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Assessment and Adjustment of Export Embodied Carbon Emissions with Its Domestic Spillover Effects: Case Study of Liaoning Province, China

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Abstract: Export embodied carbon emissions (EECE) and their domestic spillover effects (DSE) are typical interregional carbon transfer phenomena. They have diversified impacts for different regions within a country, and result in the associated effect on the economy and environment. From 2007 to 2017, the EECE of China was mainly concentrated in five provinces, and EECE intensity mostly decreased. Liaoning Province had the largest EECE intensity and EECE growth from 2012 to 2017. Based on the multi-region input-output tables of China, we applied the Multi-region Input-output Model and constructed the Coupling Relationship Model for trade value and carbon emission, quantitatively assessed the EECE and its DSE for Liaoning Province, depicted the spatial-temporal evolution patterns, proposed sectoral adjustment countermeasures, and evaluated the adjustment effects. The research found that the EECE and its DSE of Liaoning Province was 32.08 $MtCO_2$ and 5.43 $MtCO_2$ in 2017. It was mainly concentrated in the metal smelting and rolling processing sector (MetalSmelt) and the petroleum processing, coking and nuclear fuel processing sectors (RefPetral). The spatial agglomeration effect was obvious, and Jilin Province was the largest DSE region. According to the Coupling Relationship Model of export trade value and export embodied carbon emissions, the sectors were divided into four types, and different adjustment countermeasures were proposed, such as encouragement, control, targeted promotion and targeted reduction. For the MetalSmelt and the RefPetral, if the export value reduced 100 million CNY, the EECE would be reduced by 21.57 $ktCO_2$ and 23.35 $ktCO_2$, respectively, and the DSE would be reduced by 1.59 $ktCO_2$ and 1.65 $ktCO_2$, respectively. The conclusions could provide a decision-making basis for the case area to formulate lower-cost and better-effective carbon reduction adjustment countermeasures. It could also provide reference and scientific support for the achievement of "Carbon Neutrality" and sustainable development in similar regions of the world with the rapid growth of EECE.

Keywords: export embodied carbon emissions; domestic spillover effects; adjustment countermeasures; effect assessment; Liaoning Province; China

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1. Introduction

Under the background of climate change, achieving "Carbon Neutrality" has become a common goal of the international community [1–6]. EECE accounts for 25% of the global total, which further contributes to global warming [7]. For the "Carbon Neutrality" implementation plan formulation, reducing export embodied carbon emissions (EECE) was an important aspect [8–13].

The production process of a certain export product extended from the raw materials acquisition to the final product output. All direct and indirect carbon emissions generated during the entire production process of an export product are the EECE. The EECE has an important impact on the total regional carbon emissions [14–16]. China is the largest CO_2

emitter in the world [17]. Its EECE accounted for nearly 30% of national emissions and was one of the important reasons that the total carbon emissions remained high [18–23]. The production of a certain export product not only caused the carbon emissions of an export province, but also have the domestic spillover effects (DSE) on other provinces. The DSE is the carbon emissions generated by providing raw materials for export products, which are transmitted through inter-provincial trade. In 2017, the total DSE of EECE was 580 $MtCO_2$ in China, which seriously affected the interregional carbon emission pattern [24]. Therefore, EECE and its DSE cannot be ignored in the formulation of regional carbon emission reduction policies. In recent years, the issue of EECE has gradually attracted the attention of the academic community [25–29]. However, the existing achievements were limited to the research on EECE itself, rather than the DSE [30–34]. Most of the research only looked at the level of spatial-temporal pattern analysis and rarely analyzed the sectoral sources. In addition, the existing studies lacked empirical research on targeted adjustment countermeasures, which could not effective support the "Carbon Neutrality".

Based on the above analysis, we found that the existing research results did not answer the following scientific questions well:

Research Question 1: What was the spatial-temporal evolution pattern of EECE and its DSE for the typical region?

Research Question 2: How do we reduce the EECE and its DSE?

Research Question 3: What are the carbon reduction effects of the adjustment countermeasures for EECE?

From 2007 to 2017, the EECE of China was mainly concentrated in five provinces, and EECE intensity mostly decreased. Only Liaoning Province has the largest EECE intensity and EECE growth from 2012 to 2017. Therefore, we selected Liaoning Province as the research object. Based on the multi-region input-output tables of China, we applied the Multi-region Input-output Model (MRIO Model) and ArcGIS spatial analysis tools, constructed the Coupling Relationship Model (CR Model) for trade value and carbon emissions, quantitatively assessed the EECE and its DSE for Liaoning Province, depicted the spatial-temporal evolution pattern, proposed sectoral adjustment countermeasures, and evaluated the adjustment effects. The conclusions could provide a decision-making basis for the case area to formulate lower-cost and better-effective carbon reduction adjustment countermeasures. It could also provide a reference and scientific support for achieved "Carbon Neutrality" and sustainable development in similar regions of the world with rapid growth in EECE.

The rest of this paper was organized as follows: Section 1 was the introduction, Section 2 reviews the relevant literature, Section 3 introduces the general situation of the study area, Section 4 discusses the methodological model, Sections 5 and 6 involve the results analysis and adjustment countermeasures, and Section 7 includes the conclusions of the paper.

2. Literature Review

2.1. Research on EECE

The primary problem of reducing the EECE was the scientific accounting of the amount [35–41]. Many scholars have carried out related researches. Sato et al. [42] calculated the EECE from 1995–2007 and found that EECE has the most obvious negative effects, accounting for 10–45% of total carbon emissions in China. Wang et al. [19] calculated the EECE of global high-tech products in China in 2011, and found that it accounted for 73.20% of total global EECE.

EECE has an important impact on the global carbon emission pattern [43–47]. Zhong et al. [48] analyzed the EECE spatial-temporal evolution of 39 countries, and found that the EECE transformed from developing countries to developed countries from 1995 to 2011. Zhang et al. [49] found that 72% of the embodied air pollution (including carbon monoxide, sulfur dioxide, etc.) of the export trade was borne by central and western regions of China in 2012, which were the less developed regions.

