/2 \cdot \Delta S^{R} \cdot (\mathbf{P}^{R}_{t1} \cdot \mathbf{D}^{R}_{t1} + \mathbf{P}^{R}_{t0} \cdot \mathbf{D}^{R}_{t0}) \cdot \mathbf{u}_2$$
$$+ 1/2 \cdot (S^{R}_{t0} \cdot \textstyle\sum_k^M \Delta\mathbf{P}^{R}_{k} \cdot \mathbf{D}^{R}_{t1} + S^{R}_{t1} \cdot \sum_k^M \Delta\mathbf{P}^{R}_{k} \mathbf{D}^{R}_{t0}) \cdot \mathbf{u}_2$$
$$+ 1/2 \cdot \left(S^{R}_{t0} \cdot \mathbf{P}^{R}_{t0} + S^{R}_{t1} \cdot \mathbf{P}^{R}_{t1}\right) \cdot \Delta\mathbf{D}^{R} \cdot \mathbf{u}_2. \qquad (7)$$

Similar to Eq. (6), regional exports $\hat{\mathbf{F}}^{\mathbf{RE}}$ can be written as

$$\hat{\mathbf{F}}^{RE} = \left(\mathbf{u}_3 \cdot \hat{\mathbf{F}}^{RE}\right) \cdot \left[\hat{\mathbf{F}}^{RE} / \left(\mathbf{u}_3 \cdot \hat{\mathbf{F}}^{RE}\right)\right] = S^{RE} \cdot \mathbf{P}^{RE}, \qquad (8)$$

Thus, the change of regional exports $\left(\Delta\hat{\mathbf{F}}^{RE}\right)$ can be further decomposed into two factors related to changes in regional export scale (ΔS^{RE}) and changes in regional export preferences ($\Delta\mathbf{P}^{RE}$) as shown below:

$$\Delta\hat{\mathbf{F}}^{RE} = \hat{\mathbf{F}}^{RE}_{t1} - \hat{\mathbf{F}}^{RE}_{t0}$$
$$= S^{RE}_{t1} \cdot \mathbf{P}^{RE}_{t1} - S^{RE}_{t0} \cdot \mathbf{P}^{RE}_{t0}$$
$$= 1/2 \cdot \Delta S^{RE} \cdot \left(\mathbf{P}^{RE}_{t0} + \mathbf{P}^{RE}_{t1}\right)$$
$$+ 1/2 \cdot \left(S^{RE}_{t0} + S^{RE}_{t1}\right) \cdot \Delta\mathbf{P}^{RE}. \qquad (9)$$

Given the above equations, the change of regional carbon emissions shown in Eq. (3) can be finally expressed as

$$\begin{bmatrix} 0 & \cdots & 0 \\ \vdots & \mathrm{diag}(\Delta\mathbf{C}^{S}) & \vdots \\ 0 & \cdots & 0 \end{bmatrix} = \begin{bmatrix} 0 & \cdots & 0 \\ \vdots & \mathrm{diag}\left(\mathbf{C}^{S}_{t1} - \mathbf{C}^{S}_{t0}\right) & \vdots \\ 0 & \cdots & 0 \end{bmatrix}$$
$$= \hat{\mathbf{c}}^{S}_{t1} \cdot \mathbf{B}_{t1} \cdot \mathbf{F}_{t1} \cdot \mathbf{u}_1 - \hat{\mathbf{c}}^{S}_{t0} \cdot \mathbf{B}_{t0} \cdot \mathbf{F}_{t0} \cdot \mathbf{u}_1$$
$$= \hat{\mathbf{c}}^{S}_{t1} \cdot \mathbf{B}_{t1} \cdot \textstyle\sum_R^G (\mathbf{F}^{R}_{t1} \cdot \mathbf{u}_2 + \hat{\mathbf{F}}^{RE}_{t1}) - \hat{\mathbf{c}}^{S}_{t0} \cdot \mathbf{B}_{t0} \cdot \sum_R^G (\mathbf{F}^{R}_{t0} \cdot \mathbf{u}_2 + \hat{\mathbf{F}}^{RE}_{t0})$$
$$= \hat{\mathbf{c}}^{S}_{t1} \cdot \mathbf{B}_{t1} \cdot \textstyle\sum_R^G \left(S^{R}_{t1} \cdot \sum_k^M \mathbf{P}^{R}_{k,t1} \cdot \mathbf{D}^{R}_{t1} \mathbf{u}_2 + S^{RE}_{t1} \cdot \mathbf{P}^{RE}_{t1}\right) - \hat{\mathbf{c}}^{S}_{t0} \cdot \mathbf{B}_{t0} \cdot \sum_R^G \left(S^{R}_{t0} \cdot \sum_k^M \mathbf{P}^{R}_{k,t0} \cdot \mathbf{D}^{R}_{t0} \mathbf{u}_2 + S^{RE}_{t0} \cdot \mathbf{P}^{RE}_{t0}\right)$$
$$= 1/2 \cdot [\Delta\hat{\mathbf{c}}^{S} \cdot (\mathbf{B}_{t0} \cdot \mathbf{F}_{t0} + \mathbf{B}_{t1} \cdot \mathbf{F}_{t1})] \cdot \mathbf{u}_1$$
$$+ 1/2 \cdot \left(\hat{\mathbf{c}}^{S}_{t0} \cdot \Delta\mathbf{B} \cdot \mathbf{F}_{t1} + \hat{\mathbf{c}}^{S}_{t1} \cdot \Delta\mathbf{B} \cdot \mathbf{F}_{t0}\right) \cdot \mathbf{u}_1$$
$$+ 1/4 \left(\hat{\mathbf{c}}^{S}_{t0} \cdot \mathbf{B}_{t0} + \hat{\mathbf{c}}^{S}_{t1} \cdot \mathbf{B}_{t1}\right) \cdot \textstyle\sum_R^G \left[\Delta S^{R} \cdot \left(\mathbf{P}^{R}_{t0} \cdot \mathbf{D}^{R}_{t0} + \mathbf{P}^{R}_{t1} \cdot \mathbf{D}^{R}_{t1}\right) \cdot \mathbf{u}_2\right]$$
$$+ 1/4 \left(\hat{\mathbf{c}}^{S}_{t0} \cdot \mathbf{B}_{t0} + \hat{\mathbf{c}}^{S}_{t1} \cdot \mathbf{B}_{t1}\right) \cdot \textstyle\sum_R^G \left[\Delta S^{RE} \cdot \left(\mathbf{P}^{RE}_{t0} + \mathbf{P}^{RE}_{t1}\right)\right]$$
$$+ 1/4 \left(\hat{\mathbf{c}}^{S}_{t0} \cdot \mathbf{B}_{t0} + \hat{\mathbf{c}}^{S}_{t1} \cdot \mathbf{B}_{t1}\right) \cdot \textstyle\sum_R^G \left[S^{R}_{t0} \cdot \left(\sum_k^M \Delta\mathbf{P}^{R}_{k}\right) \cdot \mathbf{D}^{R}_{t1} \cdot \mathbf{u}_2 + S^{R}_{t1} \cdot \left(\sum_k^M \Delta\mathbf{P}^{R}_{k}\right) \cdot \mathbf{D}^{R}_{t0} \cdot \mathbf{u}_2\right]$$
$$+ 1/4 \left(\hat{\mathbf{c}}^{S}_{t0} \cdot \mathbf{B}_{t0} + \hat{\mathbf{c}}^{S}_{t1} \cdot \mathbf{B}_{t1}\right) \cdot \textstyle\sum_R^G \left[\left(S^{RE}_{t0} + S^{RE}_{t1}\right) \cdot \Delta\mathbf{P}^{RE}\right]$$
$$+ 1/4 \left(\hat{\mathbf{c}}^{S}_{t0} \cdot \mathbf{B}_{t0} + \hat{\mathbf{c}}^{S}_{t1} \cdot \mathbf{B}_{t1}\right) \cdot \textstyle\sum_R^G \left[\left(S^{R}_{t0} \cdot \mathbf{P}^{R}_{t0} + S^{R}_{t1} \cdot \mathbf{P}^{R}_{t1}\right) \cdot \Delta\mathbf{D}^{R} \cdot \mathbf{u}_2\right]. \qquad (10)$$

