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Study on the initial allocation of carbon emission rights applicable to China's national conditions: From the perspective of comprehensive principles

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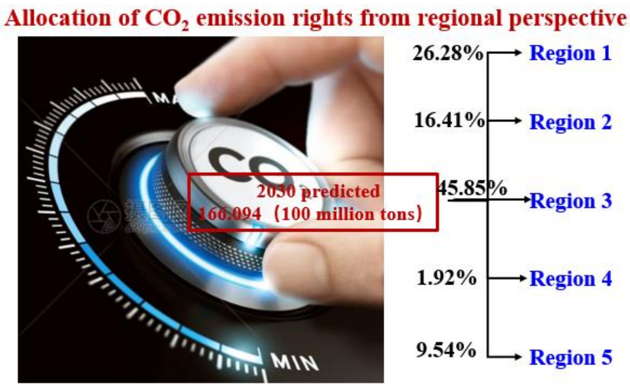
Graphical abstract



Abstract

The scientific and reasonable allocation of initial carbon emission rights is the foundation of establishing and perfecting the carbon trading system, which is directly associated with the completion of carbon emission reduction targets. Guided by the rational distribution of China's carbon emission rights, this paper adopts a multi-index method to investigate the initial distribution of China's carbon emission rights from a regional perspective according to the comprehensive principles of fairness, efficiency, sustainability, and environmental capacity limit. The results show that the use of regional historical carbon emissions or economic factors as a single indicator of carbon emission rights distribution is unreasonable according to historical emissions or GDP, and the results are quite different from the actual demand. Under the overall coordination degree allocation model, it is reasonable for Region 2, Region 3, and Region 4 to undertake higher emission reduction responsibilities, and the emission reduction tasks in these regions are likely to be completed, which shows that the carbon emission rights allocation under the comprehensive principle is more in line with the actual demand and has good operability, robustness, and compatibility. The allocation of carbon emission quota requires the scientific and reasonable formulation of the total national allocation, that all provinces and cities can form a stable quota expectation, effectively design the allocation principle scheme, give considerationto fairness and operability, and do not share the responsibility of regional emission reduction with a one-size-fits-all approach.

Keywords: carbon emission right; distribution method; region; comprehensive principle; coordination function

1. Introduction

With the increasing concentration of greenhouse gases such as carbon dioxide in the atmosphere, climate change is currently considered among the major challenges in the 21st century (Rafique and Williams 2021; Sun and Ren 2021). The Special Report on Global Warming of 1.5℃ by the Intergovernmental Panel on Climate Change (IPCC) has highlighted that the current global average temperature has increased by 1℃ compared with that before the industrial revolution. The greenhouse effect not only leads to a series of climate problems but also to melting glaciers, rising sea level, species extinction, crop reduction, and food crisis (Fleschutz *et al.* 2021; Maino *et al*. 2021; Nong *et al*. 2021; Zhang *et al*. 2021). In 2015, the report Human Cost of Climate Disasters released by the United Nations showed that the number of natural disasters related to global climate in 2005-2015 increased by 14% compared with 1995-2004 and increased by 100% compared with 1985-1994 with an obvious growth trend (Izumi *et al*. 2021; Yang *et al*. 2021). With the continuing rise of the global economy and population, the demand for fossil energy will continue to increase. Without active measures, it will lead to increasingly serious climate and environmental problems. To better cope with the global warming caused by the greenhouse effect, the United Nations convened a series of climate change conferences and formed a binding greenhouse gas emission agreement (Zhang and Hanaoka 2021; Chang and McAleer 2019; Ito 2019; Wu and Liu 2020). The main body responsible for reducing emissions in global climate governance began to change from developed countries todeveloped and developing countries, and the constraint form also began to change from compulsory governance to independent responsibility (Wang *et al*. 2019; Feng *et al*. 2018).

Finding solutions to reduce CO_2 emissions in order to develop a low-carbon economy has become a hot issue in the international community. All nations around the globe should work towards the reduction of CO_2 emissions and take corresponding responsibilities (Zhang *et al*. 2017). At present, countries all over the world have actively taken different measures to reduce emissions, including direct control, carbon tax, carbon emission trading (carbon trading), and other measures (Duan *et al*. 2020; Zhou *et al*. 2021). Although the method of direct control has the advantages of simplicity, directness, and rapidity, there may be great resistance and high management cost in its implementation. The aim of the carbon tax is to reduce carbon emissions by enhancing the cost of fossil energy, but the determination of the tax rate is still controversial (Dong *et al*. 2018; Li *et al*. 2018; Mu *et al*. 2016). A tax rate too high may affect the production of enterprises, while too low can't produce an emission reduction effect. Carbon trading means that the emission right of greenhouse gases is regarded as a tangible asset, and under the constraint of laws and regulations, the emission subject can obtain the corresponding emission demand through trading or exchange (Wu *et al*. 2019; Wang *et al*. 2018). Carbon trading is one of the most significant emission reduction measures so far. It can internalize externalities through market-oriented means, attain the lowest cost of reducing social emissions on the premise of completing emission reduction tasks and play a crucial part in the governance of global climate. Carbon emission right refers to the right given to the power subject to discharge greenhouse gases into the atmosphere to fulfill the requirements of development and survival under the condition of limited environmental capacity (Lamphiere *et al*. 2021; Zhang *et al*. 2021; Zhang and Xu 2020; Dai *et al*. 2018; Gallego-Alvarez *et al*. 2016). It stipulates that each power subject has the right to use atmospheric resources up to a certain limit. As a derivative of emission right, carbon emission right has the basic attributes of scarcity, compulsion, exclusiveness, traceability, and divisibility. The initial allocation of carbon emission rights is a process in which the government allocates appropriate carbon emission rights to actors according to their development needs (Zeng *et al*. 2020; Emir and Bekun 2019; Sun *et al.* 2014). It is the basis for the establishment of a sound carbon trading system and is directly related to the completion of carbon emission reduction targets. The initial allocation of carbon emission rights involves the allocation of subjects, principles, methods, and many other contents. It is the premise of carbon trading; therefore, its scientific and reasonable allocation is very important for the effective operation of the carbon trading market (Zhang *et al*. 2020; Yuan *et al*. 2015).