With the continuous deepening of EECE research, a global discussion of the EECE adjustments has arisen. Some scholars have proposed that more scientific sectoral structure adjustment countermeasures and more reasonable carbon reduction countermeasures should be formulated. Sun et al. [50] proposed the adjustment countermeasures of the sectoral EECE in China, such as increasing the exports of 10 sub-sectors. Xu et al. [51] found that most EECE were concentrated in a few sectoral areas in China, and that in the globally integrated market, China could reduce its emission intensity by introducing advanced technologies and management systems from developed countries.

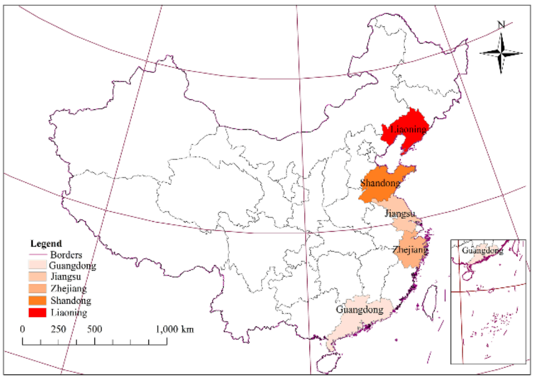
2.2. Research on DSE of EECE

The research of the EECE and its DSE was still in the initial stages. Only a few scholars have explored its account and the spatial patterns of large regional scales. Guo et al. [14] considered that EECE has an important impact on carbon emissions in different parts of the country. As a result of the 2008 financial crisis, the exports of China declined rapidly, which results in a decline in the growth rate of carbon emissions in eastern and central China to 3.96% and 5.86%, respectively. Meng et al. [52] studied the EECE and its DSE of energy-intensive intermediate products in 2012. He divided China into eight regions. The central region was a major supplier of highly energy-intensive intermediate products that are exported to coastal areas. The central region was also a major suffer region with the DSE of EECE for coastal areas.

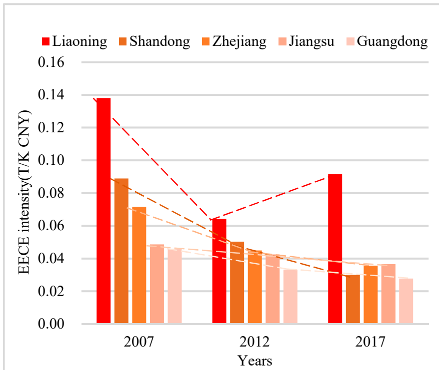
In summary, the existing studies lacked the provincial spatial-temporal pattern analysis of EECE and its DSE. Less research was carried on the EECE sectoral sources, adjustment countermeasures, and even the countermeasures effects. It was unable to meet the actual needs of scientific carbon reduction policy formulation and the "Carbon Neutrality" target realization. Such issues need to be researched in depth as soon as possible.

3. Study Area

From 2007 to 2017, the EECE was concentrated in five provinces in China, which were Liaoning Province, Shandong Province, Zhejiang Province, Jiangsu Province and Guangdong Province, and their total EECE had remained above 60% (Figure 1a). Among them, the EECE intensity of four provinces remained decreased. However, the EECE intensity of Liaoning Province decreased from 2007 to 2012 and then increased from 2012 to 2017, which became the largest province (Figure 1b). In 2017, the EECE intensity of Liaoning Province was 0.09 T/K CNY, higher than the national average of 0.06 T/K CNY. In addition, the EECE of Liaoning Province also decreased from 2007 to 2012 and then increased from 2012 to 2017. The EECE increased from 21.42 $MtCO_2$ in 2012 to 32.08 $MtCO_2$ in 2017, which was the fastest growth, with a growth rate of 49.78%.



(**a**)



(**b**)

Figure 1. The location (**a**) and EECE intensity of the top five provinces with EECE from 2012 to 2017 (**b**). Source: authors' own creation.

According to the change trends of EECE intensity and EECE, we found that the ecological environmental effects of export were improving for most provinces in the most recent 10 years. However, for Liaoning Province, it had seriously deteriorated from 2012 to 2017. Therefore, we selected Liaoning Province as the study area, chose 2012 to 2017 as the study period, quantitatively assessed the EECE and its DSE, and proposed adjustment countermeasures. This research could provide a reference for carbon reduction and regional sustainable development achievement in similar regions around the world.

4. Models and Methods

4.1. Research Methods

4.1.1. MRIO Model

Assessing the EECE and its DSE requires a clear understanding of the relationships among the various sectors in different regions (Table 1). The Multi-region Input-output Model (MRIO Model) can quantitatively express the sectoral correlation within and among regions. It is a commonly used model for calculating the carbon emissions of interregional trade and tracking spillover and feedback relationships among regions [53]. Therefore, we used this method to quantitatively assess the EECE and its DSE, as well as the adjustment countermeasures effects.

In the Multi-region Input-output Tables, the row vectors include intermediate use, final use, and total output. S_i (i =1, 2, . . . , n) is the sectors. X_{rd}^{ij} (i, j =1, 2, . . . , n and r, d = 1, 2, . . . , m, in this research n = 29, m = 31) is the intermediate use of r region i sector put into the d region j sector. The final use is consisted of internal final use and export. F_{rd}^{ij} is the internal final use of r region i sector put into the d region j sector i. EX_r^i is the export of r region i sector. X_r^i is the total output of r region i sector.

The column vectors are intermediate inputs, imports, value added and total inputs. IM_r^{ij} and IMF_r^{ij} are respectively the import of i sector put into the intermediate use and internal final use of r region j sector. V_r^i is the added value of r region i sector. X_r^i is the total input of r region i sector.

The direct consumption coefficient is also known as the input coefficient or the technical coefficient, usually expressed by the letter a, and the formula is:

$$a_{rd}^{ij} = \frac{X_{rd}^{ij}}{X_d^j} \quad (i, j = 1, 2, \ldots, n; r, d = 1, 2, \ldots, m) \tag{1}$$

where a_{rd}^{ij} expresses the proportion of the intermediate input from the r region i sector in the total input of d region j sector.

The basic equation for the Multi-region Input-output Model is

$$\sum_{j=1}^{n} a_{rd}^{ij} X_{rd}^{ij} + Y_r^i = X_r^i \tag{2}$$

where Y_r^i is the final use of r region i sector, which is composed of F_{rd}^{ij} and EX_r^i.