Obviously, the change of a representative region S's emissions ($\Delta\mathbf{C}^{S}$) can be decomposed into seven factors, which are related to (1) changes in region S's carbon intensity ($\Delta\hat{\mathbf{c}}^{S}$), (2) changes in the input coefficients ($\Delta\mathbf{A}^{R}$) representing regional production technology, (3) changes in domestic final demand scale (ΔS^{R}), (4) changes in export scale (ΔS^{RE}), (5) changes in domestic final demand preferences ($\Delta\mathbf{P}^{R}_{k}$), (6) changes in export preferences ($\Delta\mathbf{P}^{RE}$), and (7) changes in the expenditure structure of domestic final demand ($\Delta\mathbf{D}^{R}$). It should be noted that changes in all factors (except $\Delta\hat{\mathbf{c}}^{S}$) with superscript R can be grouped into two parts, where one group represents the intra-regional effect and the other represents the spillover effect coming from all other regions. For example,

$$\sum_{\mathrm{R}=1}^{\mathrm{G}} \Delta\mathbf{A}^{\mathrm{R}} = \Delta\mathbf{A}^{\mathrm{S}} + \sum_{\mathrm{R}\neq\mathrm{S}}^{\mathrm{G}} \Delta\mathbf{A}^{\mathrm{R}}. \tag{11}$$

The first part on the right-hand side of Eq. (11) represents the change in target region S's production technology, while the second part represents changes in all other regions' production technologies. The entire decomposition process is shown in Figure 2.

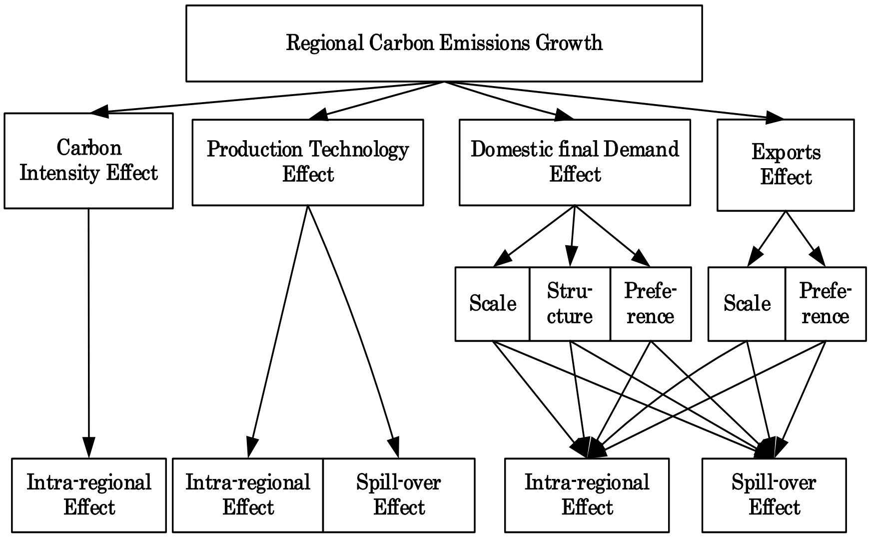


Figure 2 Spatial structure decomposition of regional carbon emissions growth

2.2 Data sources

The main data sources used in this paper are the 2007 and 2010 Chinese IRIO tables. The 2007 Chinese IRIO table was compiled by China's State Information Center (Zhang and Qi, 2012) in consultation with experts from IDE-JETRO. The 2010 IRIO table was an updated version of the 2007 table based on an international joint research project conducted by IDE-JETRO, Tsinghua Univ., USITC and Nagoya Univ. in 2014.[5] Following the regional and sector classifications used in Chinese IRIO tables, mainland China is grouped into seven geographical regions: Northeast (NE), North Coast (NC, including North Municipalities), East Coast (EC), South Coast (SC), Central (CT), Northwest (NW), and Southwest (SW); sectors are grouped into 17 products (see Appendix 1).

Regarding the comparability between these two tables and their specific features, four aspects must be taken into consideration:

(1) The 2007 Chinese IRIO table is constructed using a hybrid method (survey-based + non-survey-based). The survey-based table mentioned here means that the inter-regional trade information is drawn from surveys, such as the survey on inter-regional commodity flows. Although the non-survey-based method applies different types of gravity models when estimating inter-regional trade flows, the

[5] http://www.ide.go.jp/English/Info/Profile/Nenpo/pdf/2014_11.pdf

parameters and original data sources are calibrated using officially published information. To produce the 2010 Chinese IRIO table, the 2007 IRIO table was updated using the 2010 national IO table, 2010 provincial IO tables (including officially published and updated tables), China's census data, national and provincial statistic yearbooks, inter-regional transportation-related information, and Chinese provincial customs statistics based on UNSD's Classification by Broad Economic Categories (BEC)[6].

(2) In compiling the Chinese IRIO tables, one arising problem concerns the absence of Tibet's original IO tables for both 2007 and 2010. Fortunately, industry-specific data on value added and final demand for Tibet can be obtained from officially published statistics. This information has been added to the Southwest region to maintain consistency with the officially published national value-added and final-demand information when carrying out the final balancing work (total inputs should equal total outputs by sector) for the entire set of IRIO tables. In addition, this treatment for Tibet introduces very limited bias on the analytical results because Tibet's GRP as a share in China's total GDP is just 0.137% for 2007 and 0.195% for 2010.

(3) For ease of comparison across different years, China's provincial GDP deflator is used to make the 2010 figure reflect constant prices (base year 2007).

In addition, to estimate CO_2 emissions at national, regional, and provincial levels, 18 types of combustion of fuels and industrial processes are used in this study: raw coal, cleaned coal, other washed coal, briquettes, coke, coke oven gas, other gas, other coking products, crude oil, gasoline, kerosene, diesel oil, fuel oil, liquid petroleum gas, refinery gas, other petroleum products, natural gas, and other energy. Fuel data in physical units for 44 industries and for 30 provinces were collected and estimated using the China Provincial Statistical Yearbooks (energy-use data for 18 fuel types and 38 manufacturing sectors covering all state-owned and non-state-owned industrial enterprises with principal business revenue greater than 5 million RMB) and China Energy Statistical Yearbooks (including national and provincial energy balance tables) for the target year. Using the above information and following the Intergovernmental Panel on Climate Change's reference approach (IPCC 2006), China's national and provincial CO_2 emissions by industry can be estimated (for further details on the estimation method, see Appendix 2).

