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Provincial Carbon Emissions Reduction Allocation Plan in China Based on Consumption Perspective

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Abstract: China is a country with substantial differences in economic development, energy consumption mix, resources, and technologies, as well as the development path at the provincial level. Therefore, China's provinces have different potential and degrees of difficulty to carry out carbon emission reduction (CER) requirements. In addition, interprovincial trade, with a large amount of embodied carbon emissions, has become the fastest growing driver of China's total carbon emissions. A reasonable CER allocation plan is, therefore, crucial for realizing the commitment that China announced in the Paris Agreement. How to determine a fair way to allocate provincial CER duties has become a significant challenge for both policy-makers and researchers. In this paper, ecological network analysis (ENA), combined with a multi-regional input-output model (MRIO), is adopted to build an ecological network of embodied emissions across 30 provinces. Then, by using flow analysis and utility analysis based on the ENA model, the specific relationships among different provinces were determined, and the amount of responsibility that a certain province should take quantified, with respect to the embodied carbon emission (ECE) flows from interprovincial trade. As a result, we suggest a new CER allocation plan, based on the detailed data of interprovincial relationships and ECE flows.

Keywords: carbon emission reduction allocation; embodied carbon emission flow; input-output analysis; ecological network analysis

1. Introduction

One of the most essential discussions in 21st century is how the global community can work together to deal with the threat of climate change by keeping the global temperature rise within a reasonable range in this century [1]. Many efforts have been made to reach a consensus whereby every country and individual on the planet takes some level of responsibility for reducing carbon emissions. After many years' negotiation and countless compromises, the Paris Agreement was finally agreed upon, with ambitious goals that limit the global temperature to below two degrees Celsius above pre-industrial levels [2].

China, as the world's largest carbon emitter, accounting for nearly 29% of global emissions [3], has set a target of reaching its emissions peak before 2030, reducing its greenhouse emissions intensity of its Gross Domestic Product (GDP) by 60–65% over 2005 level by 2030 with respect to the Paris Agreement [4]. However, the Paris Agreement is mainly focused on the distribution of differentiated responsibilities at the national level. China is a country with substantial regional differences with respect to the economic development level, energy consumption structure, resources, and technologies, as well as the development path at the provincial level. Therefore, China's different provinces have different potential and degrees of difficulty in carrying out CER [5] and we need to determine a CER plan at the sub-national level. Considering that China is experiencing significant urbanization and industrialization, it is anticipated that carbon emissions and energy consumption will keep increasing in the near future [6]. CER will, to some extent, influence the economic performance and social transition [7,8]. An unreasonable CER allocation plan will not only slow down China's economic growth as a whole, but will also become a crucial impediment for realizing the commitment that China announced in the Paris Agreement. According to Chen et al. (2016), unsuitable CER allocation in China imposes increasing pressure on both Chinese central and local governments and could slow down the GDP growth in some provinces [9]. How to formulate a fair CER allocation plan at the provincial level, based on the different provinces' characteristics, is a significant challenge for both policy-makers and researchers.

Carbon emissions reduction allocation, essentially, is the distribution of the responsibility of emissions to specific agents (producers or consumers) based on a certain criterion (such as strict equality or sufficiency) [10]. There are three main principles for CER allocation that are used to determine how the CER responsibility can be attributed to different agents [11]: Firstly, the production-based principle (PBP), as a widely accepted principle, allocates the CER duty to the producers, who use fossil fuels and directly produce carbon emissions during their economic activities [12]. When PBPs are applied to allocate CER at the regional level, there were some unfair problems [13]. Specifically, for most China's emissions provinces, they produce a large amount of goods for meeting other provinces' demands. Considering the large volumes of interprovincial goods trade, a very large amount of carbon emissions transfers from one province to another occurs [14]. PBP lacks an understanding of provincial carbon emission transfers when it is used as the principle for China' provincial CER allocation. Secondly, the community-based principle (CBP) originally allocated agents' CER based on their membership with a certain community, in which previous members caused a large amount of emissions. This principle requires detailed data of every single community in different circumstances, which contributes to extremely difficult-to-apply CBP at the national or provincial levels. Thirdly, according to the consumer-based principle, consumers (more specifically, the final users) should undertake the CER responsibility of productions that they have consumed. Considering the fairness principle, which is that those who consume should undertake the responsibility [11], consumption-based accounting can perform better in providing the actual features and responsibility for carbon emissions that a certain province should take [15]. The concept of embodied carbon emission (ECE), based on the consumption-based perspective, is introduced in this paper to measure the detailed statistic of carbon emission consumption of a certain province, and establishes reasonable CER policies.

According to the 13th Five-Year Plan of the Chinese central government, the national allocation plan is shown in Figure 1 in which all the provinces are divided into five categories. This allocation plan is mainly based on a production-based perspective and does not take the large amount of interprovincial carbon emission transfers into consideration [4,9,11,15]. Therefore, in this paper, we introduced an MRIO model to calculate the ECE flows among China's 30 provinces based on a consumer-based perspective. Then, using the ENA model to build an embodied carbon emission network enables us to comprehensively assess the interprovincial ECE transfers. We identify the relationships among the regions in terms of their ECE exchanges, and determine the responsibility that each province should take.

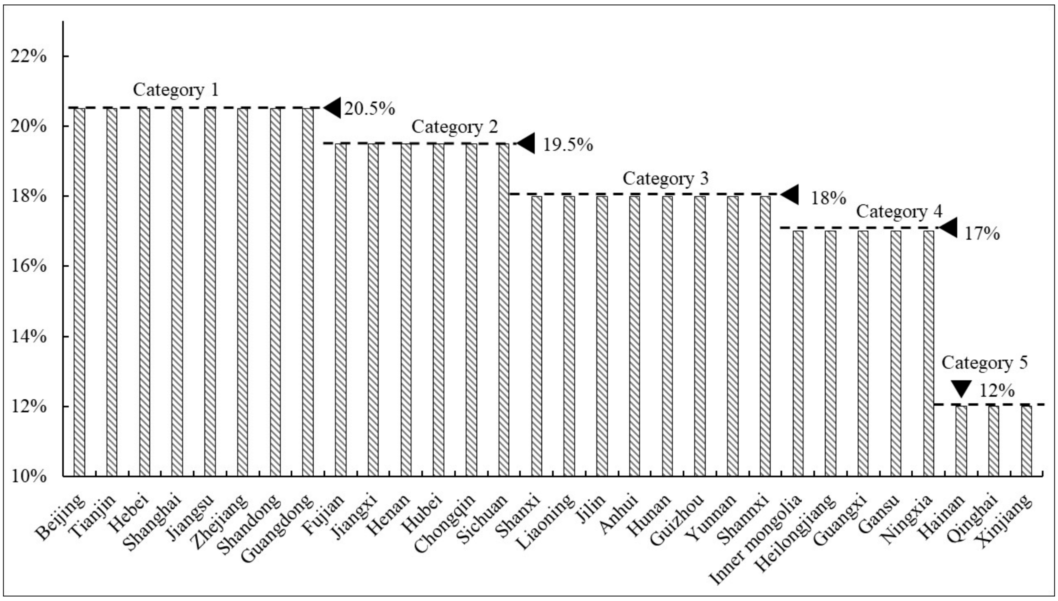


Figure 1. Carbon emission reduction allocation plan in the 13th Five-Year Plan.

2. Literature Review

In order to realize China's carbon emission reduction commitment, every province in China has to undertake a certain CER task. In light of the characters and interests of different provinces in China, it is extremely difficult for policy-makers to make a relatively fair distribution plan. A wide range of researchers have studied this topic.

2.1. Previous Carbon Emission Reduction Task Allocation Research

There are three basic types of studies about the allocation of CER tasks. Firstly, some researchers were looking for criteria for a CER plan between countries. Some researchers hold the principle that all countries and individuals should have an equal right to produce carbon emissions. As a result, one country's historical carbon emission [16] and population [17] were regarded as allocation criteria to allocate the CER tasks. Walther et al. (2002) took the ability of paying the cost as the criteria for CER tasks [18]. Miketa et al. (2006) used the emission intensity and energy consumption structure to show the potential of CER for a specific country and took it as the allocation criteria to distribute the CER tasks [19].

Secondly, several attempts have been made to clarify the key factors that affect the fairness of CER task allocation. Geng et al. (2017) took five factors, which were CER potential, CER cost, strategic positioning, economic level, low carbon level, and social stability, into consideration to establish an evaluation framework for CER responsibility. This method provides an efficient way to allocate the CER tasks to different cities [20]. Sun et al. (2016) studied the effect of economic spillover on regional CER task transfer [21]. The results show that the reduction in task transfer between certain provinces is relatively efficient for the overall reduction target. However, these studies did not provide the specific transfer requirement between all the provinces in China.

Thirdly, some authors studied the conditions and methods for China to achieve its CER target. Yang et al. (2016) analyzed whether the Chinese government could meet its goal in 2020 by implementing different reduction strategies [22]. The results show that developing technologies is the most effect way to achieve carbon emission reduction and economic growth goals in 2020. Zhao et al. (2016) applied an integrated method that allocated CER targets to China's 41 different industries [23]. According to the results, electric power and heat power should take the largest responsibility to reduce carbon emission intensity. Yang et al. (2017) introduced a Nash game to solve emissions reduction decisions between manufactures and indicated that a cooperative strategy leads to higher CER rates. This method is quite useful for a small network where every strategy is available and accessible for each player [24].

Overall, these previous studies tried to solve the problem of allocation of CER tasks at provincial or industrial levels only from the perspective of mathematical improvement and model selection. However, few studies considered the large amount of trade, which has significant embodied carbon emissions, between different provinces.

2.2. Carbon Emission Allocation Plan Based on a Consumption-Based Perspective

Despite the various methods and perspectives that previous studies adopted, most of them used production-based accounting of emissions, which focuses on the direct carbon emissions. In order to fully understand the consumption of goods and services, we need to take both direct and indirect emissions into consideration [4].

According to a definition [25] provided by Munksgaard et al. (2001), embodied carbon emissions refers to carbon emissions that occur across the whole life cycle, reflecting both the direct and indirect emissions in the system. There are two main methodological foundations for evaluating embodied emissions: life-cycle assessment models and input-output models. Life-cycle assessment, as a bottom-up method, requires a large amount of data, which is impossible for researchers to calculate for every province. As a result, this method is mainly used to calculate embodied emissions of a certain small region or industry with accessible data [26]. Multi-Regional Input-Output analysis, as a top-down method, is generally used by researchers addressing the global and regional levels. I-O has been used to calculate ECE in China's global trade [27–29] and regional trade [30,31], and also for quantifying the driving factors of ECE in China's global trade [4] and interprovincial trade [32,33]. Quite a few studies give a clear description of carbon emissions in each province and their underlying drivers, while few of them have studied the effects of interprovincial ECE transfers [34]. Since a gradually increasing volume of interprovincial trade has been occurring, relatively developed provinces tend to import a large amount of ECE from relatively underdeveloped provinces in China [22], which forms an ECE flow system. To make a comprehensive allocation plan, it is necessary to take the interprovincial trade with ECE flows into consideration.