Equation (2) is the balanced expansion in Multi-region Input-output Tables, and could be converted in matrix form as follows:

$$X = (I - A)^{-1} Y \tag{3}$$

where $(I - A)^{-1}$ is the Leontief inverse matrix. X is the output matrix, Y is the final use matrix for all regions, which is composed of F and EX.

We used EX instead of Y and obtained the following:

$$C = (I - A)^{-1} \cdot EX \cdot e \cdot \mu \tag{4}$$

where C represents EECE, e is the intensity of energy consumption matrix, and μ is the carbon emission coefficient matrix.

Table 1. Multi-region Input-output Table of a country.

			Intermediate Use							***Final Use***								***Total Output***
			Region $_1$			...	***Region*** $_m$			***Region*** $_1$			...	***Region*** $_m$			***EX***	
			S_1	...	S_n	...	S_1	...	S_n	S_1	...	S_n	...	S_1	...	S_n		
Intermediate input	***Region*** $_1$	S_1	X_{11}^{11}	...	X_{11}^{1n}		X_{1m}^{11}	...	X_{1m}^{1n}	F_{11}^{11}	...	F_{11}^{1n}		F_{1m}^{11}	...	F_{1m}^{1n}	EX_1^1	X_1^1
		...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
		S_n	X_{11}^{n1}	...	X_{11}^{nn}		X_{1m}^{n1}	...	X_{1m}^{nn}	F_{11}^{n1}	...	F_{11}^{nn}		F_{1m}^{n1}	...	F_{1m}^{nn}	EX_1^n	X_1^n
	...	...		...		...		...			...		...		...		...	...
	Region $_m$	S_1	X_{m1}^{11}	...	X_{m1}^{1n}		X_{mm}^{11}	...	X_{mm}^{1n}	F_{m1}^{11}	...	F_{m1}^{1n}		F_{mm}^{11}	...	F_{mm}^{1n}	EX_m^1	X_m^1
		...	...	...	...	...		...		...	...	...	...	...	...		...	...
		S_n	X_{m1}^{n1}	...	X_{m1}^{nn}		X_{mm}^{n1}	...	X_{mm}^{nn}	F_{m1}^{n1}	...	F_{m1}^{nn}		F_{mm}^{n1}	...	F_{mm}^{nn}	EX_m^n	X_m^n
	IM	S_1	IM_1^{11}	...	IM_1^{1n}	...	IM_m^{11}	...	IM_m^{1n}	IMF_1^{11}	...	IMF_1^{1n}	...	IMF_m^{11}	...	IMF_m^{1n}		
		...	...	...	...	...	...	...	...	...	...	...	...	...	...	...		
		S_n	IM_1^{n1}	...	IM_1^{nn}	...	IM_m^{n1}	...	IM_m^{nn}	IMF_1^{n1}	...	IMF_1^{nn}	...	IMF_m^{n1}	...	IMF_m^{nn}		
Value added			V_1^1	...	V_1^n	...	V_m^1	...	V_m^n									
Total Input			X_1^1	...	X_1^n	...	X_m^1	...	X_m^n									

4.1.2. CR Model

In order to adjust the EECE and its DSE, as well as formulate adjustment countermeasures with less economic impact and better carbon reduction effects, upon referring to previous studies [27], we constructed a Coupling Relationship Model (CR Model) for trade values and carbon emissions.

In the CR Model for trade value and carbon emission, we used "change in contribution rate" to measure "change in the trade value " and "change in carbon emission". Thus, we got the following formula:

$$\begin{cases} \Delta R_T = R_T^1 - R_T^0 = T_i^1/T_{total}^1 - T_i^0/T_{total}^0 \\ \Delta R_C = R_C^1 - R_C^0 = C_i^1/C_{total}^1 - C_i^0/C_{total}^0 \end{cases} \tag{5}$$

where ΔR_T and ΔR_C represent the change in the contribution rate. And the superscripts 0 and 1 represent two different years. In this research, 1 represents 2017 and 0 represents 2012. $T_{total}^t = \sum_{i=1}^{m} T_i^t$, $C_{total}^t = \sum_{i=1}^{m} C_i^t$, T_{total}^t and C_{total}^t indicate the total trade value and the total carbon emission, respectively. T_i^t and C_i^t represent them in the t year i sector.

Based on the coupling relationship between ΔR_T and ΔR_C, we divided the sector into 4 types, as follows: Type I: $\Delta R_T > \Delta R_C > 0$. Type II: $\Delta R_T > 0$, $\Delta P_C < 0$. Type III: $\Delta R_T < 0$, $\Delta R_C < 0$. Type IV: $\Delta R_T < 0$, $\Delta R_C > 0$.

In this research, if the trade value is ETV, the carbon emission expresses EECE, which is the Coupling Relationship Model of export trade value and the export embodied carbon emissions(ETV-EECE CR Model), which were used for the adjustment classification of EECE; if the trade value is the interprovincial trade value (ITV), the carbon emission means the DSE, that is Coupling Relationship Model of interprovincial trade value and the domestic spillover effects (ITV-DSE CR Model), which was used for the adjustment classification of DSE.

4.2. Data Source

The export and interprovincial trade data comes from the China multi-region input-output tables of 2007, 2012 and 2017 (excluding Hong Kong, Macao and Taiwan). It was compiled by the Development Research Center of the State Council and the National Bureau of Statistics. China's multi-region input-output tables were compiled every 5 years. The latest version is from 2017.