3 Empirical results

3.1 Evolution of China's regional CO_2 emissions between 2007 and 2010

Figure 3 provides an overall view of China's regional CO_2 emissions between 2007

[6] Using BEC can help separate the HS-based international trade statistics into different categories according to the end-use properties of traded goods (e.g.,., intermediate goods, final consumption goods, capital goods, and so on). This can further help improve the results' quality when estimating regional import matrixes for the construction of Chinese IRIO tables.

and 2010. At the absolute level, the Central and North Coast regions are the largest two emitters followed by the East Coast, Northwest, Southwest, Northeast and South Coast. From the supply-side perspective (production-based emissions accounting), variations in emissions among regions can be explained by differences in regional economic scale, carbon intensity, and industrial structure. Table 1 confirms this assertion. For example, the largest emitter, the Central region, accounts for 17% of China's total output (ranking third), while its average carbon intensity (CO_2 emissions/output) ranks second highest (0.98 kg per Yuan) and its industrial structure is more concentrated on the production of highly carbon-intensive products (27%). The second-largest emitter, the North Coast, has a relatively lower carbon intensity (0.71 kg per Yuan; lower than the national average level of 0.74 kg per Yuan), but it ranks second in terms of economic scale (accounting for 21% of China's total output) and it has the most carbon-intensive industrial structure (28% of output consists of highly carbon-intensive products). The East Coast is the most developed region in China with the largest economy (accounting for 23% of the national output), but it ranks third in CO_2 emissions (14% of China's total CO_2 emissions). This is mainly because most sectors in this region have low carbon intensity, with 44 of its production concentrated in low carbon-intensity products. The Northwest has the smallest economic size (6% of the national output) but the highest carbon intensity for most sectors (1.62 kg per Yuan on average); thus, it ranks as the fourth-largest emitter. The Northeast and Southwest are both remote developing regions of average economic size, carbon intensity level, and industrial structure; thus, they have similarly lower emissions.

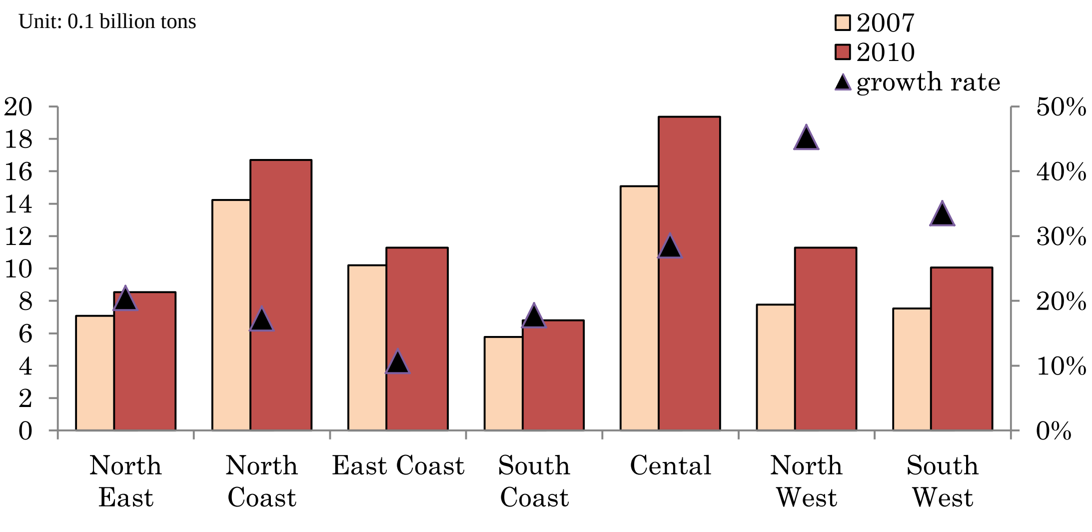


Figure 3 Evolution of regional CO_2 emissions between 2007 and 2010

Figure 3 also shows the change rate of regional CO_2 emissions between 2007 and 2010. In general, all regions show an increasing tendency, but very large variations exist in terms of their growth rates. Obviously, the Northwest experienced a very rapid increase (45%), followed by the Southwest (33%) and Central regions (29%), while the growth rates for all coastal regions are relatively low.

Table 1 China's regional and industrial output, CO_2 emissions, carbon intensity, and industrial structure (2010)

Output (Billion Yuan)	Agriculture	Low-carbon intensive manufacturing sector	High-carbon intensive manufacturing sector	Construction	Services	Total	Share by region
North East	612	3,113	2,363	836	2,034	8,956	8%
North Coast	879	9,126	6,717	1,657	5,652	24,030	21%
East Coast	536	11,607	7,074	1,935	5,524	26,676	23%
South Coast	583	8,078	4,190	1,067	3,835	17,753	16%
Central	1,473	6,239	5,190	1,803	4,686	19,392	17%
North West	493	1,818	1,818	914	1,775	6,819	6%
South West	1,043	2,845	2,273	1,220	2,767	10,149	9%
Total	5,620	42,825	29,625	9,432	26,273	113,775	100%
CO2 emissions (10K ton)	Agriculture	Low-carbon intensive manufacturing sector	High-carbon intensive manufacturing sector	Construction	Services	Total	Share by region
North East	680	9,619	63,251	1,424	11,005	85,980	10%
North Coast	770	14,831	128,793	1,154	25,417	170,965	20%
East Coast	255	10,304	89,122	665	13,529	113,876	14%
South Coast	106	6,492	52,484	957	8,864	68,903	8%
Central	790	15,793	153,044	3,852	15,974	189,452	23%
North West	1,092	7,954	86,175	2,392	12,542	110,155	13%
South West	1,217	5,085	78,418	1,342	12,953	99,015	12%
Total	4,910	70,077	651,288	11,786	100,284	838,345	100%
Carbon intensity (Kg per Yuan)	Agriculture	Low-carbon intensive manufacturing sector	High-carbon intensive manufacturing sector	Construction	Services	Total	
North East	0.11	0.31	2.68	0.17	0.54	0.96	
North Coast	0.09	0.16	1.92	0.07	0.45	0.71	
East Coast	0.05	0.09	1.26	0.03	0.24	0.43	
South Coast	0.02	0.08	1.25	0.09	0.23	0.39	
Central	0.05	0.25	2.95	0.21	0.34	0.98	
North West	0.22	0.44	4.74	0.26	0.71	1.62	
South West	0.12	0.18	3.45	0.11	0.47	0.98	
Average	0.09	0.16	2.20	0.12	0.38	0.74	
Industrial structure	Agriculture	Low-carbon intensive manufacturing sector	High-carbon intensive manufacturing sector	Construction	Services	Total	
North East	7%	35%	26%	9%	23%	100%	
North Coast	4%	38%	28%	7%	24%	100%	
East Coast	2%	44%	27%	7%	21%	100%	
South Coast	3%	46%	24%	6%	22%	100%	
Central	8%	32%	27%	9%	24%	100%	
North West	7%	27%	27%	13%	26%	100%	
South West	10%	28%	22%	12%	27%	100%	

3.2 Determinants of China's regional CO_2 emission growth at the aggregate level

From the supply-side perspective, changes in regional emissions can be explained by changes in output, carbon intensity, and/or industrial structure using the IDA, as previously mentioned. In this sense, the IDA-based result provides a way to explain changes in emissions from the supply side rather than considering the supply–demand equilibrium in an economic system, where production is induced both directly and indirectly by final demand via comprehensive domestic supply chains.

Using the IO-based SDA results, Figure 4 shows how and to what extent changes in production-based regional emissions are affected by various factors corresponding to changes in national final demand levels via domestic supply chains (without distinguishing between intra- and inter-regional spillover effects). For most regions, changes in the scale of domestic final demand can be considered the dominant driving force for regional carbon emission growth, followed by changes of export scale and final expenditure structure. In contrast, changes in carbon intensity and production technology play the dominant role in reducing regional emissions, followed by changes in household consumption preferences and export preferences (foreign export preferences). Changes in investment preferences positively affect the Central, North Coast, and East Coast regions' emissions growth but negatively affect other regions' emissions growth, especially in the Northeast. It is clear that in the interplay between various factors, the total positive effects mainly stemming from increased final demand and export scales cannot be canceled out by the total negative effects, which for most regions mainly arise from technology improvements.