Since the effect of ECE flows between different provinces is normally different, the relationships between them could cause different results for China [35]. To fully understand these relationships, in this study we introduced Ecological Network Analysis (ENA) to build China's 30 provinces' ECE system. The ENA model, which evolved from the MRIO analysis model, was first introduced by Hannon (1973) and simulates the relationships among an ecological system's components, which allow researchers to build an ecological network based on certain material flows [36]. Fath (1998) further improved the initial method by adding flows into the system and simulating relationships [37], which was named "network environment analysis". A wide range of researchers have used this method to analyze socioeconomic systems [38], such as energy systems [39,40], carbon flows [7], urban metabolic systems [41], embodied particulate matter 2.5 [42], and the energy metabolism of Beijing's socioeconomic sectors [43]. The ENA model contains utility analysis, which provides a method to examine qualitative relationships among the members in a system. Compared with natural ecosystems, there are four categories of relationships in socioeconomic systems, which are: competition, control, mutualism, and exploitation [37]. The benefits of this analogy are combining the relationships in a socioeconomic system with the concept of synergism in natural ecology [44].

In summary, previous studies have made some achievements in describing ECE flows among China's provinces from a consumption-based perspective and creating an approach to analyze relationships of interprovincial ECE flows. However, few of them have tried to allocate China's CER tasks by taking every province integrated as a whole system. When allocating provincial CER tasks, most of the previous studies tried to solve this problem by choosing a production-based approach [23], or focusing on mathematics improvement [45] and model selection [46].

3. Methodology and Data

3.1. Methodology

There are two types of model that can analyze the embodied carbon emissions from a consumer-based perspective: the single input-output model, SIO, and multi-regional input-output model, MRIO [11]. SIO is mainly focused on the calculation of ECE, while MRIO tends to focus on the ECE flows between different regions [21,35,40]. Therefore, in this paper, we applied the MRIO model to analyze the ECE flows among China's provinces. At the same time, the Ecological Network Analysis (ENA) model is a mature model that can be used to build an ecological network based on a certain material flow and analyze the relationships among this socioeconomic system [7,38,40–44]. Many researchers have applied MRIO and ENA models to analyze ECE flows and ecological relationships among China's different provinces, respectively. However, few of them tried to apply MRIO and ENA to analyze carbon emission allocation issues. Therefore, in this paper, we combined the MRIO model and ENA model to build China's ECE network to analyze China's provincial CER allocation plan through calculating the amount of ECE flows and analyzing the ecological relationships among China's provinces.

3.1.1. Multi-Regional Input-Output Model

MRIO analysis has been widely used to quantify embodied carbon emissions. Figure 2 shows the basic framework of input-output tables, which, in this case, contains 30 economic provinces and 30 × 30 economic sectors. In the MRIO framework, different provinces are connected through interprovincial trade [29,47].

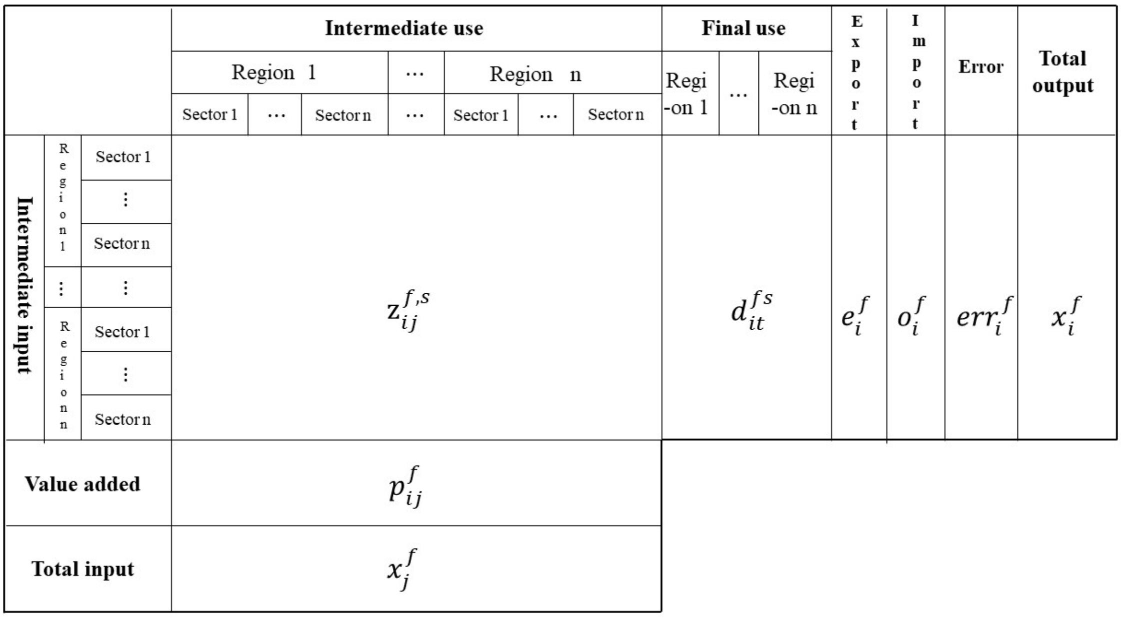


Figure 2. Basic framework of multi-regional input-output tables.

$$x_i^f = \sum_{s=1}^{30}\sum_{j=1}^{30} Z_{i,j}^{f,s} + \sum_{s=1}^{30}\sum_{t=1}^{5} d_{i,t}^{f,s} + e_i^f + o_i^f = \sum_{s=1}^{30}\sum_{j=1}^{30} Z_{i,j}^{f,s} + \mathrm{p}_i^f \qquad (1)$$

where x_i^f is the total output of sector i in province f; $Z_{i,j}^{f,s}$ is the intermediate use of sector j in province s supplied by sector i in province f; $d_{i,t}^{f,s}$ is the final use in province s supplied by sector i in province f, including rural (t = 1) and urban household consumption (t = 2), government consumption (t = 3), fixed capital formation (t = 4), and stock increase (t = 5); e_i^f is the export of sector i in province f; o_i^f is the import of sector *i* in province *f*. err_i^f are the errors to equate the equation; x_{j}^f is the total output of sector *j* in province *f*; p_i^f is the output of carbon emission contained in the final demand category in province *f*.

Total carbon emission balance of sector *i* in province *f* can be formulated as:

$$\begin{aligned} & c_i^f \times \theta_i + \sum_{s=1}^{30} \sum_{j=1}^{30} \varepsilon_j^s \times Z_{\mathrm{j},i}^{f,s} = \sum_{s=1}^{30} \sum_{j=1}^{30} \varepsilon_{\mathrm{i}}^f \times Z_{i,j}^{f,s} + \sum_{s=1}^{30} \sum_{t=1}^{5} \varepsilon_{\mathrm{i}}^f \times d_{i,t}^{f,s} + \varepsilon_i^f \times e_i^f + \varepsilon_i^f \times o_i^f \\ & = \sum_{s=1}^{30} \sum_{j=1}^{30} \varepsilon_{\mathrm{i}}^f \times Z_{i,j}^{f,s} + \varepsilon_{\mathrm{i}}^{\mathrm{f}} \times p_i^f \end{aligned} \tag{2}$$

where c_i^f is the primary energy input of sector *i* in province *f*; θ_i is the carbon emission coefficient; ε_j^s is the embodied carbon emission intensity of output from sector *j* in province *s*; other variations are the same as shown in Equation (1).

For the whole system, which contains 30 provinces and 900 sectors giving:

$$\left\{ \begin{array}{c} c_1^1 \times \theta_1 + \sum\limits_{s=1}^{30} \sum\limits_{j=1}^{30} \varepsilon_j^s \times Z_{j,1}^{1,s} = \sum\limits_{s=1}^{30} \sum\limits_{j=1}^{30} \varepsilon_1^1 \times Z_{1,j}^{1,s} + \varepsilon_1^1 \times p_1^1 \\ c_2^1 \times \theta_2 + \sum\limits_{s=1}^{30} \sum\limits_{j=1}^{30} \varepsilon_j^s \times Z_{j,2}^{1,s} = \sum\limits_{s=1}^{30} \sum\limits_{j=1}^{30} \varepsilon_2^1 \times Z_{2,j}^{1,s} + \varepsilon_2^1 \times p_2^1 \\ \vdots \\ c_{30}^{30} \times \theta_{30} + \sum\limits_{s=1}^{30} \sum\limits_{j=1}^{30} \varepsilon_j^s \times Z_{j,30}^{30,s} = \sum\limits_{s=1}^{30} \sum\limits_{j=1}^{30} \varepsilon_{30}^{30} \times Z_{30,j}^{30,s} + \varepsilon_{30}^{30} \times p_{30}^{30} \end{array} \right. \tag{3}$$

For simplicity, we introduce the following description:

$$\begin{aligned} & E^* = \begin{bmatrix} \begin{pmatrix} \varepsilon_1^1 \\ \vdots \\ \varepsilon_{30}^1 \end{pmatrix} \\ \vdots \\ \begin{pmatrix} \varepsilon_1^{30} \\ \vdots \\ \varepsilon_{30}^{30} \end{pmatrix} \end{bmatrix}, C^* = \begin{bmatrix} \begin{pmatrix} c_1^1 \\ \vdots \\ c_{30}^1 \end{pmatrix} \\ \vdots \\ \begin{pmatrix} c_1^{30} \\ \vdots \\ c_{30}^{30} \end{pmatrix} \end{bmatrix}, Z^* = \begin{bmatrix} \begin{pmatrix} z_{1,1}^{1,1} & \cdots & z_{1,30}^{1,1} \\ \vdots & \ddots & \vdots \\ z_{30,1}^{1,1} & \cdots & z_{30,30}^{1,1} \end{pmatrix} & \cdots & \begin{pmatrix} z_{1,1}^{1,30} & \cdots & z_{1,30}^{1,30} \\ \vdots & \ddots & \vdots \\ z_{30,1}^{1,30} & \cdots & z_{30,30}^{1,30} \end{pmatrix} \\ \vdots & \ddots & \vdots \\ \begin{pmatrix} z_{1,1}^{30,1} & \cdots & z_{1,30}^{30,1} \\ \vdots & \ddots & \vdots \\ z_{30,1}^{30,1} & \cdots & z_{30,30}^{30,1} \end{pmatrix} & \cdots & \begin{pmatrix} z_{1,1}^{30,30} & \cdots & z_{1,30}^{30,30} \\ \vdots & \ddots & \vdots \\ z_{30,1}^{30,30} & \cdots & z_{30,30}^{30,30} \end{pmatrix} \end{bmatrix} \\ & X = \begin{bmatrix} \begin{pmatrix} \sum\limits_{s=1}^{30} \sum\limits_{j=1}^{30} z_{1,j}^{1,s} + p_1^1 \\ \vdots \\ \sum\limits_{s=1}^{30} \sum\limits_{j=1}^{30} z_{30,j}^{1,s} + p_{30}^1 \end{pmatrix} \\ \vdots \\ \begin{pmatrix} \sum\limits_{s=1}^{30} \sum\limits_{j=1}^{30} z_{1,j}^{30,s} + p_1^{30} \\ \vdots \\ \sum\limits_{s=1}^{30} \sum\limits_{j=1}^{30} z_{30,j}^{30,s} + p_{30}^{30} \end{pmatrix} \end{bmatrix} \end{aligned} \tag{4}$$

Using familiar matrix notation and dropping the subscripts, the above equations can be expressed in a compressed form as:

$$C^* + Z^* \times E^* = X \times E^* \text{ or } E = C(X - Z)^{-1} \tag{5}$$

where C^*, Z^*, and E^* are the transposes of *C*, *Z*, and *E*.