In contrast to being a responsible country, China is also the largest consumer of energy and carbon emitter around the globe and has been under tremendous pressure from the international community to reduce emissions. China has committed to promoting the signing and implementation of international climate change agreements by actively participating in emission reduction and alleviating climate warming. The country has been an active participant in the governance of global climate and has successively signed the Kyoto Protocol, Paris Agreement, and other contracts. In 2016, the Chinese government made a solemn commitment to lower the emission of CO_2 per unit of GDP by 18% by the year 2020 in comparison to 2015 and by 60% to 65% by 2030 (Nguyen *et al*. 2019). To realize the above commitments, China has actively helped in lowering carbon emissions by developing clean energy, improving the use of energy effectively, and developing a carbon emission trading mechanism. Since 2011, the Chinese government has successively carried out carbon trading pilot projects in seven regions, including Tianjin, Chongqing, and Shenzhen. In 2013, China started developing regional carbon pilot projects. After several years of exploration and accumulation, the country officially launched the national unified carbon market at the end of 2017. China is in the initial stage of the establishment of a carbon trading mechanism, and there is much room for improvement in various institutional measures (Ma *et al*. 2018). However, we can learn from the systems of other countries, although copying other countries' carbon trading systems are probably not applicable to the actual situation in China due to the international differences. The development and improvement of the carbon trading system still need a lot of research work, among which the initial allocation of carbon emission rights is crucial to the establishment of the carbon trading market, which has a major impact on the costs of carbon trading and emission reduction. Therefore, the rational allocation of carbon emission rights is crucial to China's sustainable development. In the trading cycle, the first step is to allocate carbon emission allowances. The factors that determine China's initial allocation of carbon emission right mainly are region, enterprise type, enterprise scale and profit level, among which the region is the basis for discussion of other factors and is the most critical factor (Lu *et al*. 2023; Hong *et al*. 2022). For a long time, China's regional economy has shown a gradient decline from the eastern coastal region to the central and western regions. It is unfair for enterprises to ignore regional differences in distribution. If the principle of equal distribution is adopted, it will inevitably lead to uneven distribution of carbon emission rights. To effectively lower the consumption of energy and related emissions, the first thing to do is to determine the quota allocation scheme for provincial regions. However, due to the unbalanced and uncoordinated regional development, there are many variations in the economic structure, development stage, and energy use among provincial regions. Distributing carbon emission rights fairly and effectively in all provinces, municipalities, and autonomous regions is the focus and hotspot of the government, the public, and academic circles. Considering that China's carbon market is in the initial stage of establishment and various systems need to be improved, it is very important to study the initial allocation of carbon emission rights, which can promote the healthy development of the carbon trading market.

Based on systematically combing the relevant national and international literature, combined with the available distribution modes and methods of major carbon trading markets at present, this research is aimed at optimizing the initial distribution of carbon emission rights and seeks a more reasonable and easy-to-implement carbon emission rights distribution scheme. Guided by the rational allocation of carbon emission rights in China, according to the comprehensive fairness, efficiency, and sustainability principles along with environmental capacity limit, population number, inverse carbon emission intensity, initial demand for carbon emission rights in each region, and the initial carbon emission rights quantity index is selected respectively, and the model for carbon emission rights allocation is established from the regional perspective. Finally, the regional carbon emissions are analyzed according to the distribution results of carbon emission rights calculated by the model, and corresponding emission reduction suggestions are put forward in combination with the advantages and shortcomings of each region.

2. Literature research

This paper will sort out the related works of literature on the initial allocation of carbon emissions from three aspects, including allocation principles, allocation methods, and allocation objects.