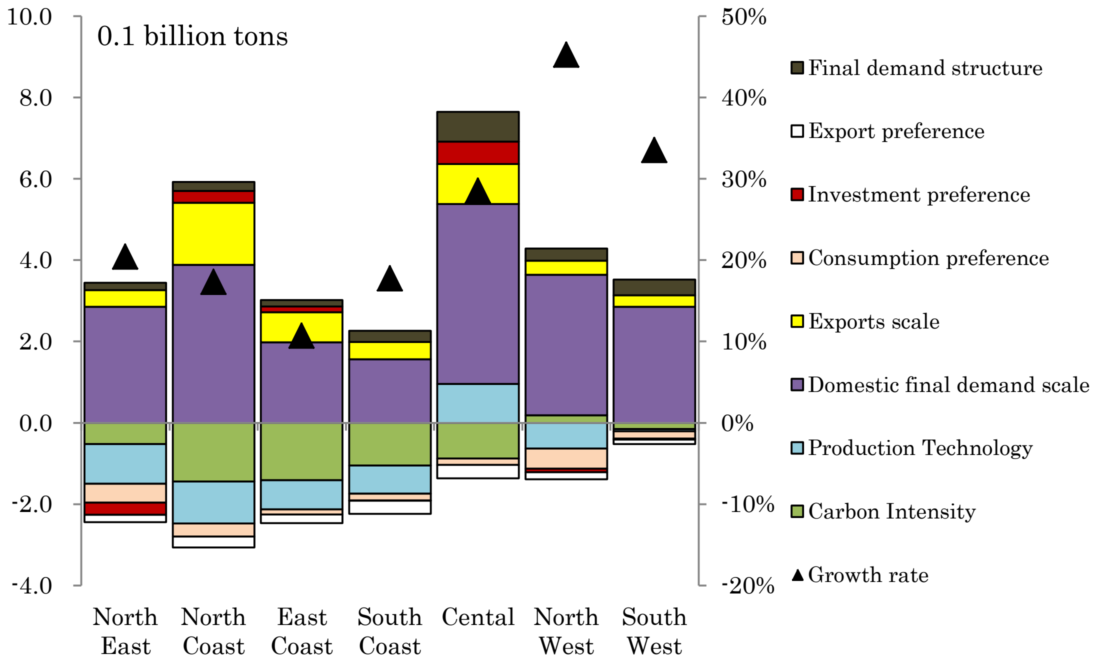
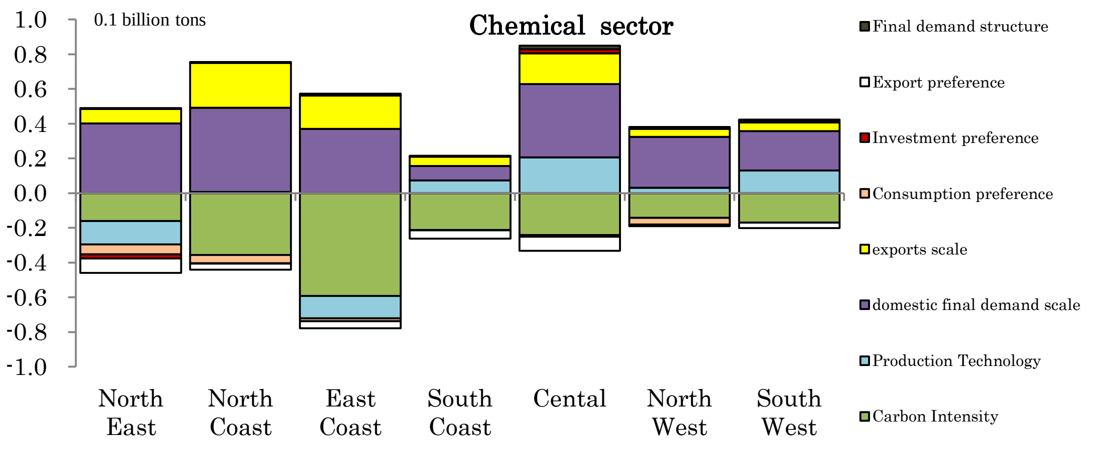
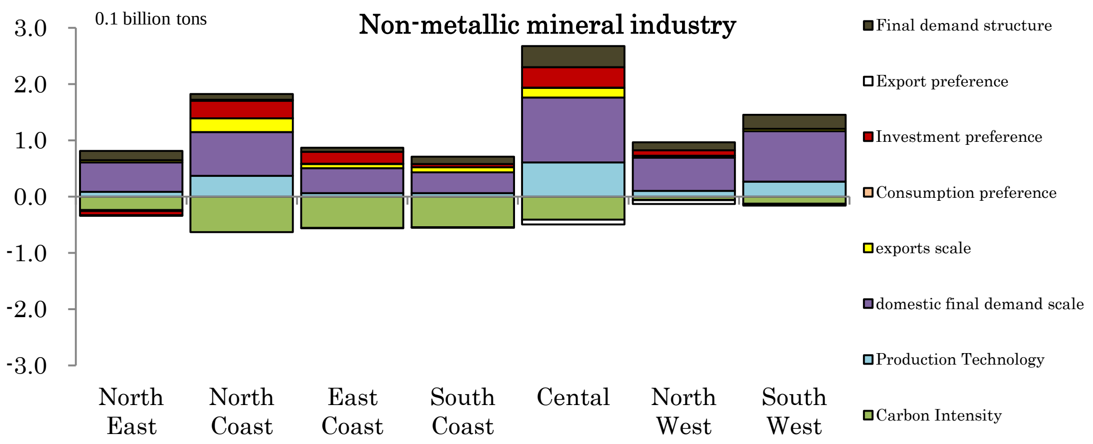
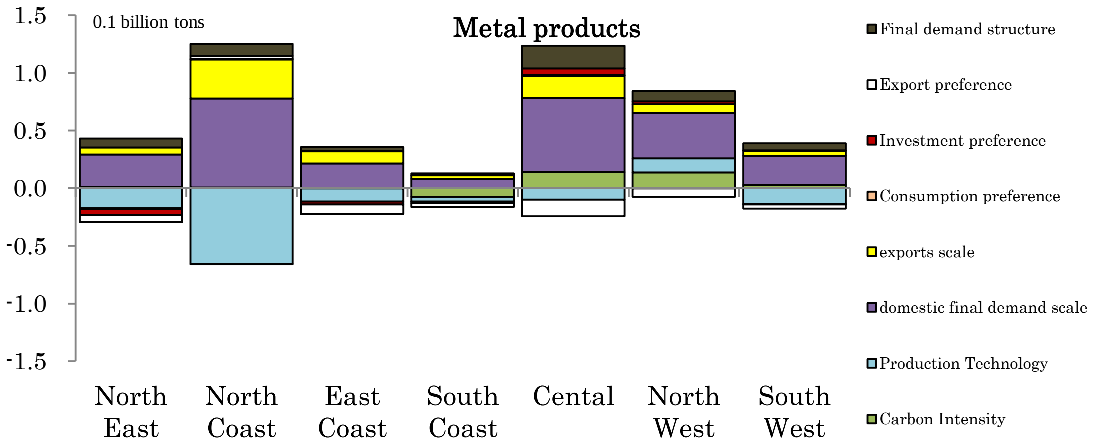