The embodied carbon emission ($C_{Embodied}$) of a certain final demand category $P^* = [\mathrm{p}_1, \mathrm{p}_2, \cdots, \mathrm{p}_{900}]$ (p_i is the output of sector i included in the final demand category, and P^* is the transposes of P) can be described as:

$$C_{Embodied} = E \times P \tag{6}$$

Thereafter, embodied carbon flow in the final demand can be calculated on the basis of the data of monetary transactions of services among the interprovincial transfers. The embodied carbon (EC) introduced by total final demand, or a certain category of it, such as rural or urban consumption, can be directly calculated by multiplying the embodied carbon emission intensity matrix E by the corresponding final-use vector. Therefore, all of China's 30 provinces' final demand can be calculated through this method [40].

For the calculation of embodied carbon emissions in interprovincial trade, we adopt the method introduced by Liu (2014) [4], in which the interprovincial trade, including intermediate goods and services, is regarded as a set of endogenous variables. The embodied carbon in interprovincial exports (ECIE) of a certain province can be expressed as:

$$\begin{gathered}
ECIE^1 = C^1 \times E^1 \times (X - Z)_1{}^{-1} \times \left(\sum_{s=2}^{30}\sum_{t=1}^{5} d_t^s + e^s + o^s\right) = \sum_{s=2}^{30} ECEF^{1s}, (\mathrm{s} \neq 1) \\
\mathrm{C}^1 = [(\mathrm{c}_1^1, \cdots, \mathrm{c}_{30}^1), (0, \cdots, 0), \cdots, (0, \cdots, 0)] \\
d_t^{2*} = [(\mathrm{d}_{1,t}^{1,2}, \cdots, \mathrm{d}_{30,t}^{1,2}), (\mathrm{d}_{1,t}^{2,2}, \cdots, \mathrm{d}_{30,t}^{2,2}), \cdots, (\mathrm{d}_{1,t}^{30,2}, \cdots, \mathrm{d}_{30,t}^{30,2})], (\mathrm{s} = 2) \\
e^{2*} = [(0, \cdots, 0), (\mathrm{e}_1^2, \cdots, \mathrm{e}_{30}^2), (0, \cdots, 0), \cdots, (0, \cdots, 0)], (\mathrm{s} = 2) \\
o^{2*} = [(0, \cdots, 0), (o_1^2, \cdots, o_{30}^2), (0, \cdots, 0), \cdots, (0, \cdots, 0)], (\mathrm{s} = 2)
\end{gathered} \tag{7}$$

where $ECIE^1$ is the total embodied carbon in interprovincial exports of province 1; $(\mathrm{c}_1^1, \cdots, \mathrm{c}_{30}^1)$ is the 1×30 row vector of the primary energy input by sectors for province 1; d_t^{2*} is the transpose of the 1×30 row vector of the final demand of province 2; $(\mathrm{e}_1^2, \cdots, \mathrm{e}_{30}^2)$ is the 1×30 row vector of exports of province 2; $(o_1^2, \cdots, o_{30}^2)$ is the 1×30 row vector of imports of province 2, and $ECEF^{1s}$ is the transfer of embodied carbon flows from province 1 to province s ($s \neq 1$).

Similarly, the total import of embodied carbon from province s to province 1 is calculated by:

$$ECII^1 = \sum_{s=2}^{30} ECEF^{s1} \tag{8}$$

where $ECII^1$ is the total embodied carbon emissions in interprovincial imports.

3.1.2. Ecological Network Analysis

Ecological network analysis is based on the input-output model and was first introduced by Hannon et al. (1973) [36]. This model uses data of internal flows of resources, including energy, water, and materials, to represent the system [38].

In this paper, we described the flows among China's 30 provinces, based on the data calculated in the previous section. Then we built an ecological network of ECE to analyze the influence of embodied carbon flows. Using flow analysis, one of the ENA analysis tools, we can evaluate the indirect carbon flows (which go through intermediates, with a path length normally larger than 1). Figure 3 shows an example of direct and indirect flows. In flow analysis, it is necessary to distinguish the node receiving flows and the pathways between the nodes that the flows travel along [38].

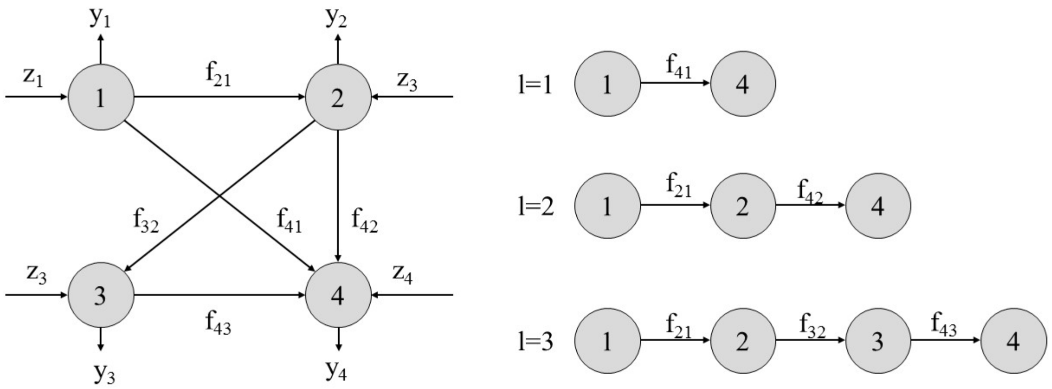


Figure 3. The carbon flows among the nodes of a simplified system.

f_{ij} is a flow from node j to node i, and l is the path length (the number of flows undertaken to reach the final node). Flow analysis here is based on the total carbon flux (T). Firstly, we calculated the ratio (g'_{ij}) of direct carbon flow f_{ij} to the total flow flux into node i (T_i). The equation is shown below [48]:

$$g'_{ij} = f_{ij}/T_i \tag{9}$$

T_i is the total flow of carbon from other nodes and from the external environment into node i:

$$T_i = \left(\sum_{j=1}^{n} f_{ij}\right) + \mathrm{z}_i \tag{10}$$

where n is the total number of nodes. From the direct flow intensity matrix $G' = (\mathrm{g}'_{ij})$, the dimensionless integral flow intensity matrix $N' = (n_{ij})$ can be calculated using a power series:

$$N' = (n'_{ij}) = (\mathrm{G}')^0 + (\mathrm{G}')^1 + (\mathrm{G}')^2 + (\mathrm{G}')^3 + \ldots = (\mathrm{I} - \mathrm{G}')^{-1} \tag{11}$$

where N' indicates the non-dimensional integral carbon flux between nodes along paths with lengths that range from 0 to infinity, n'_{ij} represent the integral dimensionless value of g'_{ij}, and I is the identity matrix [37]. The self-feedback matrix $(\mathrm{G}')^0$ reflects flows that originate and return to a node.

To determine the qualitative nature of relationships among the nodes of the network, we can use utility analysis to quantify the ecological relationship and its benefits that each node receives from its exchanges with other nodes [37]. A dimensionless direct utility intensity matrix (D) can be computed:

$$\begin{gathered} d_{ij} = (f_{ij} - f_{ji})/T_i \\ D = (d_{ij}) \\ \mathrm{U} = (u_{ij}) = (\mathrm{D})^0 + (\mathrm{D})^1 + (\mathrm{D})^2 + (\mathrm{D})^3 + \ldots = (1 - \mathrm{D})^{-1} \end{gathered} \tag{12}$$

where d_{ij} are the elements of D, which represents the utility of the net flow from node j to node i. The matrix U represents the intensity and pattern of integrated actions between any of the compartments in the network (e.g., the utility u_{ij}). The path lengths range from 0 (flows of carbon with in a node) to infinity.

The positive and negative values of the elements in U define the nature of the relationship between two nodes: exploitation (+,−); control (−,+); competition (−,−); and mutualism (+,+). The definition of these is based on an analogy with the relationships among organisms in a natural ecosystem. As all nodes are at least indirectly connected, only these four categories of relationship exist. In the exploitation and control relationship, one node takes advantage of another node; in the competition relationship, both nodes suffered; while in the mutualism relationship, both nodes benefit from each other [49–51].

3.1.3. Carbon Emission Reduction Allocation Principle

Combining the data of ECE flows, based on MRIO with the interprovincial relationships based on the ENA model, we quantified the duty that a certain province should undertake and re-allocated the CER tasks at the provincial level to ensure fairness from the whole system perspective. Specifically, according to the consumer-based principle, the consumers should undertake the CER responsibility of productions that they consumed [10,11,14,15]. In our model, the provinces, which imported a large amount of ECE, should take the CER responsibility. The amount of interprovincial ECE flows decides the amount that a certain province should undertake for its imported ECE. At the same time, according to definition of ENA analysis, two provinces with control and exploitation relationships should take responsibility for one another, as shown in Figure 4.