2.1. Principle of carbon emission rights allocation

One of the key issues in the allocation of carbon emission rights is to determine the allocation principles to be followed. These principles can be sorted randomly into the fairness and efficiency principles. The fairness principle can be randomly sorted into the per capita fairness principle, historical responsibility fairness principle, ability to pay fairness principle, and future development opportunity principle (Qin *et al*. 2017). The principle of per capita equity holds that the emission right is a basic right enjoyed by all people equally, and everyone has the right to be free from climate damage. Equal opportunities and responsibilities among individuals should be considered when formulating carbon emission reduction plans. Historical responsibility equity refers to intergenerational equity, which means that the countries that caused the global climate by emitting a lot of CO_2 in the past should bear moral responsibility for the past, although they do not need to bear legal responsibility (Zhang *et al*. 2014). The principle of fair ability to pay holds that countries and individuals below a certain income threshold should not bear the cost of payment. The principle of efficiency is primarily related to the economic efficiency of emission reduction; that is, the minimum investment is required to get the maximum return. Although the principles of fairness and efficiency have their special emphasis, there is no clear boundary between them, and some indicators can reflect both fairness and efficiency.

China has a vast territory, the level of development of different regions is quite different, and the industrial structure is unbalanced. It is unfair for enterprises to ignore regional differences and industry differences in distribution. In the context of reducing carbon emissions, carbon emission rights, are analogous to economic development rights since they are a scarce resource, and the distribution of carbon emission rights among various regions is equivalent to that of development rights. Therefore, the optimal allocation of carbon emission rights in China should take into account the principles of fairness, efficiency, sustainable development and environmental capacity limit. The comprehensive principle of distribution proposed takes into account the influence of proportion of each factor on carbon emission rights allocation in this paper. It is a distribution method that not only care the needs of all parties, but also regulates carbon emission entities, reflecting fairness and efficiency.

2.2. Carbon emission rights allocation method

The existing allocation methods can be roughly divided into four categories, namely, index, optimization, game theory, and mixed methods (Gan *et al*. 2022). The index method is used most widely to allocate emission rights. It allocates emission rights according to the selected index, which can be further classified into a single index and multi-index methods. The latter is commonly used in carbon emission rights allocation research because it can integrate different standards or principles and consider many aspects. The distribution weight of each index plays a key role, which reflects the relative importance of different indexes. At present, there are usually three ways to assess the weights of related indicators, namely, subjective weighting, objective weighting, and comprehensive weighting. Optimization methods include linear or nonlinear programming models, among which data envelopment analysis (DEA), as a typical method in linear programming models, is favored by many scholars in the research of carbon emission rights allocation. It is easy to construct various constraints and can reflect various standards and principles of carbon emission rights allocation, so it is widely used in different levels of CO_2 emission rights allocation (Cheng *et al*. 2022). The game means that the allocation of CO_2 emissions usually requires different participants to negotiate, and the purpose of each participant is to win more emission rights, which can be regarded as a game. Compared with the index method, the game theory method is more complicated. It involves different participants in the negotiation of CO_2 emission rights allocation, which is more closely related to the actual situation. The hybrid method can realize the combination of various methods, thus making the distribution result more reasonable. In the mixed method, one way is to use multiple indicators for multi-stage allocation. Compared with other methods, the hybrid method is more complex, so the distribution outcomes aren't as clear. However, the hybrid method is widely used because it can consider fairness and efficiency at the same time.

2.3. Carbon emission rights allocation object

According to different distribution objects, the literature can be divided into regional carbon emission rights distribution and industry carbon emission rights distribution, among which the carbon distribution based on regional perspective appeared earlier, and according to the distribution scope, it can be sorted into inter-country and inter-regional carbon distributions. Developed countries led by the United States advocate the allocation of carbon emission rights among countries based on per capita emissions. Carbon emission right is equivalent to a kind of development right. The dispute about the distribution of carbon emission rights is essentially a dispute of interests between developing countries and developed countries. Only by considering the interests of many parties can a consensus be reached. For large countries with vast lands, when the national carbon emission rights are determined, it is necessary to further clarify the carbon emission rights of different regions. Carbon distribution among countries is more concerned with fairness, while internal distribution, besides the fairness principle, will also focus on the efficiency of distribution. The allocation of carbon emission rights among industries can be sorted into two categories (Qi *et al*. 2022). The first one is the allocation of carbon emission rights between regions or between enterprises for a specific industry, among which the industries with more research are the electric power industry, steel industry, petrochemical industry, and construction industry. The other is the allocation of carbon emission rights among different industries.

2.4. Literature summary

In this paper, the related literature on carbon emission rights is sorted out from three aspects: allocation principles, allocation methods, and allocation objects. The following comments and summaries are also made from these three aspects.

From the distribution, fairness and efficiency principles are two recognized principles in the research of carbon emission rights distribution. As per the different distribution objects, the distribution focus will be different. For example, the distribution of carbon among countries is mainly based on the principle of fairness because the carbon emission rights distribution among countries is equal to the distribution of interests among countries to a certain extent, and only fair distribution can reach a consensus in the international community. However, the distribution among regions or industries within a country mostly focuses on the principle of efficiency, and fairness is considered based on efficiency. In addition, although the fairness and efficiency principles have been recognized by most researchers, there is still a big controversy about how to express them, and even opposite results will appear based on the same principles, such as fairness in the ability to pay and fairness in future development. The former advocates that distribution objects with high GDP should be more responsible for the reduction of emissions and get fewer carbon emission rights, while the latter thinks that distribution objects with high GDP should get higher carbon emission rights. Therefore, further discussion on the specific meaning of the fairness and efficiency principles based on the actual situation in China is crucial.