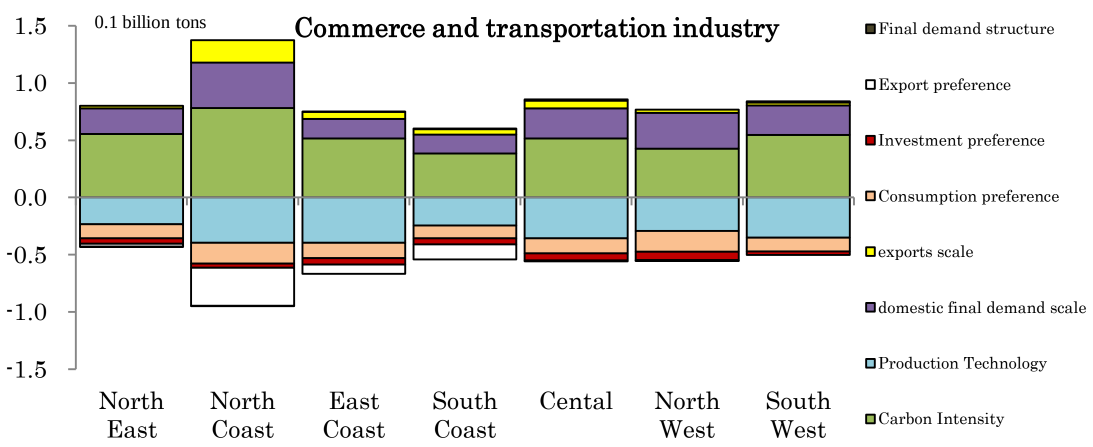
Figure 4 Decomposition result of regional CO_2 emissions at the aggregate level

In addition, looking at the determinants of regional emission growth at the industrial level, as shown in Figure 5 (depicting the top five emitting industries), more variation can be observed. For example, carbon intensity changes in the chemical industry play a very important role in reducing regional emissions growth, while in the commerce and transportation industry, such changes in turn greatly boost regional emission growth. Changes in investment preference produce relatively outstanding and positive effects on regional emission growth for the non-metallic mineral industry but not for other industries; the positive effect arising from changes in export scale can be easily seen for the chemical, metal, and electricity industries. Consumption preference changes help reduce emissions growth for the electricity and transportation industries, but no significant effects can be found for other industries.


Chemical sector
0.1 billion tons
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
North East
North Coast
East Coast
South Coast
Cental
North West
South West
Final demand structure
Export preference
Investment preference
Consumption preference
exports scale
domestic final demand scale
Production Technology
Carbon Intensity


Non-metallic mineral industry
0.1 billion tons
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
North East
North Coast
East Coast
South Coast
Cental
North West
South West
Final demand structure
Export preference
Investment preference
Consumption preference
exports scale
domestic final demand scale
Production Technology
Carbon Intensity


Metal products
0.1 billion tons
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
North East
North Coast
East Coast
South Coast
Cental
North West
South West
Final demand structure
Export preference
Investment preference
Consumption preference
exports scale
domestic final demand scale
Production Technology
Carbon Intensity


Commerce and transportation industry
0.1 billion tons
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
North East
North Coast
East Coast
South Coast
Cental
North West
South West
Final demand structure
Export preference
Investment preference
Consumption preference
exports scale
domestic final demand scale
Production Technology
Carbon Intensity

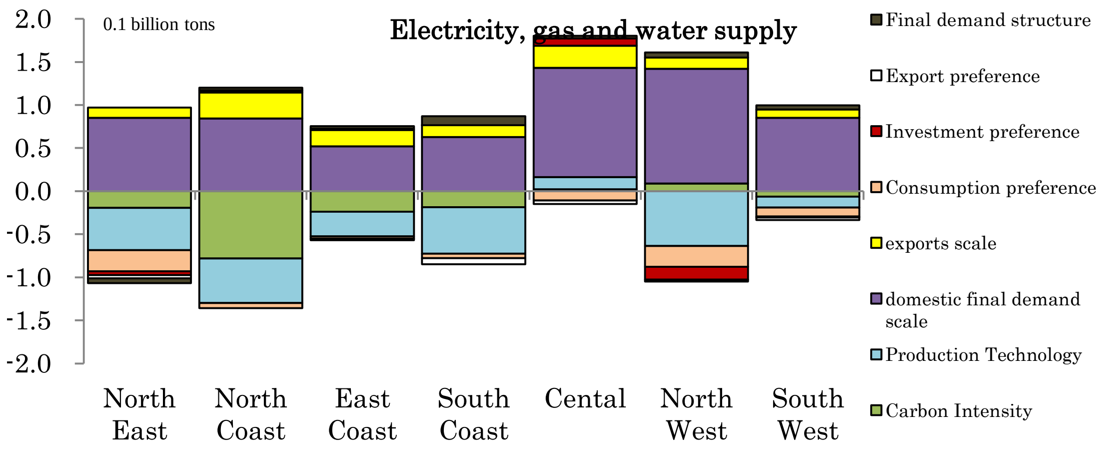


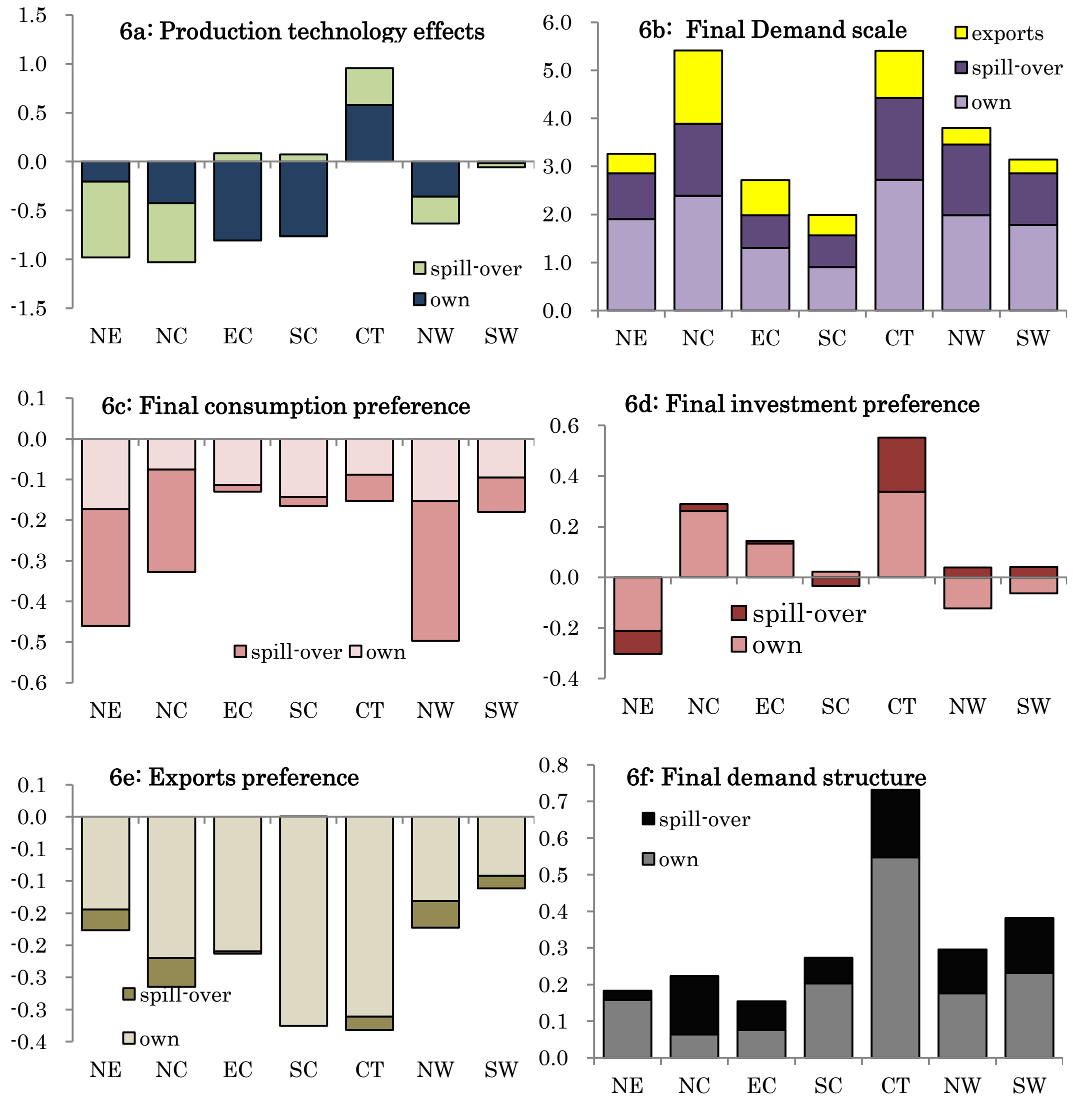
Figure 5 Determinants of regional emission growth at the industrial level

3.3 Spatial spillover effects in determining China's regional CO_2 emissions growth

The previous section describes how changes in national final demand affect regional emissions growth through various channels. This section focuses on clarifying the bilateral relationship of spillover effects in determining regional emissions growth. As explained previously, changes in a region's final demand may affect its own emission growth through intra-regional supply chains. In addition, it may affect other region's emissions growth through inter-regional supply chains. Figure 6 shows the results concerning spillover effects by different determinants at the aggregate level and Figure 7 shows the results at the bilateral level. Each of these will be explained in detail in the following sections.