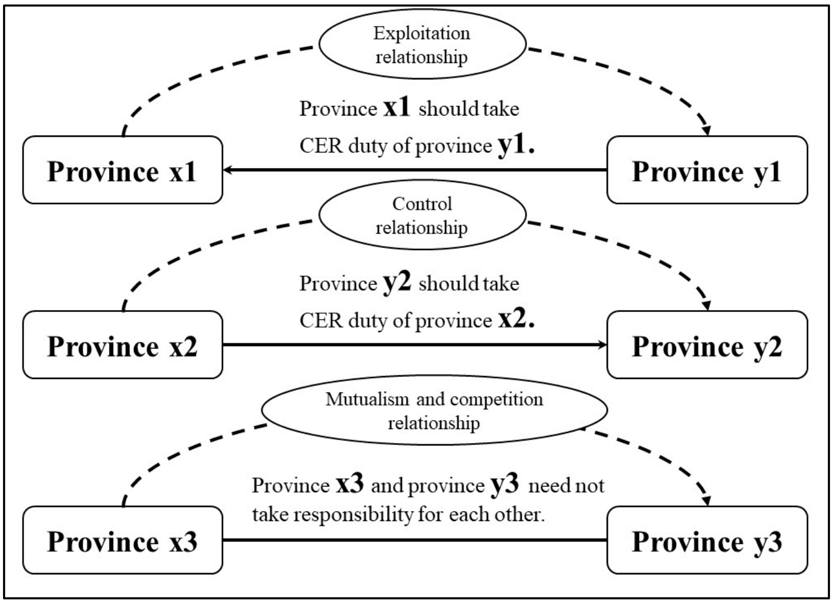


Figure 4. Carbon emission reduction allocation principle, based on ecological network analysis (a dotted line reflects the relationship between two provinces, and a solid line reflects the ECE flow between two province).

3.2. Data

For simplicity, we will refer to all the areas that make up the regions of China as "provinces", even for some provincial-scale municipalities (e.g., Beijing) and autonomous regions (e.g., Xinjiang).

In this paper, the embodied carbon emissions include the emissions from direct fossil fuel combustion and indirect emissions, such as emissions occurring in the production process and delivery of products and services when two provinces exchange these products or services. Energy consumption data, including raw coal, crude oil, natural gas, etc., at the province level were obtained from the Chinese Energy Statistical Yearbook [52], we summarized these data and show them in Supplemental Material Table S4. The values of emission factors of various energies, adopted in this paper, come from the Intergovernmental Panel on Climate Change (IPCC), which is shown in Supplemental Material Table S4. The amount of transferred embodied carbon emissions in different provinces is calculated through MRIO. The latest province-level MRIO table available for China was published in 2017 for 2012 data. The MRIO tables in 30 provinces and 30 sectors of China are published by National Bureau of Statistics and complied by the Institute of Geography Sciences and Natural Resources Research, Chinese Academy of Sciences [53,54]. The embodied carbon emission network is built based on the ENA model to show the effect of interprovincial trade.

4. Results

4.1. The Characteristics of Energy Consumption and Carbon Emissions in Different Provinces of China

China is a country with distinct features at the provincial level Figure 5 provides a brief description of the direct energy consumption, direct carbon emissions, and embodied carbon emissions for selected provinces, which are ranked from highest to lowest. A presentation of the provinces' locations in a map are shown in Appendix A Figure A1.

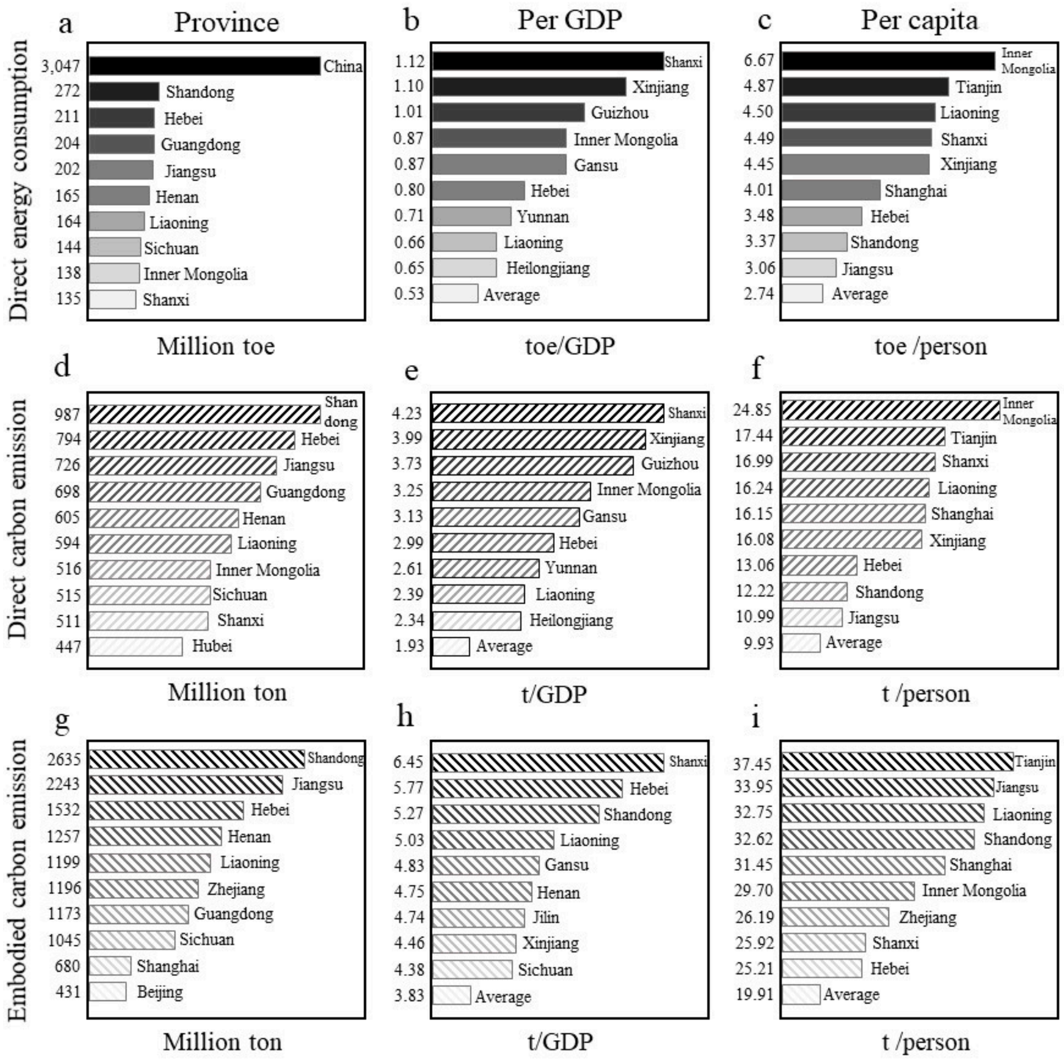


Figure 5. The comparison of direct energy consumption, direct carbon emission, and embodied carbon emission in China's different provinces, ranked from highest to lowest. (toe stands for tons of oil equivalent).

Horizontally, as shown in Figure 5a, the top nine provinces that consumed the most direct energy are mainly concentrated in the relatively developed provinces in China, such as Shandong, Jiangsu, and Guangdong, etc. This ranking is similar to the ranking of province's GDP ranking, except Hebei, which is the main coal consumption province. Energy consumption per GDP in different provinces are illustrated in Figure 5b, Xinjiang, Guizhou, and Gansu, mainly located in the northwest, have the largest index values. Those provinces are underdeveloped regions with relatively less-advanced technology and various energy-intensity industries. Resource provinces, such as Shanxi, Inner Mongolia, and Heilongjiang, also have relatively large values in terms of energy consumed per GDP. In addition, Hebei and Liaoning with large amounts of steel production and heavy industries, have a large value for this index. Figure 5c shows the direct energy consumption per person (ECPP). Resource provinces, such as Inner Mongolia, Xinjiang, and Shanxi, have a similarly large value of the ECPP index. Liaoning and Hebei, whose industry structures are focused on heavy industry, also have relatively large ECPP. It is worth mentioning that the ECPP of developed provinces, like Shanghai, Tianjin, and Jiangsu, is larger than the value of China's average.

For the direct carbon emissions (DCE) row, resource provinces (like Inner Mongolia, Shanxi, and Xinjiang) and heavy industry provinces (like Liaoning and Hebei) have relatively high DCE values, shown in Figure 5d. Considering those provinces have relatively small GDP and population, they have high DCE values per GDP (shown in Figure 5e) and DCE per capita (shown in Figure 5f). Despite a small difference in provinces' ranking between the direct energy consumption (DEC) row and the DCE row, we can find that the provinces, which consume more energy, and also produce more carbon emissions.

At the embodied carbon emission (ECE) row, the provinces with a larger amount of ECE (shown in Figure 5g) are mainly concentrated in China's relatively developed regions, like Shandong, Jiangsu, Zhejiang, Sichuan, Guangdong, etc. Although the amount of direct energy and carbon emissions of Beijing and Shanghai are not noticeable, the amount of ECE is quite large, which illustrates that Beijing and Shanghai consume a large amount of intermediate products in their production chains. Due to the outdated technology, relatively less-developed provinces, like Xinjiang, Guizhou, and Gansu also have a large value of ECE per GDP. Figure 5i shows the value of ECE per person. It is no doubt that Shanghai, Beijing, Hainan, and Tianjin have relatively large ECE per person because of the small population and large ECE. Despite the difference in technology and development stages, Zhejiang, Jiangsu, Xinjiang, Shanxi, and Inner Mongolia have large ECE and a larger value than the national average.

Vertically, for the Provinces row (shown in Figure 5a,d,g), there is a strong relationship between the provinces' DEC and DCE, which means that the provinces with large DEC normally have a large DCE, while the provinces' ECE are mainly determined by their industry structure and energy consumption mix. For the Per GDP row (as shown in Figure 5b,e,h), underdeveloped provinces (like Xinjiang, Inner Mongolia, Shanxi, Guizhou, and Gansu) and heavily-industrialized provinces (like Liaoning and Hebei) have relatively high DEC, DCE, and ECE per GDP. For the Per Capita row (as shown in Figure 5c,f,i), the provinces with larger DEC, DCE and ECE per capita than the national average value are divided into two different types of region. One includes the provinces with underdeveloped economies and small populations (like, Xinjiang, Inner Mongolia, Shanxi, and Hainan). Another category includes the provinces with developed economies and large energy consumption (like, Jiangsu, Shandong, and Zhejiang).