From the perspective of allocation methods, according to previous studies, it can be found that the allocation methods of carbon emission rights can be divided into index, optimization, game theory, and mixed methods. Among them, the single index method in index method is simple and easy, but it may not satisfy many allocation subjects. The multi-index method can contain multiple allocation criteria, and the results are more reasonable and widely used. However, there are still some problems in determining the weights of different indexes. Compared with the index method, the game theory model is more complex and less transparent. Optimization methods are mostly used to improve distribution efficiency, lacking the consideration of fairness. If we can set up multiple objectives, consider fairness and efficiency, and establish a multi-objective optimal distribution model, we may get more satisfactory results. Using multiple methods in the mixed method can make the allocation result more reasonable, but the problems of too complicated models and low transparency in the allocation process should be avoided.

From the distribution object point of view, with the promotion of the Kyoto Protocol and the submission of national independent contribution literature, although there is still a big controversy among countries, a certain consensus has been reached, so future research may be more focused on the regions and industries within countries. Especially, China is in the developing stage of the establishment of a carbon trading mechanism, and how to allocate carbon emission rights between regions and industries still needs a lot of research and demonstration. Moreover, the carbon emission rights allocation mechanisms from a regional perspective and industry perspective are indispensable, so it is necessary to integrate them into the same framework.

3. Methods

3.1. Research method

China has a vast territory, the development level of different regions is quite different, and the natural endowment and industrial structure are unbalanced. It is unfair for enterprises to ignore the distribution mode of regional differences. Theoretically speaking, taking the provincial administrative region as the research object can consider the specific situation of each province, but it also separates the links between provinces. In this paper, the administrative boundary is removed, and the purpose of serving carbon emission trading is to divide the carbon emission levels of provinces and cities in China into regions, cluster the carbon emission levels of 30 regions in China, and divide them into five regions, and study the initial allocation scheme of carbon emission rights in China from a regional perspective. Under the background of carbon emission reduction, carbon emission rights, as a scarce resource, are equal to economic development and the distribution of carbon emission rights among different regions. As a result, the optimal carbon emission rights distribution scheme should consider the principles of fairness and efficiency. According to system engineering, this paper adopts a multi-index method to integrate the allocation schemes based on the fairness principle, efficiency principle, sustainability principle, and environmental capacity limit. By calculating the weight of each index, the allocation ratio under different principles is determined, and the total carbon emission in a certain region is finally obtained by adding the carbon emission rights allocation under different allocation principles.

3.2. Regional distribution model of carbon emission rights

The date envelopment analysis (DEA) method and all kinds of derivative methods are the most common methods in the research presently available on carbon emission rights allocation. To some extent, they verify the relationship between carbon emission rights as a resource input and economic output value, and they are a kind of allocation method with the reference value. However, due to the singleness of the reference index of this method, the research results are quite different from the actual demand. From the perspective of system engineering, this paper comprehensively considers the principles of fairness, efficiency, sustainable development, and meeting the limit of environmental capacity and studies the regional allocation of carbon emission rights concerning several indicators. The goal of the system is to find a distribution result that can not only consider the needs of all parties but also regulate the main body of carbon emissions, taking into account fair factors, economic factors, social factors, and environmental factors.

3.2.1. Distribution model under the principle of fairness

The principle of fairness holds that carbon emission right is a fundamental right for all, and all people have the right to be free from climate damage. Equal opportunities and responsibilities among individuals should be considered when formulating carbon emission reduction plans. The essence of fairness is that the distribution subjects enjoy equal emission rights, which shows that the population in the region is the index that can best express the principle of fairness. Under the condition of steady economic development, it is assumed that the total carbon emission of China in 2020 will be CR (100 million tons) as the emission reduction target and the number of carbon emission rights allocated to each region is CR_i (100 million tons). The predicted population of each region in 2020 is POP_i (10,000 people), and the initial carbon emission rights of each region are CRP_i (100 million tons) under the population index (Ojo *et al*. 2020). Under the principle of fairness, the allocation function of carbon emission rights (CDFF) can be expressed as:

$$CDFF = \frac{\min\limits_{i=1,2,\ldots,n} (CR_i / CRP_i)}{\max\limits_{i=1,2,\ldots,n} (CR_i / CRP_i)} \quad (1)$$

$$CRP_i = \frac{CRP * POP_i}{\sum_{i=1}^{n} POP_i} \quad i = 1,2,\ldots,n \quad (2)$$

The predicted population POP_i of a certain region in 2020 is calculated according to formula (3) based on the population POP_i of all parts of the country in 2014.

$$POP_{i(2020)} = POP_{i(2014)}(1+\nu_P)^6 \quad (3)$$

Among them, v_P is the regional average population growth rate, and the population of a certain region is obtained by adding the population of all parts of the same region.

In the formula, the value range of CDFF is [0, 1]. The closer the final distribution result is to the initial carbon emission rights of each major region under the population index, the closer the coordination degree is to 1, which can better reflect the idea that everyone is equal before carbon emission rights.