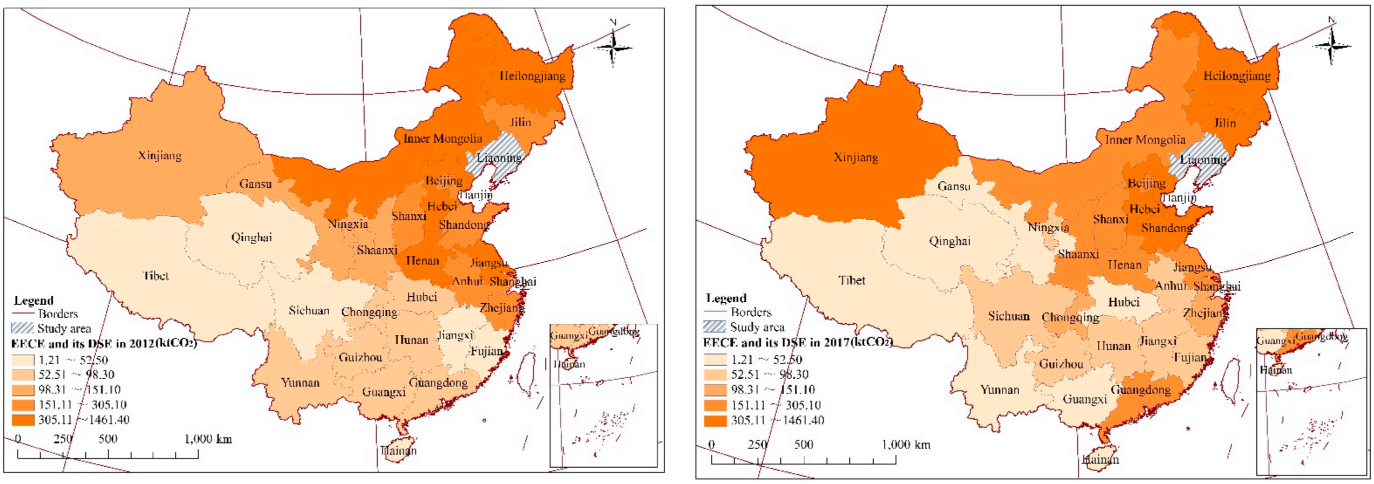
The energy consumption data were derived from the "regional energy balance", "comprehensive energy balance sheet" and "energy variety consumption by sector" provided by the *China Energy Statistical Yearbook* and the *Provincial Statistical Yearbook*. Based on the energy conversion coefficients provided by the Intergovernmental Panel on Climate Change (IPCC), the energy consumption intensity of each province and sectors were calculated.

The classification of sectors was slightly different for the multi-region input-output tables and the energy consumption data obtained from the statistical yearbook; this research categorized the sectors into 29 distinct ones.

5. Results

5.1. The EECE and its DSE of Liaoning Province

According to the MRIO Model, the total EECE of Liaoning Province rose from 21.42 $MtCO_2$ in 2012 to 32.08 $MtCO_2$ in 2017 (Figure 2a). The impact of EECE on Liaoning Province itself increased from 14.93 $MtCO_2$ in 2012 to 26.67 $MtCO_2$ in 2017. The DSE decreased from 6.49 $MtCO_2$ in 2012 to 5.43 $MtCO_2$ in 2017.



(**a**) (**b**)

Figure 2. Spatial pattern for EECE and its DSE of Liaoning Province in 2012 (**a**) and 2017 (**b**). Source: authors' own creation.

The DSE decreased, but its spatial agglomeration effect was obvious. Jilin Province became the province with the largest DSE, and the DSE increased from 265.40 ktCO_2 in 2012 to 749.13 ktCO_2 in 2017, with an increase rate of 182.27% (Figure 2b). Shandong and Tianjin were the second and third highest in growth, with DSE increasing to 213.19 ktCO_2 and 126.74 ktCO_2, respectively. The petroleum processing, coking and nuclear fuel processing sectors (RefPetral) and metal smelting and rolling processing sector (MetalSmelt) were main sectors which lead to the DSE increase in Jilin Province.

5.2. Typical Sectors of EECE and Its DSE

From the perspective of the sectors, the EECE of the MetalSmelt remained in the top place, with an increase from 9.07 MtCO_2, and accounted for 0.76% of the total in 2012 to and 1.56% in 2017. Furthermore the EECE of the RefPetral became the second largest sector in Liaoning Province, with an increase from 768.72 ktCO_2 in 2012 to 6.04 MtCO_2 in 2017, and accounted for the proportion of EECE from 0.13% in 2012 to 1.04% in 2017. RefPetral became the fastest growing sector in China (Figure 3).

The EECE of MetalSmelt has always ranked first with the impact on Liaoning Province itself increasing from 4.28 MtCO_2 in 2012 to 8.40 MtCO_2 in 2017, and the DSE of other provinces decreasing from 984.32 ktCO_2 in 2012 to 669.35 ktCO_2 in 2107. This indicates that the impact of EECE on the export region has intensified (Figure 4a). Although the DSE has weakened overall, it showed an obvious spatial agglomeration effect that DSE aggravated in the Hebei, Jilin, and Shandong Provinces. These three provinces exceeded Inner Mongolia and Heilongjiang to be the largest regions of DSE. Among them, the DSE of Jilin Province increased from 25.01 ktCO_2 in 2012 to 92.00 ktCO_2 in 2017, with an increase rate of 267.80% (Figure 4b). In order to export MetalSmelt products, Liaoning Province needed to buy MetalSmelt and Transport products from Hebei Province, buy NonMProd, TranspEq and chemical products from Jilin Province, and buy chemical, construct and other products from Shandong Province, which were the main DSE transmission processes.

The RefPetral EECE increased by 5.28 MtCO_2 from 2012 to 2017. The impact on Liaoning Province itself and the DSE both significantly increased (Figure 5a), with an increase from 705.85 ktCO_2 in 2012 to 5.62 MtCO_2 in 2017, and from 62.87 ktCO_2 in 2012 to 431.06 ktCO_2 in 2017, respectively. It showed an obvious spatial diffusion effect. The provinces of DSE exceeding 10 ktCO_2 increased from just two in 2012 to eight in 2017 (Figure 5b). Heilongjiang and Jilin Province remained the provinces with the largest DSE in 2012 and 2017. In addition, the DSE increased from 24.94 ktCO_2 and 14.73 ktCO_2 in 2012 to 162.87 ktCO_2 and 75.82 ktCO_2 in 2017, respectively, and increased more than six times. In order to export RefPetral products, Liaoning Province needed to buy RefPetral products from Heilongjiang Province and buy Coalmin and chemical products from Jilin Province, which constituted the main DSE transmission process.