4.2. Emission Transfer Embodied in Provincial Trade

Figure 6 shows all exports and imports of ECE in interprovincial trade, which were calculated through the MRIO model, as shown in Equations (2)–(8). The relatively developed provinces, such as Beijing, Shanghai, Guangdong, Zhejiang, Jiangsu, etc., are the main net ECE-importing provinces, while the resource-rich provinces, such as Shanxi, Inner Mongolia, Xinjiang, Heilongjiang, etc., and the heavily industry-based provinces, such as Hebei, Liaoning, etc., are the main net ECE export provinces. Furthermore, in developed provinces, like Guangdong, the amount of imported ECE is 1.35 times larger than the amount of exported ECE. The ratio in Hainan, Beijing, and Shanghai, are 1.35, 1.46, and 1.61, respectively. The opposite situation can be found in the main net ECE exporting provinces, for example, the amount of ECE in Hebei is almost 1.78 times larger than the amount imported. All the detailed provinces' import and export ECE data can be found in Supplemental Materials Table S3. Combined with the data in Figure 6 we can see that the developed provinces with relatively small amounts of DEC and DCE, normally have a large amount of ECE and net ECE flows. Therefore, they should take more responsibility for CER tasks. Resource provinces and heavily-industrialized provinces, however, should take less responsibility for CER tasks.

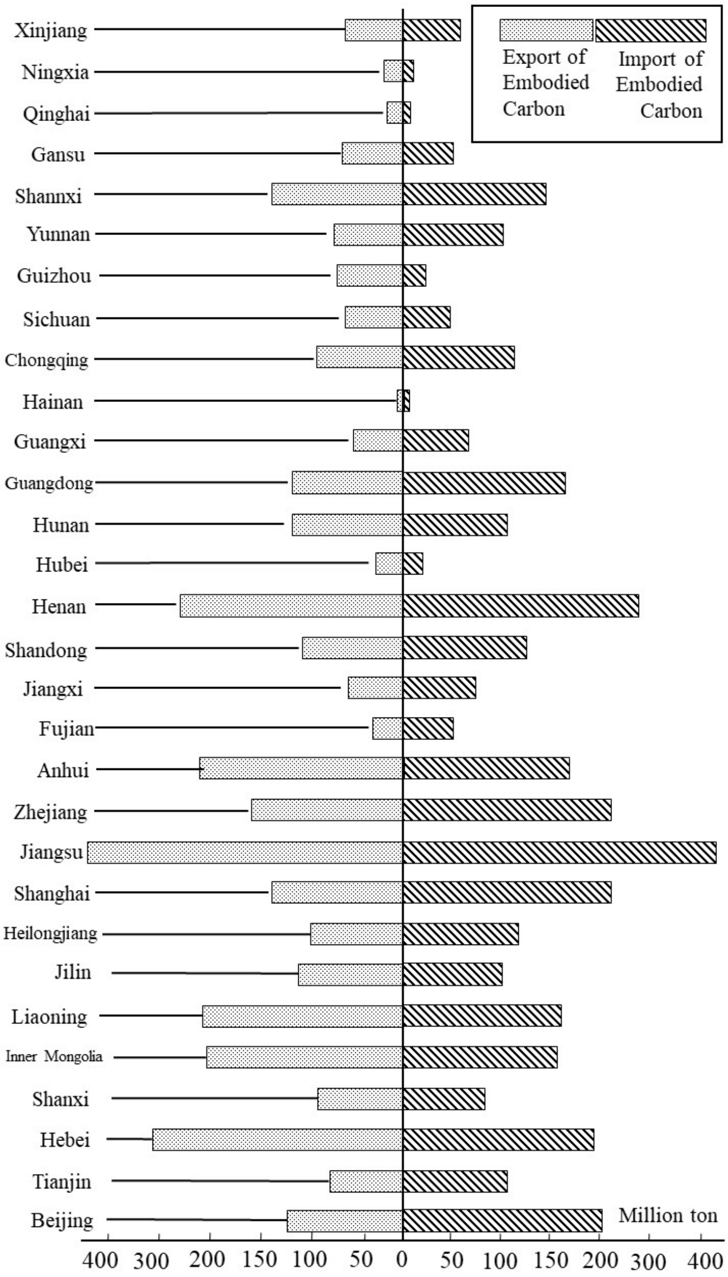


Figure 6. Embodied carbon emissions in interregional exports and imports by region in 2012 (detailed data are shown in the Supplemental Material Table S1).

From Figure 7 we can see details of interprovincial ECE flows. The length of the arc on the outer circle for each province represents the total flows including ECE imports and exports. The different colors represent the different provinces.

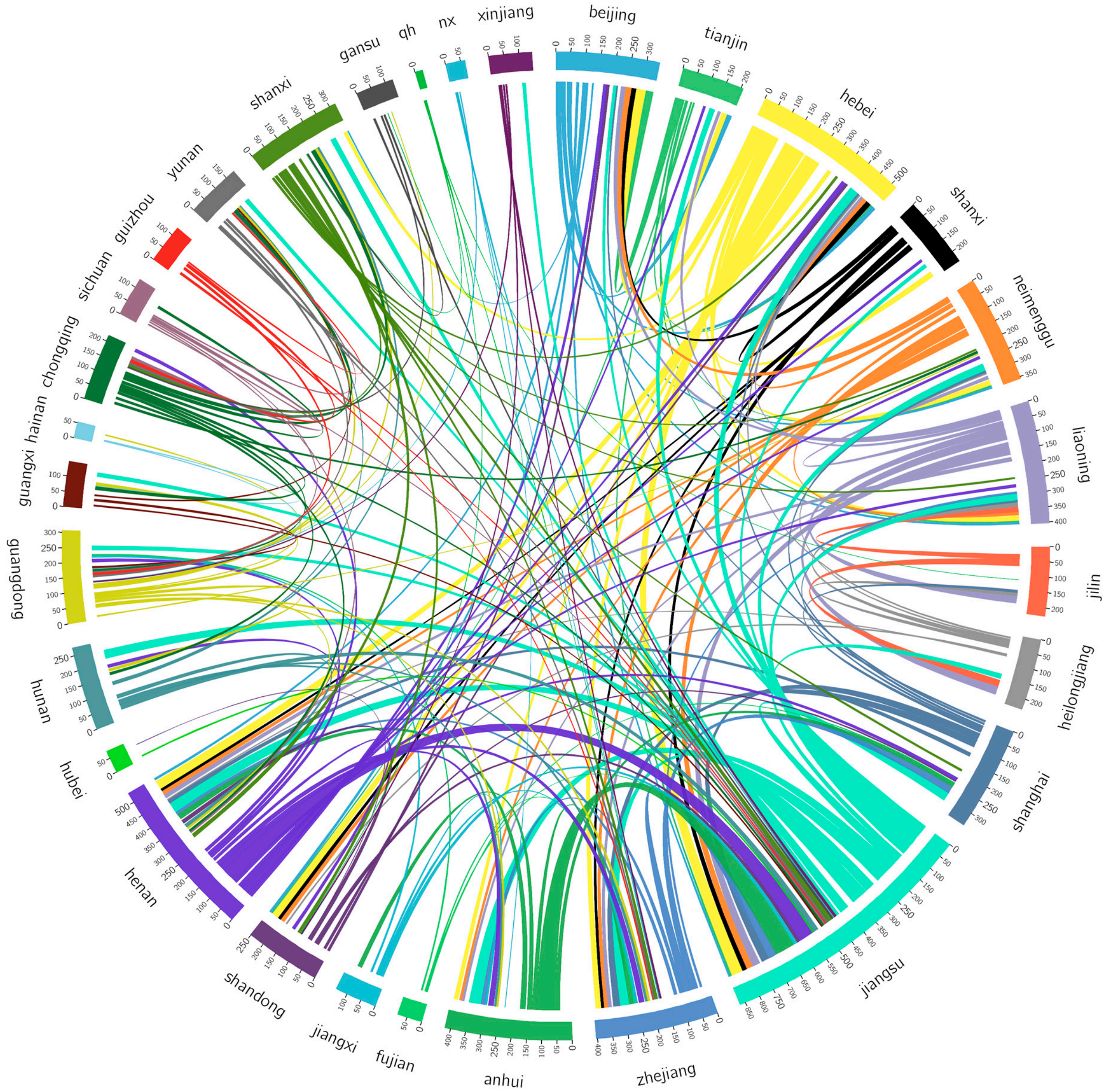


Figure 7. The interprovincial flows of embodied carbon emission in 2012, (units: million tons). The outgoing versus incoming flows are differentiated by color. Note: only the representative and determinant transfers of each province are shown in this figure. Detailed data are shown in the Supplemental Material Table S2).

Figure 7 shows the detailed interprovincial ECE flows, Different provinces have different colors, the outer circle of the arc indicates the total amount of imports and exports in a certain province, and the link color of ribbons corresponds to outflow provinces. From Figure 7, we can find that Jiangsu, with the largest amount of ECE in trade, is the major ECE exporter. Among Jiangsu's exports, Anhui imports the largest part of it, accounting for 9.7%, Henan, Zhejiang, Shanghai, and Hunan ranked from second to fifth, accounting for 8%, 7.2%, 7%, and 6.5%, respectively. From this we can see that developed provinces import a large amount of ECE from Jiangsu, which indicates those developed provinces should take a part of CER task responsibility for Jiangsu. On the import side, the opposite situation is shown in Figure 7. Beijing, as one of the most developed provinces, is the main ECE importer. Among all the trade flows between Beijing with other provinces, Hebei exports the largest percentage of total Beijing's ECE imports (16%). Shandong, Henan, Tianjin, and Liaoning follow, accounting for 10%, 10%, 8%, and 7%, respectively. Except Tianjin and Shandong, the rest of the provinces are mainly concentrated on less-developed provinces, which also indicates that we should appropriately reduce underdeveloped provinces' CER tasks. Due to the imbalanced development of China's provinces, the underdeveloped regions tend to export larger amounts of ECE to developed regions than the volume of their imports, which leads them to face challenges in both environmental protection and economic development, while developed provinces continue to take advantage from the interprovincial trade with less-developed provinces, which may strengthen the degree of China's imbalanced development.

4.3. The Relationships among China's 30 Provinces

The above sections provided a detailed quantification of ECE flows through MRIO. However, these data did not explain the effect of the interprovincial ECE flows and the impact of those flows on the whole system. Therefore, here, an ECE system is constructed, based on the ENA model, to analyze the effects of interprovincial ECE flows.

The four relationships in our analysis are based on an analogy with relationships among natural organisms. Exploitation represents that a certain element in a system receives more benefits (materials) than it transfers to another element when these two elements have trade (exchange) between them. Control reflects that one element's outputs are controlled by other elements. Competition, however, indicates that these two elements have no effect on each other. Mutualism means that two elements both benefit from each other [55].