3.2.2. Coordination function under the principle of efficiency

Efficiency is the principle of resource allocation optimization, which is related to the economic efficiency of carbon emission reduction. Under limited resources, we can get the greatest economic value possible. Carbon emission intensity is recognized as the index that can best reflect the principle of efficiency. The essence of the efficiency principle is that carbon emission rights are more inclined to be distributed to regions with high efficiency. Considering the convenience of calculation, the inverse number of carbon emission intensity, that is, the GDP value generated by unit CO_2 emission rights, is adopted. Increased carbon emission efficiency means increased GDP per unit of CO_2 emissions.

Under the condition of steady economic development, it is assumed that the preliminary carbon emission benefit of each region in 2020 is CRE_i, and the coordination degree function (CDFE) under the benefit principle can be expressed as:

$$CDFE = \frac{\sum_{i=1}^{n}(CR_i * CRE_i) - CR * \min\limits_{i=1,2,\ldots,n}(CRE_i)}{CR_i * \max\limits_{i=1,2,\ldots,n}(CRE_i) - CR * \min\limits_{i=1,2,\ldots,n}(CRE_i)} \quad (4)$$

$$, i = 1,2,\ldots,n$$

Where the value range of CDFE is [0,1], the closer the value of CDFE is to 1, the higher the coordination degree under the principle of efficiency.

3.2.3. Coordination function under the principle of sustainability

The principle of sustainable development requires that it not only meets the needs of the present generation but also does not harm future generations. Therefore, the amount of carbon emission rights allocated needs to meet the normal production activities of the region and be as close as possible to the emission reduction target. Under the condition of steady economic development, assuming that the initial demand for carbon emission rights in each region is CRD_i, the coordination degree function of economic sustainability (CDFS) can be expressed as:

$$CDFS_i = \begin{cases} \frac{CR_i}{CRD_i}, \ CR_i < CRD_i \\ 1, \ CR_i > CRD_i \end{cases}, i = 1,2,...,n \quad (5)$$

$$CDFS = \min_{i=1,2,...,n} (CDFS_i) \quad (6)$$

Where the value range of $CDFS_i$ is [0, 1]. When the carbon emission right obtained by a certain area is greater than its initial demand, it indicates that the demand of that area can be met, and the coordination degree is 1 at this time. When a certain region's carbon emission right is less than its initial demand, it indicates that the demand of the region is unsatisfied, and the coordination degree of the region is the ratio of the obtained amount to the demand amount. The overall coordination degree of national economic sustainability is the minimum of the regional coordination degree.

3.2.4. Coordination function under the limit of environmental capacity

As far as the environmental capacity limit is concerned, the areas with poor environmental carrying capacity need to develop energy conservation and emission reduction, and undertaking higher responsibility for emission reduction means less carbon emission rights are obtained, which is like the distribution mode under the population index. Under the condition of steady economic development, it is assumed that the environmental carrying capacity of each region is CE_i, and the initial carbon emission rights of each region are $CRCE_i$ under the condition of environmental sustainability. The coordination degree function (CDFCE) under the limit of environmental capacity can be expressed as:

$$CDFCE = \frac{\min_{i=1,2,...,n} (CR_i / CRCE_i)}{\max_{i=1,2,...,n} (CR_i / CRCE_i)} \quad (73)$$

$$CRCE_i = \frac{CRP * CE_i}{\sum_{i=1}^{n} CE_i}, i = 1,2,...,n \quad (8)$$

The value range of CDFCE is [0, 1]. The closer the final allocation result is to the number of initial carbon emission rights in each region under environmental sustainability, the closer the coordination degree is to 1, and the more it can embody the idea of lucid waters and lush mountains being invaluable assets.

3.2.5. Combination distribution model based on the comprehensive principle

In this paper, the entropy weight method is selected to integrate the distribution sub-models under the above principles, and the information content of data is measured by calculating the entropy value. The entropy value decreases, and the weight increases with increasing information content. On the other hand, the entropy value increases, and the weight decreases as the information content decrease. Under the comprehensive principle, the combined allocation model of carbon emission rights in a certain region can be expressed as:

$$CD = \lambda_1 CDFF + \lambda_2 CDFE + \lambda_3 CDFS + \lambda_4 CDFCE \quad (3)$$

Where λ_1, λ_2, λ_3, and λ_4 respectively represent the weights of fairness principle, efficiency principle, sustainable development principle, and environmental capacity limit (Tian *et al*. 2022). The weight is calculated according to the following steps:

(1) Standardization of data

$$x'_{ki} = \frac{x_{ki} - \min|x_k|}{\max|x_k| - \min|x_k|} (k = 1,2,3,4; i = 1,...,n) \quad (10)$$

(2) Calculating the proportion of the k-th distribution principle in region i

$$u_{ki} = \frac{x'_{ki}}{\sum_{i=1}^{n} x'_{ki}} \ (k = 1,2,3,4; i = 1,...,n) \quad (11)$$

(3) Calculating the entropy of different distribution principles

$$e_k = -(\ln n)^{-1} \sum_{i=1}^{n} u_{ki} \cdot \ln(u_{ki}) \quad (12)$$

If u_{ki} = 0, then u_{ki} ln (u_{ki}) = 0.