3.3.1 Spatial spillover effects through changes in production technology

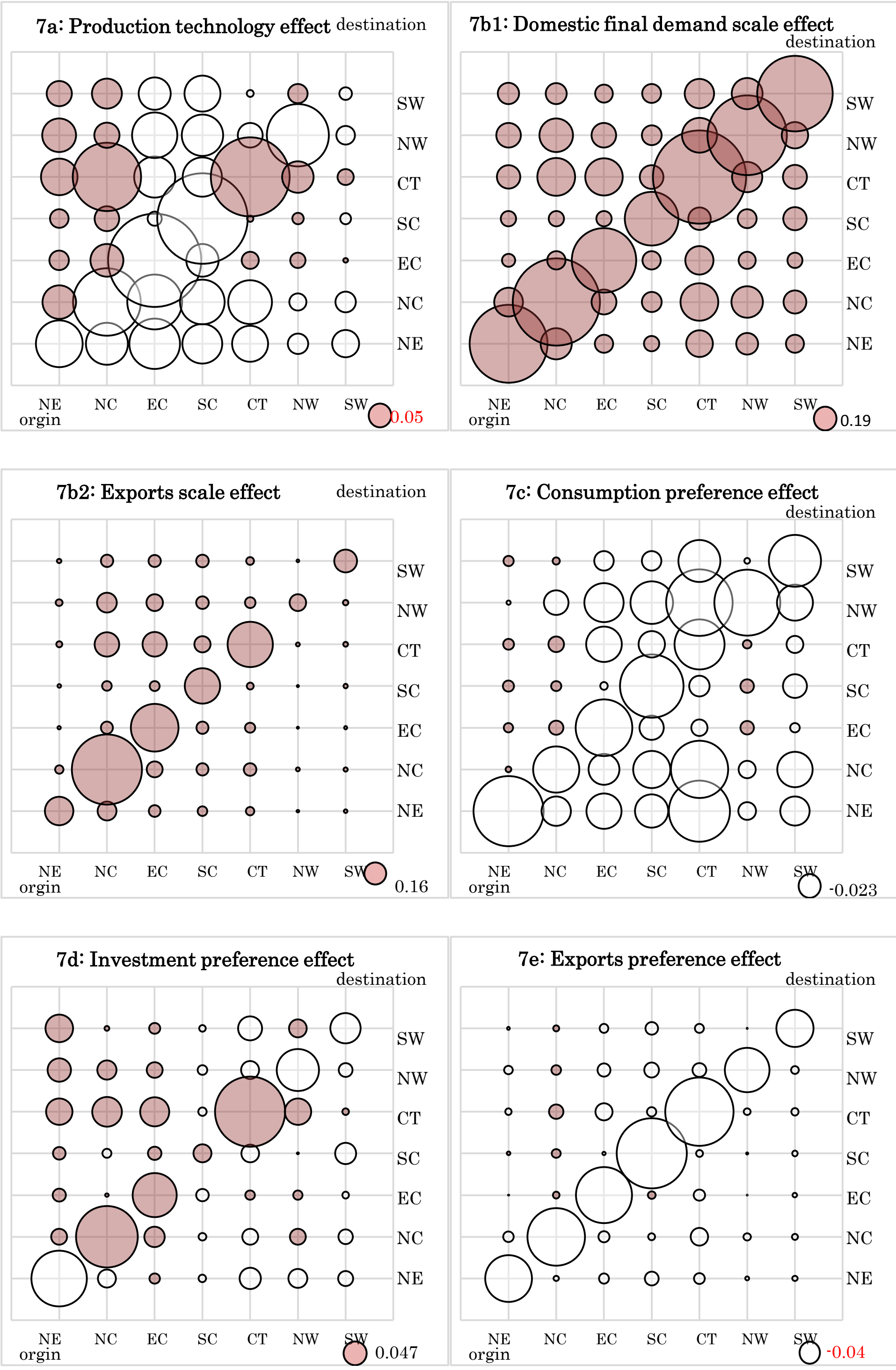
As shown in Figure 6a, for all regions except the Central region, changes in production technology reduce regional carbon emissions in absolute terms. However, large variations can be observed in terms of spillover patterns. For the two developed regions, the East Coast and South Coast, intra-regional technology changes take the dominant role in reducing carbon emissions, whereas for the Northeast and North Coast, spillover effects from other regions induce much larger emissions reductions compared with the intra-regional effect. Because a technology change is defined by a change in regional input coefficients [see the definition given in relation to Eq. (4)], the following conclusion can be drawn: if a region tends to use more highly carbon-intensive intermediate inputs, provided by other regions, to produce its output rather than producing these inputs internally, this type of technological change can reduce its own emissions but may increase its trade–partner's emissions. To investigate how regions affect each other through the channel of production technology changes, we refer to the bilateral results presented in Figure 7a. Clearly, technology changes in the East Coast and South Coast help reduce emissions in all regions, including the East and South Coasts. This is mainly because these two regions' production patterns are becoming more service-oriented (using fewer intermediate goods produced internally); simultaneously, they highly depend on processing trade[7] (using a large quantity of intermediate imports from other countries rather than from other domestic regions to produce exports). In contrast, technology changes in the Northeast and North Coast positively affect almost all other regions' emissions, especially those of the Central region. This reflects the fact that these two regions tend to use more high carbon-intensity intermediate goods provided by the Central region.

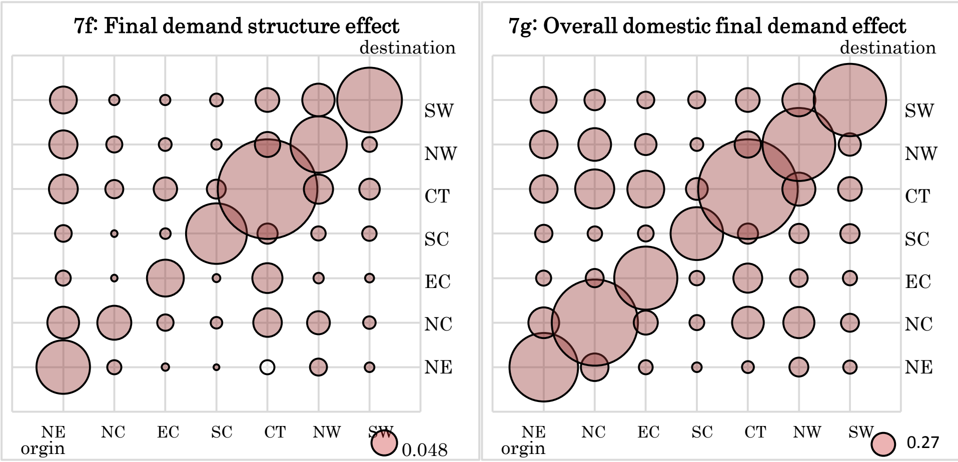


* Unit: 0.1 billion tons

Figure 6 Decomposition results of regional CO_2 emissions by different factors

[7] According to the regulations used by Chinese customs (EUSME, 2011), processing trade refers to importing all or part of raw and auxiliary materials, parts, components, accessories, and packaging materials from abroad duty free and re-exporting the finished products after processing or assembling by enterprises within mainland China (e.g., Foxconn assembles iPhones for Apple in China and exports the phones to the United States). This definition implies that regions with more firms engaged in the processing trade use more imported intermediate goods than those engaged in domestic production.