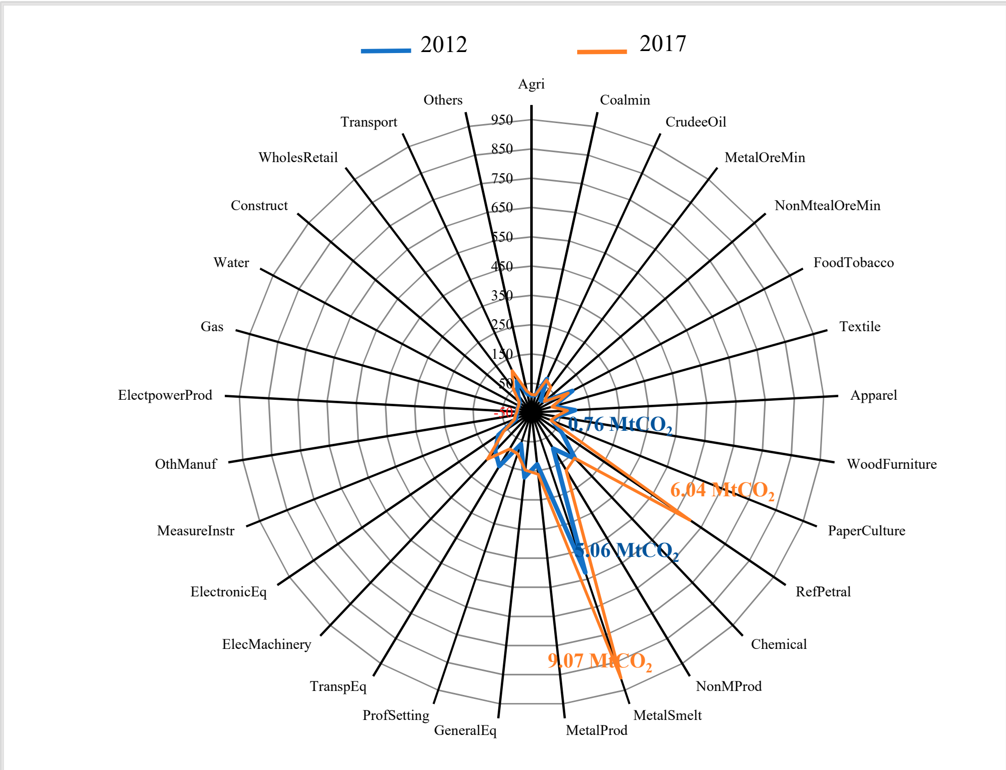
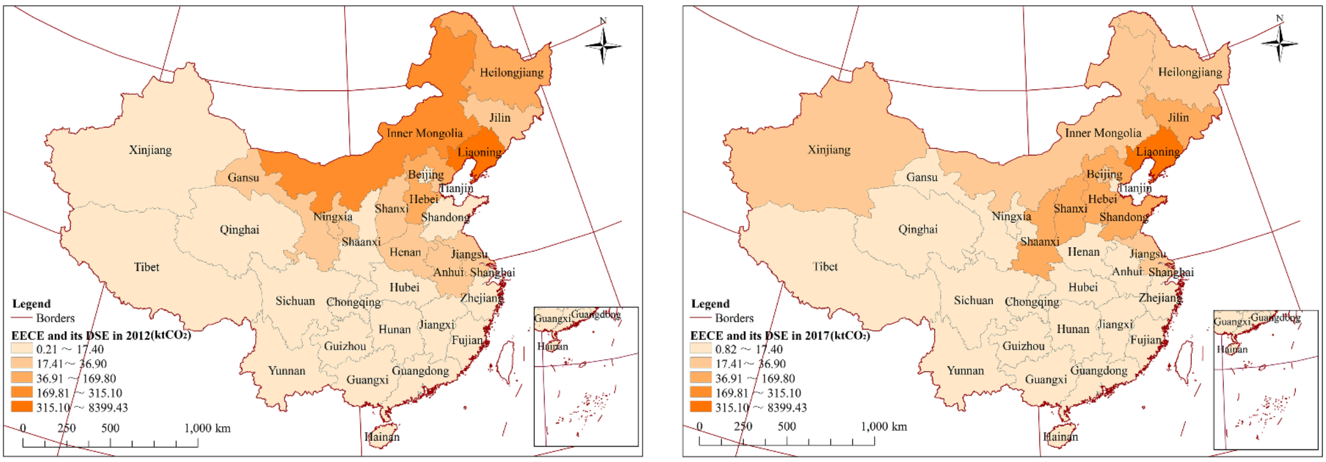


Figure 3. EECE of Various Sectors in Liaoning Province in 2012 and 2017. Note: The full name and abbreviation of the sectors are shown in the Table A1. Source: authors' own creation.



(**a**) (**b**)

Figure 4. Spatial pattern for MetalSmelt EECE and its DSE of Liaoning Province in 2012 (**a**) and 2017 (**b**). Source: authors' own creation.