$$\omega_k = \frac{1 - e_k}{\sum_{k=1}^{4} (1 - e_k)} (k = 1,2,3,4) \quad (13)$$

$$\lambda_k = \frac{\omega_k}{\sum \omega_k} \ (k = 1,2,3,4) \quad (14)$$

(4) Calculating the weight of the distribution scheme under each principle

$$s.t. \begin{cases} \sum_{i=1}^{n} CR_i = CR \\ \sum_{i=1}^{n} CRD_i = CRD \\ \sum_{j=1}^{4} \lambda_j = 1 \\ 0 < \lambda_j < 1, j = 1,2,3,4 \\ 0 < CR_i < CR, i = 1,2,...,n \\ 0 < CRD_i < CRD, i = 1,2,...,n \end{cases} \quad (15)$$

The value range of CD is [0, 1], and maximizing CD's value is the ultimate goal of the carbon emission rights' regional allocation. The following plans can be obtained:

In this paper, carbon emission variables should be combined with carbon emissions on the consumption and production sides. Production-side carbon emissions are the carbon dioxide emitted by the direct energy consumption of each province. According to the energy balance table, production-side carbon emissions are mainly divided into three parts: CO_2 produced by the combustion of thermal power generation energy in the processing and transformation part, CO_2 produced by heating in the processing and transformation part, and CO_2 produced by the non-raw material energy consumption (except electricity and heat) in various industries at the terminal. To approach the actual carbon emissions as close as possible, this paper selects 22 kinds of energy sources in the energy balance table, which include raw coal, cleaned coal, other washed coal, briquette, coal gangue, coke, blast furnace gas, coking coal furnace gas, other gas, other coking products, crude oil, gasoline, kerosene, diesel oil, fuel oil, petroleum coke, liquefied petroleum gas, refinery dry gas, other petroleum products, natural gas, and liquefied natural gas. In accordance with the 2006 IPCC Guidelines for National Greenhouse Gas Inventory, the carbon emission coefficients of various energy sources are determined as follows:

$$CO_2 = \sum_{i=1}^{22} E_i \times CV_i \times CF_i \times CR_i \times 44/12 \qquad (16)$$

Where the E_i stands for the i-th fossil energy, CV_i stands for the average low calorific value of the i-th fossil energy, CF_i stands for the carbon content per unit calorific value of the i-th fossil energy, CR_i stands for the carbon oxidation rate of the i-th fossil energy, and 44/12 stands for the conversion coefficient of carbon dioxide and carbon.

The carbon emissions on the consumption side are carbon dioxide produced by various energy sources consumed by various provinces. It mainly includes two parts, direct and indirect carbon emissions. Indirect carbon emissions are CO_2 generated by power and heat consumption, in which the carbon emission coefficient of power is recalculated according to the data of power transfer in and out across provinces. Direct carbon emissions come from the CO_2 produced by the terminal energy consumption of various industries (except electricity and heat).

4. Results

4.1. Division of carbon emission regions

More than thirty provinces and regions in China are grouped into the eastern, central, and western regions in accordance with the traditional regional division standard. Tibet, Hong Kong, Macau, and Taiwan Province are excluded from this study since energy consumption data of these regions is lacking. The carbon emission levels of different provinces and cities in China are grouped geographically in this study based on historical total carbon emissions, per capita carbon emissions, carbon emission intensity, and environmental capacity. Table 1 shows the cluster centers.

Table 1. Cluster center results

The final cluster center					
	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 4**	**Cluster 5**
Historical total carbon emissions	25.86	28.37	37.10	25.34	16.18
Per capita carbon emissions	3.69	5.52	6.66	4.42	2.64
Carbon emission intensity	3.27	3.34	3.60	2.91	2.20
Environmental capacity	12866.00	10601.80	15718.90	0.00	9161.00

Table 2. Cluster results

	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 4**	**Cluster 5**
Provinces and cities included	Jilin, Jiangsu, Hubei, Guangdong, Guangxi, Guizhou, Gansu, Qinghai, Anhui	Nei Mongol, Zhejiang, Chongqing, Sichuan, Xinjiang	Beijing, Tianjin, Hebei, Shanxi, Liaoning, Shanghai, Shandong, Henan, Shaanxi, Ningxia	Heilongjiang	Fujian, Jinagxi, Hunan, Hainan, Yunnan
Characteristics of carbon emission	medium carbon emission areas	next high carbon emission areas	high carbon emission areas	Next low carbon emission area	low carbon emission areas

Table 3. CO_2 emissions by region from 2007 to 2021 (unit: 100 million tons)

	Region 1	**Region 2**	**Region 3**	**Region 4**	**Region 5**
2007	18.83	11.61	29.34	1.89	7.05
2008	18.17	11.94	31.23	2.45	6.97
2009	19.22	13.17	32.87	2.54	7.25
2010	21.55	13.88	36.73	2.92	7.68
2011	23.16	15.25	39.58	3.07	8.31
2012	23.91	15.90	41.55	3.16	8.82
2013	25.61	17.59	44.66	3.22	9.27
2014	27.13	19.54	47.82	3.47	9.56
2015	29.54	20.75	50.31	3.52	10.14
2016	31.76	21.26	53.27	3.61	10.61
2017	32.11	21.87	56.80	3.69	10.95
2018	32.87	22.18	59.22	3.74	11.36
2019	33.25	22.83	61.94	3.81	11.80
2020	33.47	23.52	65.46	3.89	12.05