7a: Production technology effect
destination
SW NW CT SC EC NC NE
NE NC EC SC CT NW SW
orgin
0.05
7b1: Domestic final demand scale effect
destination
SW NW CT SC EC NC NE
NE NC EC SC CT NW SW
orgin
0.19
7b2: Exports scale effect
destination
SW NW CT SC EC NC NE
NE NC EC SC CT NW SW
orgin
0.16
7c: Consumption preference effect
destination
SW NW CT SC EC NC NE
NE NC EC SC CT NW SW
orgin
-0.023
7d: Investment preference effect
destination
SW NW CT SC EC NC NE
NE NC EC SC CT NW SW
orgin
0.047
7e: Exports preference effect
destination
SW NW CT SC EC NC NE
NE NC EC SC CT NW SW
orgin
-0.04



Note: "Origin" represents the region that externally affects other regions; "destination" represents the region affected by other regions' actions

Figure 7 Bilateral spatial spillover effects by different determinants

3.3.2 Spatial spillover effects through changes in final demand scale

As shown in Figure 6b, for all regions, changes in a region's own final demand scale plays a dominant role in increasing regional emissions. This is not surprising because a large proportion of a region's own final demand is normally fulfilled by products produced internally. However, one important finding is that a change in another region's final demand scale is the main determining factor influencing emissions growth in the Central, Northwest, and Southwest regions. This partly reflects the fact that these three regions' production highly depends on changes in other regions' final demand scales. Figure 7b1 provides more detailed results at the bilateral level. It is clear that the Central region attracts more attention because emissions growth in this region absorbs more spillover effects from other regions while simultaneously producing more spillover effects in other regions. This clearly reflects the fact that the Central region serves as the most important bridge in China's domestic supply chains, although it is not the largest economy in terms of output.

In addition, Figure 6b indicates that changes in export scale have a larger effect (compared with the effect from a change in other regions' final demand scale) on emissions for the North Coast and East Coast. More detailed bilateral relations are shown in Figure 7b2. Clearly, coastal regions' emissions growth mainly derives from changes in their own exports scale while emissions growth for interior regions heavily depends on changes occurring in other regions, especially in coastal regions' export scales. This is mainly because interior regions do not directly export more products to the global market but provide a very large quantity of intermediate goods to coastal regions for the latter's export-oriented production, thus easily accepting spillover effects from coastal regions. A good example is the Northwest region, which experiences more spillover effects from changes in other regions' export scales than from a change in its own.

3.3.3 Spatial spillover effects through changes in final consumption preferences

Lifestyle changes occurring in regional households may affect the respective region's own emissions and those of other regions through domestic supply chains. As shown in Figure 6c, the spillover effect arising from changes in other regions' final consumption preferences plays a dominant role in reducing emissions from all northern regions (Northeast, North Coast, and Northwest) compared with changes attributable to variations in these regions' own final consumption preferences. When looking at the bilateral relations of this type of spillover effect (Figure 7c), we can see that the most important contributors are the Central, East Coast, and South Coast regions, whose final consumption preference changes greatly help reduce all other region's emissions. Based on more detailed data, this phenomenon can be explained by the fact that these regions tend to have more services in their so-called "consumption baskets." Compared with the fragmented production style of manufacturing goods, services production normally relies on more local resources rather than needing extensive intermediate inputs provided by other regions. Therefore, if a region's consumption preferences become more service oriented, such a change will exert a positive spillover effect on other regions' emissions reduction. It should be noted that income growth might lead people to consume more manufactured goods than in the past, but the expenditure share of manufactured goods out of the total disposable income may decline. The change in consumption preferences measured here focuses on component changes in the consumption structure rather than changes in the consumption amount because this element has already been captured by changes in the final demand scale.

3.3.4 Spatial spillover effects through changes in investment preferences

As shown in Figure 6d, changes in investment preferences show a very different spillover-effect pattern compared with that of consumption preferences. Changes in intra-regional investment preferences produce the largest effect for most regions. A large positive spillover effect can be found for the Central region, whereas a relatively large negative spillover effect appears in the Northeast. From the viewpoint of supply chains, if a region's investment uses more highly carbon-intensive capital goods produced inside the region, the intra-regional effect should be larger. Accordingly, if this region uses more highly carbon-intensive capital goods provided by other regions, the corresponding emissions may occur in other regions through a spillover effect in domestic supply chains. This phenomenon is clearly confirmed in Figure 7d, which shows detailed inter-regional relations for such a spillover effect. For example, changes in investment preferences in the Northeast help reduce its own emissions but increase other regions' emissions. In contrast, changes in investment preferences in the Central region will normally increase its own emissions but help reduce those from other regions.

3.3.5 Spatial spillover effects through changes in export preferences

Changes in export preferences (foreign demand preferences regarding exports) can also affect regional emissions through domestic supply chains. As shown in Figure 6e, a change in regional emissions due to a change in export preferences normally occurs intra-regionally because most intermediate goods used to produce exports are provided intra-regionally. The spillover effect is a rather small element for most regions. However, a clear difference across regions regarding the spillover effect can still be confirmed. Namely, the two most developed coastal regions, the East Coast and South Coast, experience very small spillover effects from changes in other regions' export preferences at the aggregate level. For other regions, spillover effects can be much more remarkable. Detailed bilateral relations concerning such a spillover effect are shown in Figure 7e. Clearly, changes in export preferences induce greater reductions in the North Coast's own emissions but positively affect other regions' emissions. This is mainly because exports produced in the North Coast use more high-carbon intermediate goods provided by other regions rather than producing them internally. In contrast, the East Coast and South Coast regions give negative spillover effects to almost all other regions. This phenomenon reflects several underlying dynamics. One is the increasing portion of services in the exports of these two regions. The production of services needs fewer intermediate inputs compared with the production of manufacturing goods; this helps reduce emissions in supply chains. In addition, the increasing share of the processing trade in these two regions means that they need more intermediate goods from other countries rather than from other domestic regions. Therefore, changes in export preferences in these two regions may reduce other domestic regions' emissions but increase foreign countries' emissions due to these two regions' imports of high-carbon intermediate goods.

3.3.6 Spatial spillover effects through changes in the final demand structure

From the viewpoint of regional expenditures, final demand can be separated into (1) consumption and (2) investment. Different combinations of these two items may also affect regional emissions though domestic supply chains. As shown in Figure 6f, changes in the final demand structure increased regional emissions for all regions. This is mainly attributable to the increased investment expenditures of all regions, which need a substantial amount of capital goods with relatively high carbon intensity compared with consumption goods. In addition, the importance of spillover effects varies considerably across regions. Namely, regional emissions changes due to changes in the final demand structure mainly arise from the intra-regional channel for most regions; however, for the North Coast and East Coast, spillover effects occupy a larger portion. More detailed results at the bilateral level can be found in Figure 7f. For example, changes in the Northeast's final demand structure give large spillover effects to other regions. Based on more detailed data, we see that this occurs because the share of investment in the total final demand for this region increased rapidly between 2007 and 2010; this also occurs due to two facts: (1) relatively more capital goods used to fulfill this region's investment demand were provided by other regions and (2) producing capital goods for its own investment use needs relatively more intermediate goods from other regions.