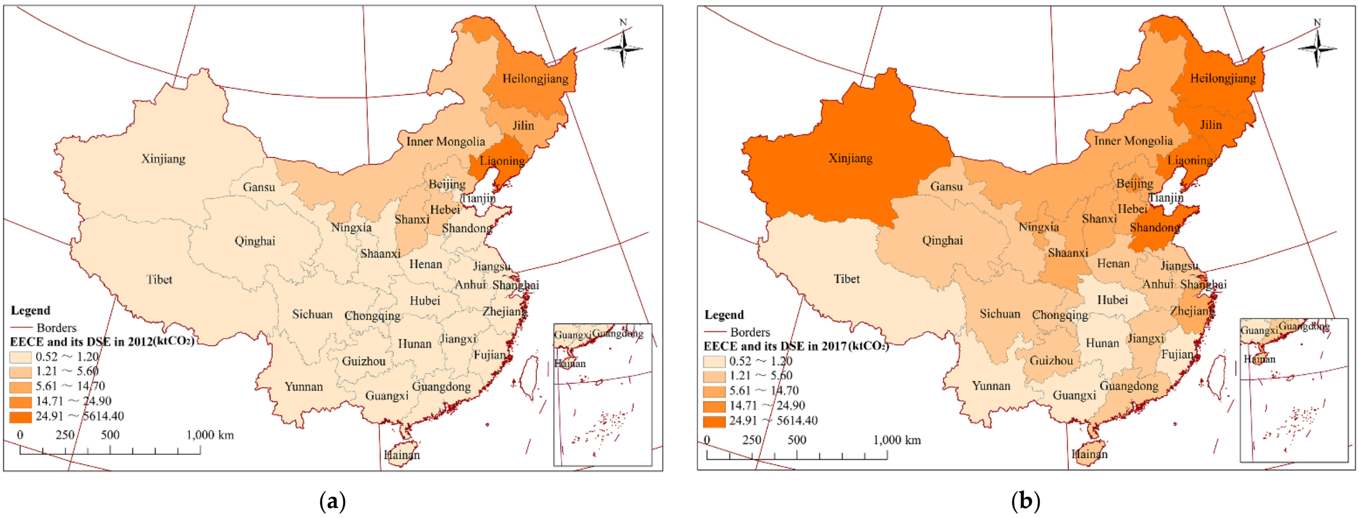


Figure 5. Spatial pattern for RefPetral EECE and its DSE of Liaoning Province in 2012 (**a**) and 2017 (**b**). Source: authors' own creation.

6. Adjustment Countermeasures and Its Effects

6.1. Sectoral Adjustment Countermeasures

Based on the above analysis, the EECE were not uniformly distributed in all sectors, but rather were relatively concentrated in some key sectors, such as MetalSmelt and RefPetral. However, these key sectors with higher EECE might be not with the highest ETV. Therefore, according to the export trade value and the ETV-EECE CR Model, we proposed the sectoral adjustment countermeasures to achieve the purpose of reducing EECE, while maximizing the export economic benefits.

6.1.1. Classification of Sectoral Adjustment Types

According to the ETV-EECE CR Model, we classified the 27 sectors into the following four types (Figure 6). The ETV and EECE of the ElectpowerProd and the Water were 0, so they did not participate in the classification. There are nine sectors in Type I, zero sectors in Type II, 11 sectors in Type III, and seven sectors in Type IV, respectively.

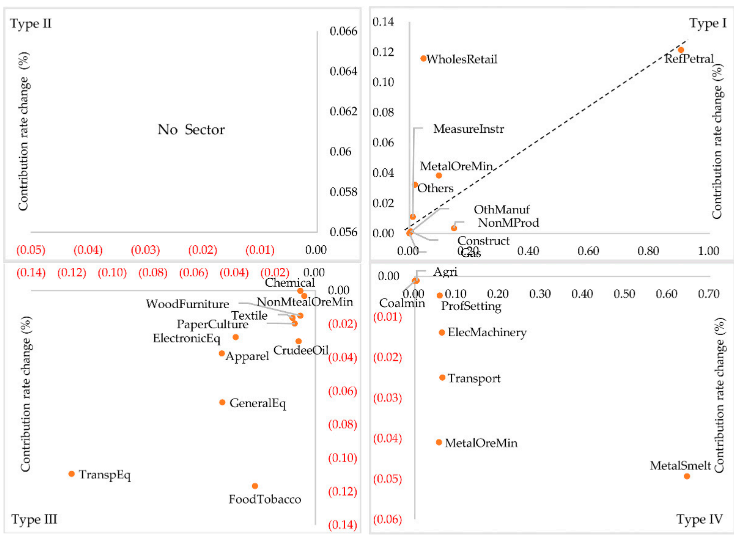


Figure 6. Changes in the contribution rate of ETV and EECE for various sectors from 2012 to 2017. Source: authors' own creation.

6.1.2. Countermeasures for Different Sectoral Types

According to the characteristics of different types, different adjustment countermeasures are proposed (Figure 7). For Type I, regulation countermeasures should be implemented. According to the different growth rate, we should apply different regulation countermeasures. For Type I-A, targeted promotion countermeasures, such as Apparel and the other five sectors, should be implemented. For Type I-B, targeted reduction countermeasures, such as the RefPetral and the other two sectors should be implemented. For Type II, the positive countermeasures which were not involved in this research should be implemented. For Type III and IV, the control countermeasures, such as CrudeOil and ElecMachinery should be implemented.

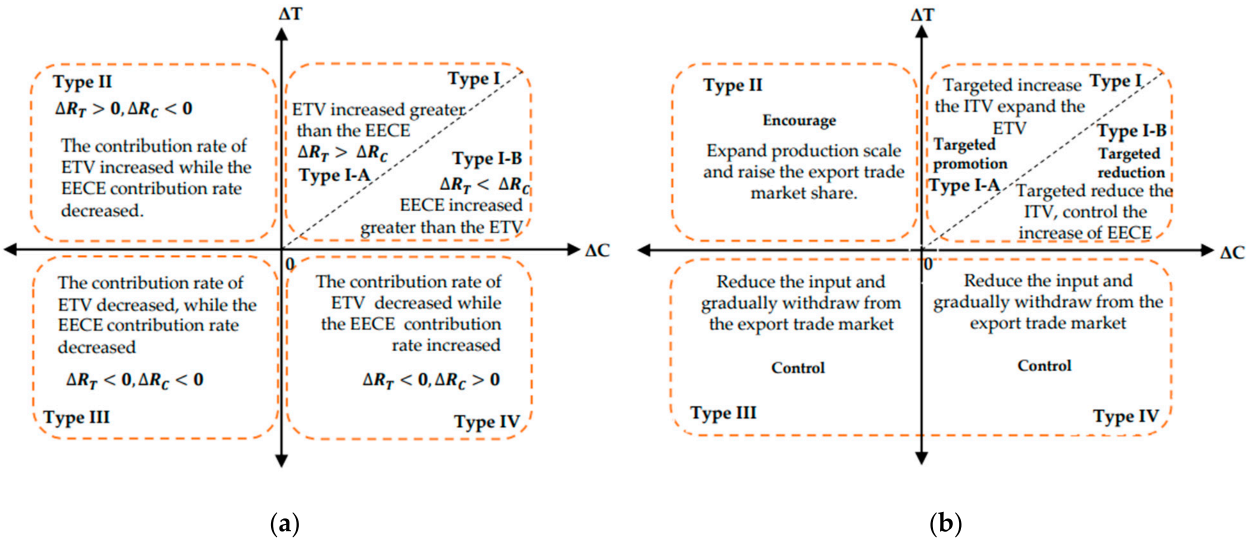


Figure 7. Characteristics (**a**) and adjustment countermeasures (**b**) of four sectoral types. Source: authors' own creation.