2021	34.83	24.36	66.37	3.97	12.49

As shown in Table 2, thirty provinces and cities are grouped into five regions, and the main body in each region has the characteristics of consistent carbon emission levels. According to the data in the table, the central data values of the four indicators of cluster 3 are all the highest, which means that the areas in this category have the characteristics of high historical and per capita carbon emissions, high carbon emission intensity, and low environmental carrying capacity, and belong to high carbon emission areas. The central data values of the four indicators of clusters 1 and 2 decrease in turn, which can be classified into the next high and medium carbon emission areas, respectively. Cluster 4 is special, its total historical and per capita carbon emissions are close to and exceed those of medium-carbon emission areas, respectively; however, its environmental carrying capacity is the best, and its environmental self-regulation ability is strong, so it is classified as the next low carbon emission area. Cluster 5 is classified as a low-carbon emission area as it has the lowest index values of historical and per capita carbon emissions and carbon emission intensity.

4.2. Estimation of carbon emissions by region

The China Energy Statistics Yearbook contains information on many types of energy consumption in Chinese provinces and regions. As per the formula (16), the CO_2 emissions of each province and region from 2007 to 2021 can be acquired. Add up the CO_2 of each province and city according to the regional division standard. The annual CO_2 emissions of each region are shown in Table 3.

Table 4. Per capita carbon emissions of five regions in 2030 (unit: 100 million people, tons/person)

	predicted population values in 2030	**per capita CO_2 emissions in 2030**
Region 1	4.746152	9.1946
Region 2	2.325331	11.7182
Region 3	5.232518	14.5527
Region 4	0.385680	8.2346
Region 5	2.336805	6.7869

Table 5. Data of environmental carrying capacity of five regions (unit: RMB $(hm^2\ a)^{-1}$)

	Region 1	**Region 2**	**Region 3**	**Region 4**	**Region 5**
Environmental carrying capacity	70797	33986	16801	17399	41190

Table 6. Regional carbon emission reduction rights allocation plan and emission reduction rate in 2030

Region	**Carbon emission reduction rights in 2030(100 million tons)**	**Carbon intensity in 2030 (tons/10000 Yuan)**	**Carbon intensity in 2020 (tons/10000 Yuan)**	**Emission reduction rate**
Region 1	43.6435	1.1738	1.6516	28.93%
Region 2	27.2531	1.1598	1.6770	30.84%
Region 3	76.1548	0.8517	1.5046	43.39%
Region 4	3.1809	1.3021	1.7269	24.60%
Region 5	15.8617	1.9584	2.3390	16.27%
Nationwide	166.0843	1.1411	1.6781	32.00%

4.3. Calculation results of corresponding indicators under different principles

According to the population data of 30 provinces and cities in the China Demographic Yearbook from 2007 to 2021, the regional population data required for the coordination function under the principle of equity can be used to calculate the average population growth rate, to obtain the predicted population of each province and city in 2030. On this basis, the predicted population values and per capita CO_2 emissions of five regions in 2030 are determined (Table 4).

Table 7. Comparison of results of different distribution methods

	Allocated by the comprehensive principle model	**Allocated by the historical emissions**	**Allocated by the GDP**
Region 1	43.6435	38.9145	45.6678
Region 2	27.2531	29.2289	28.5173
Region 3	76.1548	85.3761	81.1157
Region 4	3.1809	3.6742	3.0816
Region 5	15.8617	11.1894	13.6725

The limit coordination function's quantitative expression of the required environmental carrying capacity is comparable to Costanza's 1997 proposal of the ecosystem service value. The higher the ecosystem service value in a certain region, the stronger the environmental carrying capacity and the lower the pressure of emission reduction in that region. The environmental carrying capacity data of 30 Chinese provinces and cities required in this paper comes from Chen Zhongxin's research results, and subsequently, the environmental carrying capacity of five regions is obtained, as shown in Table 5.

The weights of indicators under different principles can be calculated according to formulas (10) ~ (14). The weights of fairness principle, efficiency principle, sustainable development principle, and environmental capacity limit $\lambda_1 = 0.41$, $\lambda_2 = 0.32$, $\lambda_3 = 0.16$, and $\lambda_4 = 0.11$. The results of the initial allocation of carbon emission rights and emission reduction rate of the five regions in China in 2030 are shown in Table 6. It can be seen that the region 3 has the highest emission reduction rate, which is significantly higher than the national total emission reduction rate, and has the greatest emission reduction pressure. The emission reduction rates in regions 1 and regions 2 are lower than the overall national emission reduction rates, but the emission reduction pressure in these two regions is still relatively high. Regions 4 and 5 are under less pressure to reduce emissions and will be able to meet the 2030 emission reduction target based on their previous production levels.