Figure 8 shows the ecological relationships between different provinces based on the interprovincial ECE flows. The different numbers represent different provinces, for example number 1 represents Beijing (detailed information attached in Appendix A Table A1). Taking Beijing as an example, exploitation and competition are the main relationships between Beijing and the other 29 provinces, specifically, exploitation relationships account for 69% of the total relationships, competition makes up 14%, and control relationships make up 17%. There are two kinds of provinces among the exploitation relationships with Beijing, one category is resources provinces, such as Inner Mongolia, Heilongjiang, Shanxi, Gansu, Guangxi, etc. Beijing imports a large amount of energy, including coal, oil, nature gas, electricity, and other natural resources, from them. Another category is heavily-industrialized provinces, such as Hebei, Liaoning, Hunan, Chongqing, etc. Beijing mainly imports immediate products, such as steel, transistors, and other industry materials from those provinces. Considering the large amount of ECE in this trade, Beijing imported a larger amount of ECE than it exported. At the same time, from the system's perspective, Beijing had exploitation relationships with these provinces. According to the principles of ENA, Beijing should take responsibility for the CER tasks arising from these relationships. At the same time, Shandong, Guangdong, Shannxi, etc., had competition relationships with Beijing, which means that they competed with each other in a system. Therefore, there is no need for them to take any responsibility for the CER of each other. Control relationships also existed in Beijing with the rest of the provinces, such as, Jilin, Jiangxi, and Hubei. The main reason why this relationship occurred, considering these provinces are relatively underdeveloped regions, was that these regions lack capacities to self-sustain their internal consumption demand and need supply from developed provinces. In principle, these provinces should take a certain duty for Beijing's CER requirement.

In summary, there are 435 ecological relationships in China's ECE system. The control relationship is the most common relationship in this system, accounting for 47%. Exploitation relationships (essentially exploitation and control are the same relationship based on different reference) account for 36% of the total percentage. When it comes to the distribution of the CER tasks at the provincial level, we should take control and exploitation relationships into consideration to realize a fair allocation plan. Competition relationships, another important relationship, accounted for 14%. As this type of relationship will not affect the whole system's performance, it is not necessary for provinces with this relationship to take any responsibility for each other. Mutualism relationships, with the lowest number in this system, do not need to take any responsibility for each other.

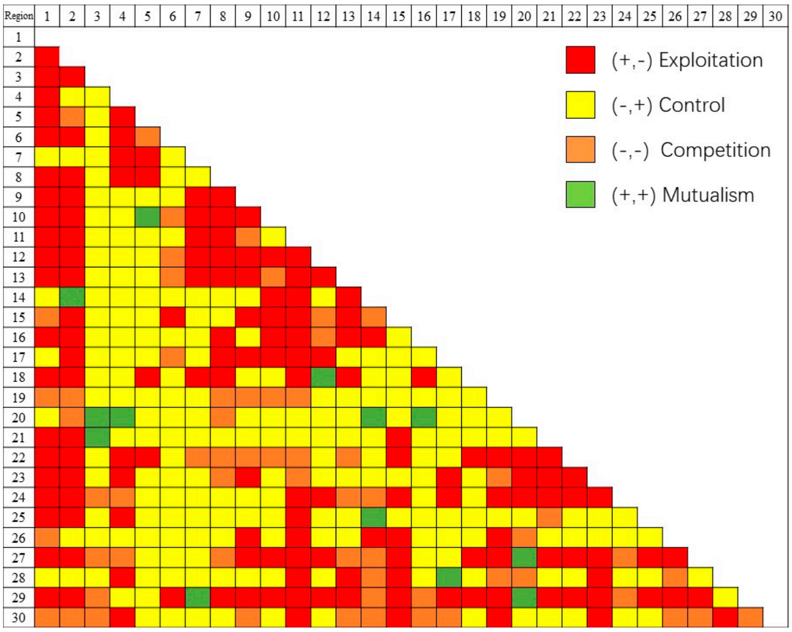


Figure 8. The ecological relationships between different regions in China.

4.4. A Carbon Emissions Reduction Allocation Plan Based on a Consumer Perspective

Combining the data of ECE flows based on MRIO with the interprovincial relationships based on the ENA model, we quantified the duty that Beijing should undertake and re-allocated the CER tasks at the provincial level to ensure fairness from the whole system perspective. According to the definition of ENA analysis, two provinces with control and exploitation relationships should take responsibility for one another.

Specifically, as shown in Figure 9, Beijing has exploitation relationships with Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Heilongjiang, Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Henan, Hunan, Hainan, Chongqing, Sichuan, Gansu, and Ningxia, which means Beijing should take responsibility for these ECE flows. The figures are 3.9%, 7.7%, 2.3%, 1.8%, 3.5%, 0.8%, 1.2%, 2.6%, 1.4%, 2.2%, 0.2%, 4.8%, 0.1%, 1.1%, 0.5%, 0.4%, 0.5%, 0.5%, and 0.4% of the total of Beijing's CER tasks, respectively. At the same time, Beijing has control relationships with Jilin, Jiangxi, Guanxi, and Qinghai, which means these provinces should undertake Beijing's CER tasks, accounting for 2.5%, 0.6%, 0.3%, 0.4%, and 0.1%, respectively. Other provinces, such as Shandong, Guangdong, Shannxi, and Xinjiang have competition relationships, which means that it is not necessary to undertake any CER tasks from each other. According to these principle, we obtain specific information about the proportion that Beijing should undertake for other provinces in an embodied carbon emission ecological system.

The same method can be applied to adjust the data of all the other 29 provinces, with the result shown in Figure 10. Figure 10 represents the percentage of one province's CER, meaning what one province should take from another province. The detailed implication of control and exploitation relationships is similar to the situation of Beijing. Policy-makers could distribute provincial CER tasks based on this information.

According to all the data, including the interprovincial ECE flows, interprovincial relationships and the specific CER tasks that one province should undertake for others, we can obtain a CER allocation plan.

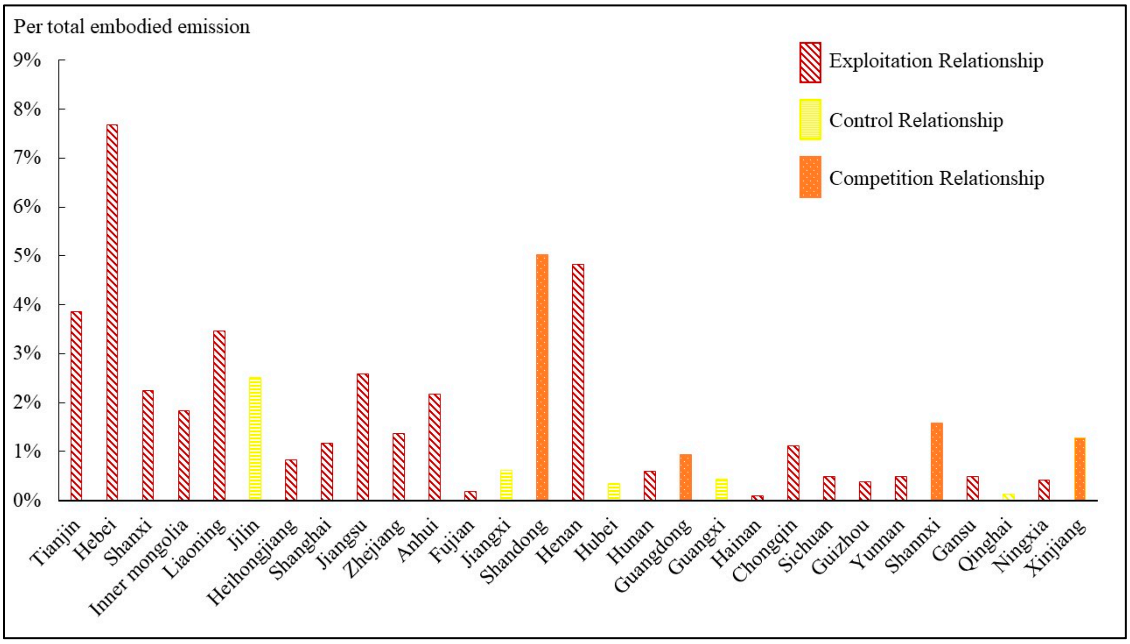
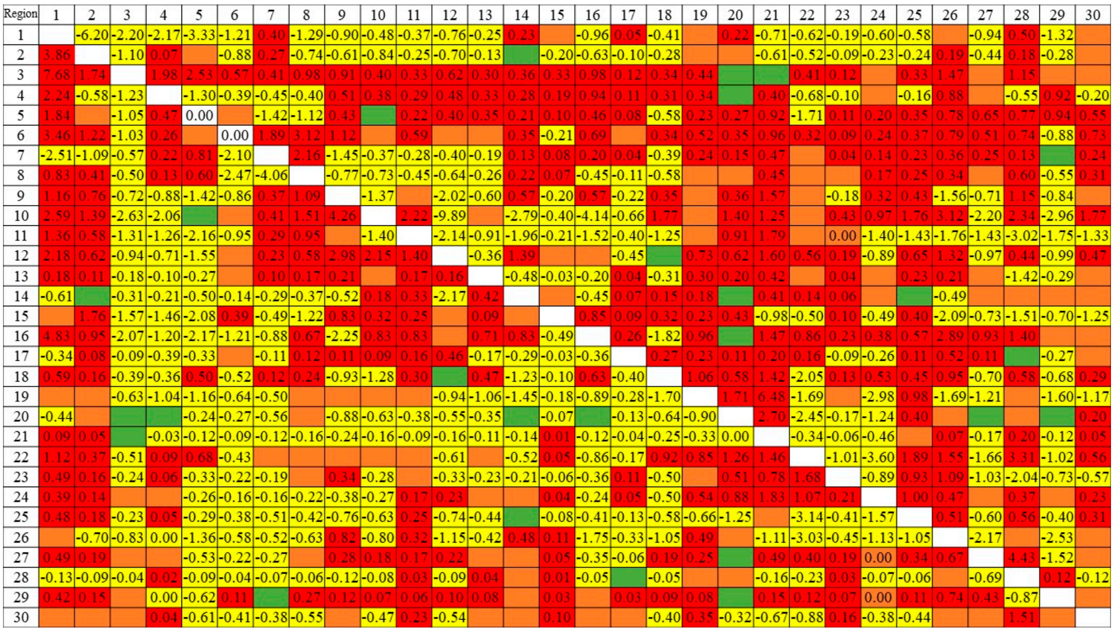


Figure 9. The proportion that Beijing should undertake for other provinces in an embodied carbon emission ecological system.