For the above four sectoral types, we could apply regulation (including targeted promotion and targeted reduction), encouragement and control countermeasures. Through policy tools, such as finance and taxation subsidies, we could achieve the goal of minimizing EECE, in addition to the lower-cost and DSE on other provinces. It could provide the scientific support for the realization of the 2060 "Carbon Neutrality" target.

6.2. Adjustment Effects for Typical Sectors

6.2.1. Adjustment Effects for MetalSmelt

The products of MetalSmelt mainly included steel making, iron making, steel rolling processing and ferroalloy smelting and other steel processing and manufacturing industries. In 2017, the major export countries of MetalSmelt in Liaoning Province were South Korea, Japan, Vietnam, the United States and the Philippines. Liaoning Anshan Iron and Steel Group Company limited is an important steel enterprise in China, with a wide range of overseas trade partners [54]. It has 31 overseas companies and institutions, as well as more than 500 domestic and foreign customers and partners. Its product sales covered more than 70 countries and regions. It is also the global supplier of many international well-known enterprises.

According to the ETV-EECE CR Model, MetalSmelt belonged to Type IV, the controlled type. It showed that ETV decreased while EECE increased. It should reduce input and make the sector gradually withdraw from the export trade market. According to the MRIO Model, if the ETV reduced 100 million CNY, the EECE could reduce by 21.57 $ktCO_2$. The DSE could reduce by 1.59 $ktCO_2$, with Hebei and Jilin seeing the largest reductions, which totaled 0.32 $ktCO_2$ and 0.22 $ktCO_2$, respectively (Figure 8).

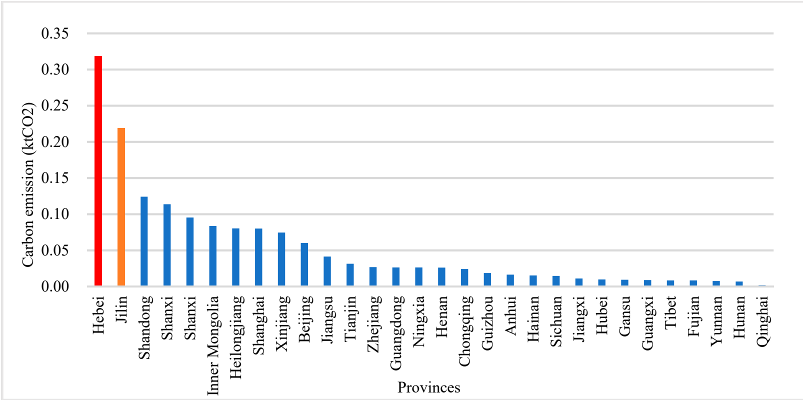


Figure 8. The DSE of MetalSmelt reduction with its ETV reduced by 100 million CNY. Source: authors' own creation.

6.2.2. Adjustment Effects for RefPetral

The products of RefPetral mainly included refined petroleum products manufacturing, crude oil processing and petroleum products manufacturing, other crude oil manufacturing and the nuclear fuel processing industries. Dalian City was one of the important petroleum product export bases for Liaoning Province and for all of China. The Dalian Petrochemical Engineering Company mainly produces 129 kinds of petrochemical products in four categories, such as gasoline, jet coal, diesel and lubricating oil base oil. Singapore, South Korea, Japan, the United States and Malaysia were the main export countries for RefPetral.

According to the ETV-EECE CR Model, the RefPetral was Type I-B, the targeted reduction type. It showed that the increase of the contribution rate of EECE was greater than that of ETV. It should reduce the ITV cooperation with the target provinces to ensure the ETV and control the increase of EECE. In order to identify the target provinces, the ITV-DSE CR Model was used for the adjustment classification of DSE. According to the coupling characteristics, the 30 provinces were divided into four types. There are 11 provinces in Type I, two provinces in Type II, 14 provinces in Type III, and three provinces in Type IV, respectively (Figure 9). The target provinces should be characterized by the decrease in ITV, while the DSE increased when they traded with Liaoning Province. As a result, the provinces of Type IV were the target provinces, which were Beijing, Sichuan, and Guangdong Province.

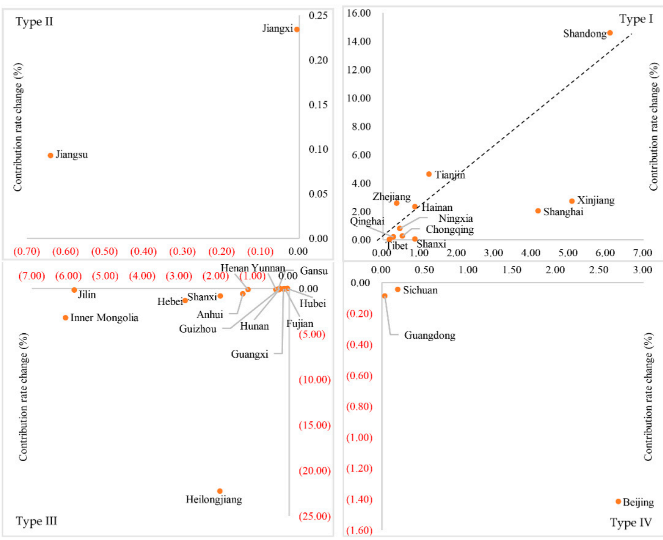


Figure 9. Changes in the contribution rate of RefPetral ITV and DSE for 30 provinces from 2012 to 2017. Source: authors' own creation.

According to the MRIO Model, if the ETV of RefPetral reduced 100 million CNY, the EECE and the DSE would be reduced by 23.35 ktCO_2 and 1.65 ktCO_2, respectively. Among them, Liaoning Province had the largest reduction of 21.70 ktCO_2, followed by Beijing with 1.29 ktCO_2, Sichuan with 0.18 ktCO_2, and Guangdong with 0.18 ktCO_2.