4. Conclusion and discussion

In the 2009 Copenhagen Climate Change Summit, China committed to reducing its carbon dioxide emissions per unit of GDP by 40–45% from 2005 levels and to use non-fossil fuels for about 15% of its energy by 2020. China has also committed to increasing its forest cover by 40 million hectares and increasing its forest stock volume by 1.3 billion cubic meters by 2020 from 2005 levels. On June 30, 2015, China submitted its Intended Nationally Determined Contribution (INDC), including the target to peak CO2 emissions by 2030 at the latest, lower the carbon intensity of GDP by 60–65% below 2005 levels by 2030, increase the share of non-fossil energy carriers in the total primary energy supply to around 20% by that time, and increase its forest stock volume by 4.5 billion cubic meters compared to 2005 levels. More recently, during the world Paris Climate Conference (COP21), China promised to cut emissions by 60% from its coal power plants by 2020. These promises were made by the central government, but they must be implemented at regional levels following a top-down process. This will be a very challenging task for the central government when allocating the responsibility to respective local governments because great variations exist concerning resource endowment, economic size, industrial structure, income level, and development stage across China's domestic regions.

This paper applied an alternative input–output-based spatial-structure decomposition analysis to Chinese regions to identify the determinants of regional CO_2 emissions growth. The identified determinants that affect regional emissions growth include carbon intensity improvements and changes in production technology, final-demand scale, consumption and investment preferences, export scale and preferences, and expenditure patterns. The empirical results based on Chinese 2007 and 2010 inter-regional input–output tables show that in the interplay of various determinants, the total positive effects mainly arising from increased final demand and export scales cannot be canceled out by the total negative effects, which mainly arise from technology improvements for most regions. More detailed results at the inter-regional level show that (1) changes in most regions' final demand scale, final expenditure structure, and export scale give positive spatial spillover effects to other regions' CO_2 emission growth, (2) changes in most regions' consumption and export preferences help reduce other regions' CO_2 emissions, and (3) changes in production technology and investment preference may positively or negatively affect other regions' CO_2 emissions growth through domestic supply chains. For some regions, the aggregate spillover effect from other regions may be larger than the intra-regional effect in determining regional emissions growth. These findings have very important policy implications because a region's ability to reduce its emissions depends not only on its own efforts but also on possible spillover effects coming from other domestic regions through various supply chain channels.

A better understanding of the determinants of regional emission growth can not only help local governments identify the most important policy targets but also support the central government's ability to make balanced environmental governance across regions, since "you can't manage what you can't measure."

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Appendix 1 Sector and regional classifications used in the paper

Table A1 Sector classification

Code	Sector name (Chinese IRIO table)
S1	Agriculture
S2	Mining and quarrying
S3	Food products and tobacco
S4	Textile and garment
S5	Wooden products and furniture
S6	Pulp, paper and printing
S7	Chemical
S8	Non-metallic mineral products
S9	Metal products
S10	General mechinary
S11	Transport equipment
S12	Electric apparatus, electronic and telecommunications equipment
S13	Other manufacturing products
S14	Electricity, gas, and water supply
S15	Construction
S16	Trade and transportation
S17	Other services

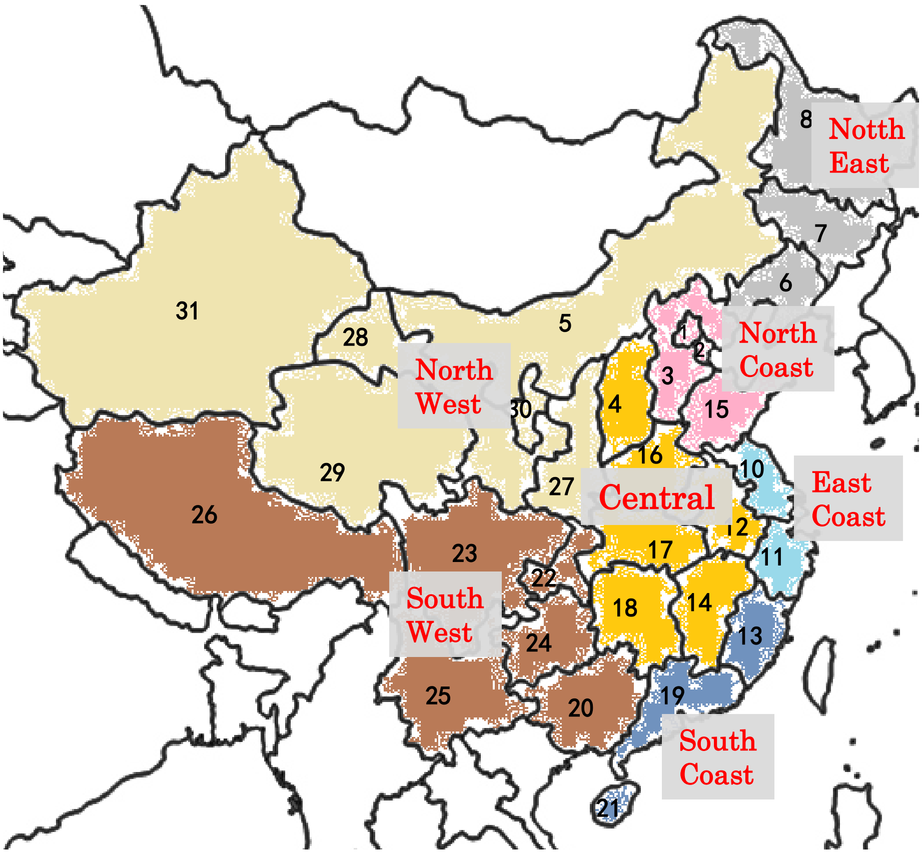

Figure A1 Regions in mainland China

Table A2 Region classification

Regions in mainland China	code 1	code 2	Region classification used in the paper						
			North East (NE)	North Coast (NC)	East Coast (EC)	South Coast (SC)	Central (CT)	North West (NW)	South West (SW)
Beijing	1	BJ		1					
Tianjin	2	TJ		1					
Hebei	3	HeB		1					
Shanxi	4	SX					1		
Neimenggu	5	NMg						1	
Liaoning	6	LN	1						
Jilin	7	JL	1						
Heilongjiang	8	HLJ	1						
Shanghai	9	SH			1				
Jiangsu	10	JS			1				
Zhejiang	11	ZJ			1				
Anhui	12	AH					1		
Fujian	13	FJ				1			
Jiangxi	14	JX					1		
Shandong	15	SD		1					
Henan	16	HeN					1		
Hubei	17	HuB					1		
Hunan	18	HuN					1		
Guangdong	19	GD				1			
Guangxi	20	GX							1
Hainan	21	HaN				1			
Chongqing	22	CQ							1
Sichuan	23	SC							1
Guizhou	24	GZ							1
Yunnan	25	YN							1
Tibet	26	TB							1
Shaanxi	27	SzX						1	
Gansu	28	GS						1	
Qinghai	29	QH						1	
Ninxia	30	NX						1	
Xinjiang	31	XJ						1	

Appendix 2 Estimation of CO_2 emissions

China's provincial CO_2 emissions by industry were estimated using the following method:

(1) CO_2 emissions from fuel combustion = E×V×F×O

E: Amount of energy combustion from different fuel types (in physical units)[1,2]

V: Chinese-specific low-calorific value of different fuel types[3]

F: Emission factors of different fuel types[4]

O: Chinese-specific oxidization rate[5, 6]

(2): CO_2 emissions from cement production = C× F

C: Cement (including clinker) production amount[7]

Notes:

1. Chinese Energy Statistics Yearbook, national and provincial energy balance tables

2. Chinese Provincial Statistical Yearbooks
3. Chinese Energy Statistics Yearbook (Conversion Factors from Physical Units to Coal Equivalent)
4. IPCC, 2006 IPCC Guidelines for National Greenhouse Gas Inventories
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