Region	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1		-6.20	-2.20	-2.17	-3.33	-1.21	0.40	-1.29	-0.90	-0.48	-0.37	-0.76	-0.25	0.23		-0.96	0.05	-0.41		0.22	-0.71	-0.62	-0.19	-0.60	-0.58		-0.94	0.50	-1.32	
2	3.86		-1.10	0.07		-0.88	0.27	-0.74	-0.61	-0.84	-0.25	-0.70	-0.13		-0.20	-0.63	-0.10	-0.28			-0.61	-0.52	-0.09	-0.23	-0.24	0.19	-0.44	0.18	-0.28	
3	7.68	1.74		1.98	2.53	0.57	0.41	0.98	0.91	0.40	0.33	0.62	0.30	0.36	0.33	0.98	0.12	0.34	0.44			0.41	0.12		0.33	1.47		1.15		
4	2.24	-0.58	-1.23		-1.30	-0.39	-0.45	-0.40	0.51	0.38	0.29	0.48	0.33	0.28	0.19	0.94	0.11	0.31	0.34		0.40	-0.68	-0.10		-0.16	0.88		-0.55	0.92	-0.20
5	1.84		-1.05	0.47	0.00		-1.42	-1.12	0.43		0.22	0.40	0.35	0.21	0.10	0.46	0.08	-0.58	0.23	0.27	0.92	-1.71	0.11	0.20	0.35	0.78	0.65	0.77	0.94	0.55
6	3.46	1.22	-1.03	0.26		0.00	1.89	3.12	1.12		0.59			0.35	-0.21	0.69		0.34	0.52	0.35	0.96	0.32	0.09	0.24	0.37	0.79	0.51	0.74	-0.88	0.73
7	-2.51	-1.09	-0.57	0.22	0.81	-2.10		2.16	-1.45	-0.37	-0.28	-0.40	-0.19	0.13	0.08	0.20	0.04	-0.39	0.24	0.15	0.47		0.04	0.14	0.23	0.36	0.25	0.13		0.24
8	0.83	0.41	-0.50	0.13	0.60	-2.47	-4.06		-0.77	-0.73	-0.45	-0.64	-0.26	0.22	0.07	-0.45	-0.11	-0.58			0.45			0.17	0.25	0.34		0.60	-0.55	0.31
9	1.16	0.76	-0.72	-0.88	-1.42	-0.86	0.37	1.09		-1.37		-2.02	-0.60	0.57	-0.20	0.57	-0.22	0.35		0.36	1.57		-0.18	0.32	0.43	-1.56	-0.71	1.15	-0.84	
10	2.59	1.39	-2.63	-2.06			0.41	1.51	4.26		2.22	-9.89		-2.79	-0.40	-4.14	-0.66	1.77		1.40	1.25		0.43	0.97	1.76	3.12	-2.20	2.34	-2.96	1.77
11	1.36	0.58	-1.31	-1.26	-2.16	-0.95	0.29	0.95		-1.40		-2.14	-0.91	-1.96	-0.21	-1.52	-0.40	-1.25		0.91	1.79		0.00	-1.40	-1.43	-1.76	-1.43	-3.02	-1.75	-1.33
12	2.18	0.62	-0.94	-0.71	-1.55		0.23	0.58	2.98	2.15	1.40		-0.36	1.39			-0.45		0.73	0.62	1.60	0.56	0.19	-0.89	0.65	1.32	-0.97	0.44	-0.99	0.47
13	0.18	0.11	-0.18	-0.10	-0.27		0.10	0.17	0.21		0.17	0.16		-0.48	-0.03	-0.20	0.04	-0.31	0.30	0.20	0.42		0.04		0.23	0.21		-1.42	-0.29	
14	-0.61		-0.31	-0.21	-0.50	-0.14	-0.29	-0.37	-0.52	0.18	0.33	-2.17	0.42			-0.45	0.07	0.15	0.18		0.41	0.14	0.06			-0.49				
15		1.76	-1.57	-1.46	-2.08	0.39	-0.49	-1.22	0.83	0.32	0.25		0.09			0.85	0.09	0.32	0.23	0.43	-0.98	-0.50	0.10	-0.49	0.40	-2.09	-0.73	-1.51	-0.70	-1.25
16	4.83	0.95	-2.07	-1.20	-2.17	-1.21	-0.88	0.67	-2.25	0.83	0.83		0.71	0.83	-0.49		0.26	-1.82	0.96		1.47	0.86	0.23	0.38	0.57	2.89	0.93	1.40		
17	-0.34	0.08	-0.09	-0.39	-0.33		-0.11	0.12	0.11	0.09	0.16	0.46	-0.17	-0.29	-0.03	-0.36		0.27	0.23	0.11	0.20	0.16	-0.09	-0.26	0.11	0.52	0.11		-0.27	
18	0.59	0.16	-0.39	-0.36	0.50	-0.52	0.12	0.24	-0.93	-1.28	0.30		0.47	-1.23	-0.10	0.63	-0.40		1.06	0.58	1.42	-2.05	0.13	0.53	0.45	0.95	-0.70	0.58	-0.68	0.29
19			-0.63	-1.04	-1.16	-0.64	-0.50					-0.94	-1.06	-1.45	-0.18	-0.89	-0.28	-1.70		1.71	6.48	-1.69		-2.98	0.98	-1.69	-1.21		-1.60	-1.17
20	-0.44				-0.24	-0.27	-0.56		-0.88	-0.63	-0.38	-0.55	-0.35		-0.07		-0.13	-0.64	-0.90		2.70	-2.45	-0.17	-1.24	0.40					0.20
21	0.09	0.05		-0.03	-0.12	-0.09	-0.12	-0.16	-0.24	-0.16	-0.09	-0.16	-0.11	-0.14	0.01	-0.12	-0.04	-0.25	-0.33	0.00		-0.34	-0.06	-0.46		0.07	-0.17	0.20	-0.12	0.05
22	1.12	0.37	-0.51	0.09	0.68	-0.43						-0.61		-0.52	0.05	-0.86	-0.17	0.92	0.85	1.26	1.46		-1.01	-3.60	1.89	1.55	-1.66	3.31	-1.02	0.56
23	0.49	0.16	-0.24	0.06	-0.33	-0.22	-0.19		0.34	-0.28		-0.33	-0.23	-0.21	-0.06	-0.36	0.11	-0.50		0.51	0.78	1.68		-0.89	0.93	1.09	-1.03	-2.04	-0.73	-0.57
24	0.39	0.14			-0.26	-0.16	-0.16	-0.22	-0.38	-0.27	0.17	0.23			0.04	-0.24	0.05	-0.50	0.54	0.88	1.83	1.07	0.21		1.00	0.47		0.37		0.23
25	0.48	0.18	-0.23	0.05	-0.29	-0.38	-0.51	-0.42	-0.76	-0.63	0.25	-0.74	-0.44		-0.08	-0.41	-0.13	-0.58	-0.66	-1.25		-3.14	-0.41	-1.57		0.51	-0.60	0.56	-0.40	0.31
26		-0.70	-0.83	0.00	-1.36	-0.58	-0.52	-0.63	0.82	-0.80	0.32	-1.15	-0.42	0.48	0.11	-1.75	-0.33	-1.05	0.49		-1.11	-3.03	-0.45	-1.13	-1.05		-2.17		-2.53	
27	0.49	0.19			-0.53	-0.22	-0.27		0.28	0.18	0.17	0.22			0.05	-0.35	-0.06	0.19	0.25		0.49	0.40	0.19	0.00	0.34	0.67		4.43	-1.52	
28	-0.13	-0.09	-0.04	0.02	-0.09	-0.04	-0.07	-0.06	-0.12	-0.08	0.03	-0.09	0.04		0.01	-0.05		-0.05			-0.16	-0.23	0.03	-0.07	-0.06		-0.69		0.12	-0.12
29	0.42	0.15		0.00	-0.62	0.11		0.27	0.12	0.07	0.06	0.10	0.08		0.03		0.03	0.09	0.08		0.15	0.12	0.07	0.00	0.11	0.74	0.43	-0.87		
30				0.04	-0.61	-0.41	-0.38	-0.55		-0.47	0.23	-0.54			0.10			-0.40	0.35	-0.32	-0.67	-0.88	0.16	-0.38	-0.44			1.51		

Figure 10. The proportion that one province should undertake for other provinces in an embodied carbon emission ecological system (the numbers in this figure represent the percentage of one province's CER).

As shown in Figure 11, each province has its specific CER tasks. In the 13th FYP, the allocation plan is mainly based on a production-based perspective, which means that the provinces with large carbon emissions should take more CER tasks. The allocation plan in the 13th FYP does not take the large amount of interprovincial carbon emissions transfer into consideration. Therefore, in the new allocation plan, a consumer-based principle is adopted. The provinces that imported a large amount of ECE should take more CER tasks. Specifically, developed provinces, such as Beijing, Shanghai, Zhejiang, Jiangsu, and Guangdong, will undertake a relatively larger number of CER tasks than the original allocation plan in the 13th Five-Year Plan, while underdeveloped provinces, such as Xinjiang, Ningxia, and Guizhou, will undertake fewer CER tasks than the original allocation plan.

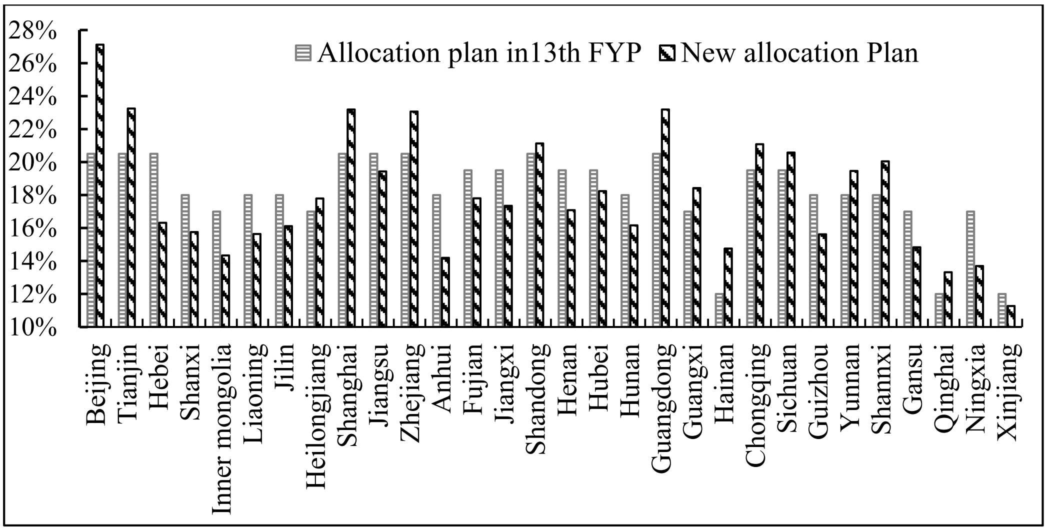


Figure 11. Allocation plan based on interprovincial ECE flows and the ECE network.