7. Conclusions

In this research, Liaoning Province from 2012 to 2017 was selected as the research object. Only Liaoning Province had the largest EECE intensity and the fastest growth of EECE over these six years. Based on the multi-region input-output tables of China in 2012 and 2017, we applied the MRIO Model and ArcGIS spatial analysis tools, constructed a CR Model for trade value and carbon emissions, quantitatively assessed the EECE and its DSE for Liaoning Province, depicted the spatial-temporal evolution pattern, proposed sectoral adjustment countermeasures, and evaluated the adjustment effects. The main conclusions were as follows:

First, in China, the EECE accounted for nearly 30% and was one of the important reasons that it remained high for the total carbon emissions. The EECE was concentrated in five provinces of China, which were Liaoning, Shandong, Zhejiang, Jiangsu and Guangdong. Among them, Liaoning Province has the largest EECE intensity, with 0.91 T/K CNY, which was higher than the national average of 0.66 T/K CNY in 2017. Meanwhile, the EECE grew the fastest, with an increase from 21.42 MtCO_2 in 2012 to 32.08 MtCO_2 in 2017, of which the growth rate was 49.78%. The EECE of Liaoning Province was not evenly distributed in all sectors, but mainly concentrated in MetalSmelt and RefPetral, with 9.07 MtCO_2 and 6.04 MtCO_2, respectively. The EECE not only caused huge carbon emissions for Liaoning itself, but also produced DSE for other provinces. In 2017, the DSE of MetalSmelt was 984.32 ktCO_2, with ranking first in China. The DSE of RefPetral increased from 62.87 ktCO_2 in 2012 to 431.06 ktCO_2 in 2017, which grew the fastest.

Second, the spatial pattern of DSE was not balanced. From 2012 to 2017, the DSE of Liaoning Province showed a spatial agglomeration effect. Jilin has become the largest province of DSE, which increased from 265.40 ktCO_2 in 2012 to 749.13 ktCO_2 in 2017, with a growth rate of 182.27%. The DSE spatial pattern of different sectors were also different. There was obvious spatial heterogeneity of agglomeration and diffusion. The MetalSmelt showed a spatial agglomeration effect in Hebei, Jilin, and Shandong Province. However, the RefPetral showed an obvious spatial diffusion effect. The number of provinces with DSE greater than 10 ktCO_2 increased from only two in 2012 to eight in 2017.

Thirdly, according to the ETV-EECE CR Model, we divided the sectors into four types, and according to the type characteristics, adjustment countermeasures were proposed. Among them, 27 sectors in Liaoning Province (except ElectpowerProd and Water) were divided into four types. Type I-A, which has six sectors, should adopt targeted promotion countermeasures. Type I-B, which has three sectors, should adopt targeted reduction countermeasures. Type II, which has zeros sector, should adopt encouraged countermeasures. Type III and Type IV, which have 11 sectors and 7 sectors, respectively, should adopt control countermeasures.

Fourth, based on the MRIO Model, the adjustment countermeasures effects were assessed. We quantitatively evaluated the adjustment countermeasures effects of MetalSmelt and RefPetral for Liaoning Province. MetalSmelt was Type IV, the controlled type. Its ETV reduced by 100 million CNY, and the EECE could be reduced by 21.57 ktCO_2, while the DSE could reduce 1.59 ktCO_2. Hebei and Jilin Province saw the largest DSE reductions, reduced by 0.32 ktCO_2 and 0.22 ktCO_2, respectively. The RefPetral was Type I-B, the targeted reduction type. Its ETV reduced by 100 million CNY, and the EECE could be reduced by 23.35 ktCO_2, while the DSE could be reduced by 1.65 ktCO_2. Liaoning Province saw the largest reduction with 21.70 ktCO_2, followed by Beijing with 1.29 ktCO_2, Sichuan with 0.18 ktCO_2, and Guangdong with 0.18 ktCO_2.

EECE not only affects the exporting province, but also leads the DSE to other provinces in a country. When formulating carbon reduction policies, we should not only consider the EECE, but also comprehensively consider the DSE to other regions. The research conclusions could provide a decision-making basis for the case area to formulate lower-cost and better-effective carbon reduction countermeasures. It also could provide reference and scientific support to achieve "Carbon Neutrality" and sustainable development in similar regions of the world with the rapid growth of EECE.

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Nomenclature

Abbreviation	**Full Name**
EECE	Export embodied carbon emissions
DSE	Domestic spillover effects
MRIO Model	Multi-region Input-output Model
CR Model	Coupling Relationship Model
ETV	Export trade value
ITV	Interprovincial trade value
ETV-EECE CR Model	Coupling Relationship Model of export trade value and the export embodied carbon emissions
ITV-DSE CR Model	Coupling Relationship Model of interprovincial trade value and the domestic spillover effects of
IPCC	Intergovernmental Panel on Climate Change

Appendix A

Table A1. The 29 sectors.

Sector Code	Full Name	Abbreviation
s1	Agriculture	Agri
s2	Coal mining and washing	Coalmin
s3	Crude petroleum and natural gas products	CrudeOil
s4	Metal ore mining	MtealOreMin
s5	Non-ferrous mineral mining	NonMtealOreMin
s6	Manufacture of food products and tobacco processing	FoodTobacco
s7	Textile goods	Textile
s8	Apparel, leather, and related products	Apparel
s9	Wood processing and furniture manufacturing	WoodFurniture
s10	Papermaking, printing and paper product manufacturing	PaperCulture
s11	Petroleum processing, coking, and nuclear fuel processing	RefPetral
s12	Chemicals and medicinal products	Chemical
s13	Nonmetal mineral products	NonMProd

Table A1. *Cont.*

Sector Code	Full Name	Abbreviation
s14	Metal smelting and rolling processing	MetalSmelt
s15	Metal products	MetalProd
s16	General Equipment	GeneralEq
s17	Professional setting	ProfSetting
s18	Transportation equipment manufacturing	TranspEq
s19	Electric equipment and machinery manufacturing	ElecMachinery
s20	Electronic and telecommunications equipment manufacturing	ElectronicEq
s21	Instrumentation and cultural, office machinery manufacturing	MeasureInstr
s22	Other manufacturing industry	OthManuf
s23	Electricity and heat production and supply	ElectpowerProd
s24	Gas production and supply	Gas
s25	Water production and supply	Water
s26	Construction	Construct
s27	Transportation, storage, and post and telecommunication services	Transport
s28	Wholesale and retail trade, catering services	WholesRetail
s29	Other services	Others

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