5. Conclusions

5.1. Discussion on regional distribution results

Facing up the fairness, efficiency, and environmental carrying capacity of carbon emission rights allocation and considering the possibility of emission reduction, it is reasonable for Regions 2, 3, and 4 to undertake higher emission reduction responsibilities under the overall coordination degree allocation model, and the task can be accomplished greatly. To prove the superiority of the coordination degree model, the calculation outcomes of the coordination degree model under the condition of equal weight are compared with those of distribution according to historical displacement and GDP (Table 7).

When allocated according to the historical emissions, region 3 with high carbon emission characteristics gets more quotas, which not only does not restrict the emission reduction of high carbon emission provinces but even is a disguised encouragement. This will cause the high carbon emission areas to continue to maintain the status quo of emissions while the low carbon emission areas cannot meet the basic production needs. When it is distributed according to GDP, region 3 gets a higher carbon quota because of the economic advantages of Beijing and Shanghai in its region and the greater economic benefits brought by the non-intensive production mode of major energy provinces. This result ignores the phenomenon that products are produced outside the province and sold inside the province in economically developed areas and also ignores the disadvantages of non-intensive economic growth. Therefore, it is unreasonable to take economic factors as a single indicator of distribution. These two traditional carbon emission rights allocation methods are one-sided and extreme, which is not conducive to the balanced development of various regions.

5.2. Considerations of China's carbon emission quota allocation scheme

The following factors should be taken into account while developing carbon emission rights allocation methods based on the existing allocation schemes in various countries and regions. The first factor is the level of development. Generally speaking, the right to development is an important foundation for the realization of economic, social, and human rights. Because if a region does not attain a certain development level, it will not be able to provide basic public services and certain social and economic rights to its residents and guarantee that they meet the minimum living standard. Therefore, on the one hand, the carbon emission rights distribution should satisfy the basic development demands of economically developed areas, thus laying the foundation for creating more material wealth and meeting the population's growing material and cultural needs. On the other hand, from the perspective of historical development, underdeveloped areas have not only failed to develop their economies but also suffered from environmental pollution, climate change, and other consequences. Nowadays, they have to undertake the obligation of emission reduction, so they have become the biggest victims of climate change. Therefore, when determining China's emission reduction target, this paper must take intra-generation equity as the basis, fully consider the sustainable development of underdeveloped areas while ensuring the reasonable economic development needs of developed areas, and to some extent, guarantee the reasonable development demands of economically underdeveloped areas.

The second factor is the population base. Climate, environment are common resources and everyone in each region has the same rights to them, no region has the right to be higher than other regions in terms of per capita emissions. From the perspective of carbon emission rights, that is, the right to subsistence and development, it is an integral part of basic human rights, and it embodies the equal rights of regional members to survive, develop and utilize natural resources. Therefore, the distribution of carbon emission rights should consider the population factor, starting from the regional population, and embody the principle of per capita emission right.

The third factor is historical responsibility. Global greenhouse gas emission is not a temporary problem. It has existed since the beginning of industrialization and modernization, and it is accumulating. Therefore, it is important to consider the historical carbon emission factors in the eastern and western regions, particularly in the developed and underdeveloped regions. Historically and currently, the largest part of greenhouse gas emissions in China comes from developed areas, and both the total and per capita historical cumulative emissions are far higher compared to those in underdeveloped areas. 70% of China's carbon dioxide emissions since the reform and opening up have come from developed areas like Shandong, Hebei, Jiangsu, and Guangdong. According to the statistics on carbon emissions of various provinces, the regions with the largest cumulative emissions from 1995 to 2007 are developed regions, accounting for 55% of the national cumulative emissions. Therefore, the developed regions should take responsibility for the environmental problems caused by greenhouse gases, be responsible for the consequences caused by their actions, and pay certain fees. Given this, in implementing the distribution of carbon emission rights, the developed regions must consider the emission space consumed by developing the economy ahead of schedule in the past and deduct it from the future emission quota accordingly to realize fairness between developed regions and underdeveloped regions.

Fourth is the principle of fairness. From the existing international allocation methods and international conventions, the carbon emission distribution indicators must follow the principle of justice and fairness. In accordance with their respective responsibilities and capacities, all parties are required under the Climate Change Convention to safeguard the climate system for the benefit of current and future generations. Therefore, in the carbon emission rights distribution process, on the one hand, we should consider the fairness among regions to ensure that developed and underdeveloped regions have the same rights; On the other hand, we should seek intra-generation as well as inter-generation equity, to ensure the basic rights enjoyed by the disadvantaged groups, especially in the underdeveloped western regions, and thus realize the fair right to subsistence and development among regions.

Fifth, other factors. When allocating carbon emission rights nationwide, other factors should be considered, such as resource endowment. For example, Shanxi and other places live on coal, and the quota should be relatively high. In addition, regional energy efficiency, industrial structure, geographical conditions, and technical level should also be considered. Consideration of these factors may be fully taken into account to adjust China's distribution of carbon emission rights.

Availability of data and material

The data and material used in the current study are available from the corresponding author on reasonable request. Email: gaohengjiao@163.com.

Competing interests

The authors declare no conflict of interest.

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