5. Discussion

In this paper, we used the MRIO and ENA models to obtain detailed interprovincial ECE flows and the relationships between all 30 provinces in China's ECE ecological system. These results provide comprehensive information about ECE flows and ecological relationships between them, which helps us to quantitatively analyze the responsibility a certain province should take and then establish a consumer-based allocation plan.

5.1. Comparison between the Allocation Plan Proposed in This Paper and Previous Allocation Plan

As shown in Figure 7, we quantified the interprovincial ECE flows, which provide us the detailed data about ECE flows. Combined with the interprovincial relationships of results of the ENA model, as shown in Figure 7, we can obtain the specific duty that any one province should undertake and specific measures that a province should take to realize that duty, as shown in Figures 10 and 11. Compared to the allocation of China's 13th Five-Year Plan, which simply allocates the CER tasks based on five simple categories from only the producer perspective, our CER allocation plan in this paper uses the more comprehensive information from the consumer perspective.

Firstly, we calculated the CER duty from a consumption-based perspective. As the consumers and producers are normally separated, it is necessary to distinguish the different duty between consumers and producers. Due to the very large differences in resource endowment, geographical position, and development planning, China's different provinces have shown totally different development trajectories in recent years. Due to the scale effect, the character of each province has become increasingly distinctive. The industries of developed provinces, such as Beijing, Shanghai, Zhejiang, etc., are mainly focused on high-tech manufacturing and high-value added tertiary industries, which are normally less energy consuming industries with fewer direct carbon emissions. Meanwhile they import a large amount of ECE from underdeveloped provinces to maintain their development. For example, most of Beijing's electricity is imported from Inner Mongolia (more than 40%), Hebei, Shanxi, and Tianjin supplied 18%, 16%, 9% of total Beijing's electricity consumption [56]. These phenomena are quite normal in China's current economic structure and industrial distribution. It is necessary to calculate the CER duty from a consumption-based perspective.

Secondly, detailed values of interprovincial flows, calculated in this paper, provide us with quantifiable information, which helps us to decide how much responsibility one province should undertake for its trade partners. The Chinese central government has implemented a series of polices to promote the underdeveloped provinces' development, including transferring industries from developed regions, mainly located in eastern coastal areas, to northwest underdeveloped areas. These policies indeed play a significant role in developing underdeveloped provinces' economies. Meanwhile, these transferred industries mainly concentrate on energy-intensive, emissions-intensive and other intermediate-production industries. These underdeveloped regions inevitably consume more energy, produce more carbon emissions, and export more ECE to developed regions. In addition, almost all developed provinces have reached a technological plateau in terms of CER methods [22], which means that further improvements of technology in these provinces are unlikely to be significant, and the cost of further CER will increase considerably [57]. Underdeveloped provinces, on the other hand, have a relatively larger potential CER and lower CER cost than developed provinces. However, underdeveloped provinces urgently want to develop their economy, so they have to export a very large amount of ECE to developed provinces and develop those energy-intensive and emission-intensive industries transferred from developed provinces. They are reluctant to undertake too much CER, which may impede their development. Since developed provinces consume a large amount of ECE, imported from underdeveloped provinces through interprovincial trade [34], they should take part of the responsibility for this. As a result, the values of interprovincial flows help us to quantify the specific CER responsibility, which is fairer for all China's provinces.

Thirdly, from a system perspective, it is not necessary to share responsibility for every ECE import. The relationships among all the 30 provinces help us to decide whether a certain province should undertake CER responsibility based on a specific relationship. According to the concept of the ENA model, there is no need for provinces with competition or mutual relationships to take any responsibility for each other. In an ecological system, these relationships do not have any directional effect on the operation of this system. Therefore, in this paper, we made a comprehensive calculation of how much responsibility of CER tasks each province should undertake to make a fair CER allocation plan.

5.2. The Challenges for Carrying out This Fair Carbon Emission Reduction Allocation Plan

Theoretically, we obtained a fair CER allocation plan based on the analysis in this paper. There are some challenges to carrying out this plan in practice.

On one hand, a consumption-based allocation plan does not completely solves the fairness issue. For example, Beijing imports a large amount of ECE, contained in steel, from Hebei province. In our allocation assumptions, Beijing should undertake the CER duty of this trade, because Beijing is the one who consumes those ECE. However, this kind of allocation plan will inevitably decease the enthusiasm of Hebei to update their technology of ECE, when Beijing undertakes the responsibility for their carbon emissions.

On the other hand, we should take specific measures to undertake the CER task. For example, Beijing imported a large amount of ECE and exported a small amount of ECE from Inner Mongolia. At the same time, the relationship between the two provinces is an exploitation relationship, which means Beijing should take the main responsibility for ECE flows between them. Specifically, Inner Mongolia provides a large part of Beijing's electricity supply, which contains a large ECE flow. As a result, Beijing should undertake a part of the CER tasks of Inner Mongolia's electric industry. Normally, developed regions could transfer relative high technology to underdeveloped regions to complete the duty of sharing CER tasks. Considering that the technology of power generation in Inner Mongolia is quite advanced [58], there is little potential for further improvement in this field. Therefore, Beijing might take other measures, such as paying extra prices for these ECE consumptions, or supporting energy efficiency and emissions programs in other areas.

6. Conclusions

China is a country with substantial regional differences in economic development level, energy consumption structure, resources, and technologies, as well as their own development path, which means they have different potential and difficulties to carry out CER tasks. Therefore, we built an ECE ecological network based on MRIO and the ENA model, which provides us with the detailed ECE flows and ecological relationships among China's 30 provinces. As a result, a relatively fair CER allocation was proposed, based on the relationships and ECE flows among China's 30 provinces. The specific findings of this study are as flows:

(1) There is a very large difference between China's provinces when examining the data of direct energy consumption, direct carbon emission, and embodied carbon emissions. Owing to these differences, it is unreasonable to put some provinces with different carbon emission features in the same class, as shown in the China's 13th Five-Year plan.
(2) There are large ECE flows between China's 30 different provinces, which reflects the causes of unfairness in the CER task allocation. The underdeveloped provinces, such as resource provinces (Shanxi, Inner Mongolia, etc.) and heavy industrial provinces (Liaoning, Hebei, etc.), tend to export larger amounts of ECE to developed regions than the volume of their imports, while developed provinces continue to take advantage from the interprovincial trade with less developed provinces by importing a large amount of ECE.
(3) Control and exploitation relationships are the major relationships existing among China's 30 provinces. For the developed provinces, the major relationship between them and other provinces is exploitation, which means they should take responsibility for this ecological relationship. The underdeveloped provinces, however, have the opposite situation. Therefore, developed provinces will undertake more responsibility for CER tasks and underdeveloped provinces will decrease part of the CER tasks in the new CER allocation plan.

Overall, we applied ecological network analysis (ENA), combined with a multi-regional input-output model (MRIO), to build an ecological network of embodied emissions across 30 provinces, which provides a model to support policy-makers in allocating CER tasks at the provincial level. In addition, we adopted the consumer-based principle to reconsider the allocation of CER tasks, which performed better in providing the actual features and responsibility for carbon emissions that a certain province should take. The application of this principle provides a fairness perspective for decision-makers to consider CER allocation plans.

It is worth mentioning that how to fairly allocate the primary CER tasks is the just the first step of achieving CER targets. There is still a wide range of specific measures that should be achieved to further develop China's economy, reduce carbon emissions, and achieve sustainable development. It is essential for those underdeveloped provinces to continue to improve their technology level, improve the energy and emission efficiency, and narrow the gap between them and developed provinces. As a result, the energy efficiency and carbon emissions of the whole system will improve and reduce the carbon emissions, thereby realizing the Chinese government's international commitment.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/10/5/1342/s1, Table S1: The detailed data of Embodied Carbon emissions in interregional exports and imports by region in 2012, Table S2: The detailed data of interprovincial flows of embodied carbon emission in 2012. Table S3: The comparison of direct energy consumption, direct carbon emission and embodied carbon emission in China's different provinces. (toe, stands for tones of oil equivalent). Table S4: Carbon emissions coefficient; Energy consumption coefficient; Embodied carbon emissions coefficient by sectors.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. The code for each province in China.

Code	Province	Code	Province	Code	Province
1	Beijing	11	Zhejiang	21	Hainan
2	Tianjin	12	Anhui	22	Chongqing
3	Hebei	13	Fujian	23	Sichuan
4	Shanxi	14	Jiangxi	24	Guizhou
5	Inner mongolia	15	Shandong	25	Yunnan
6	Liaoning	16	Henan	26	Shannxi
7	Jilin	17	Hubei	27	Gansu
8	Heilongjiang	18	Hunan	28	Qinghai
9	Shanghai	19	Guangdong	29	Ningxia
10	Jiangsu	20	Guangxi	30	Xinjiang

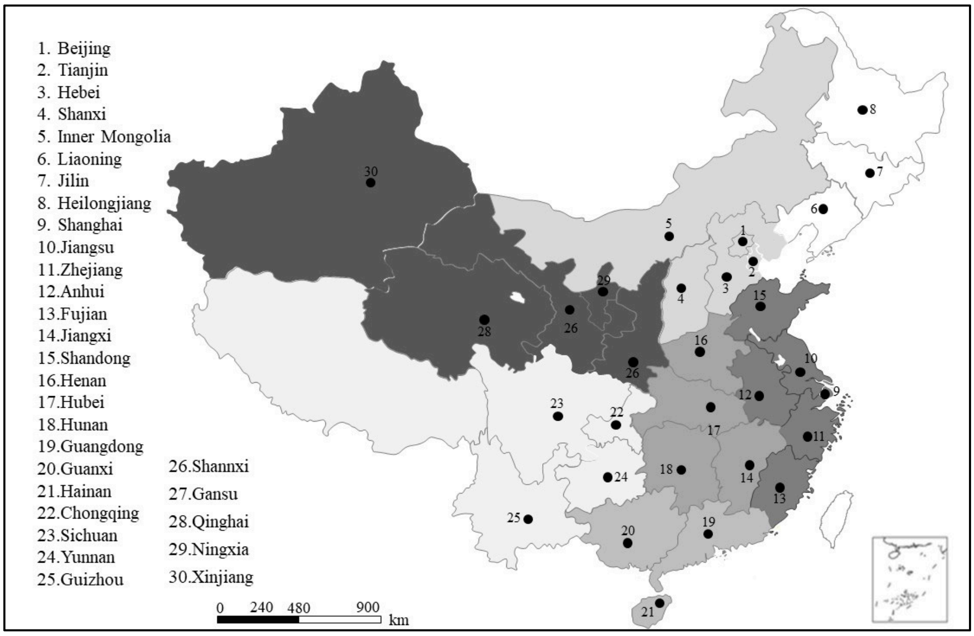

Figure A1. Map of China's provinces.

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