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Research on the Initial Quota Allocation Scheme for Carbon Emission Rights in the Yangtze River Delta Region

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Abstract

Under the severe challenge of global climate change, the scientific allocation of carbon emission rights is of decisive significance for achieving regional emission reduction targets and accelerating low-carbon transformation. As one of the most developed regions in China's economy, the Yangtze River Delta region has a relatively high proportion of total carbon emissions in the country, and there are significant differences in the level of economic development and carbon emission intensity within the region. This difference not only reflects the imbalance between regions, but also poses challenges to the fair and efficient allocation of carbon emission rights. This article takes three provinces and one city in the Yangtze River Delta region, including Shanghai, Jiangsu, Zhejiang, and Anhui, as the research object, and studies three initial carbon emission quota allocation schemes to promote carbon peak in 2030. The aim is to provide theoretical support and practical guidance for the construction of carbon markets in the Yangtze River Delta region and even the whole country. Firstly, this article proposes a carbon quota allocation scheme guided by fairness. This plan is based on the principles of historical responsibility and transfer of responsibility, and uses an improved grandfather law model for quota allocation. The principle of historical responsibility emphasizes that each region should bear corresponding emission reduction responsibilities based on its past carbon emissions, while transferring responsibilities considers the spatial transfer effect of carbon emissions. Through this method, the plan not only considers the economic development level and carbon emission history of each region, but also takes into account the fairness between regions. The research results indicate that this scheme significantly reduces the Gini coefficient of quota allocation between regions, demonstrating strong fairness. However, this approach may also suppress the emission reduction enthusiasm of some high emission areas, thereby affecting the overall emission reduction efficiency. Secondly, this article proposes an efficiency oriented carbon quota allocation scheme. This scheme introduces the idea of zero sum game and uses the ZSG-SBM model to calculate the efficiency of each region and allocate quotas accordingly. The core of this plan is to optimize resource allocation and ensure that carbon emission rights can flow reasonably between different regions, thereby maximizing overall efficiency. Through multiple iterations and adjustments, this plan has enabled more regions to reach the forefront of technological efficiency. However, the Gini coefficient of this plan is relatively high, and there is a risk of the Matthew effect, where economically developed regions receive more quotas while underdeveloped regions face the problem of insufficient quotas. Finally, this article proposes a hybrid approach that balances fairness and efficiency. This scheme adopts the entropy method to integrate the results of fairness and efficiency schemes, forming a comprehensive allocation scheme. The entropy method determines the weights by calculating the information entropy of each indicator, avoiding the bias that may be caused by subjective weighting methods. The research results indicate that the emission reduction cost of the comprehensive plan is lower than that of a single plan. This plan not only ensures the low-carbon transformation space in economically developed areas, but also reserves development rights for underdeveloped areas, achieving a synergistic optimization of efficiency and fairness. This study not only provides theoretical support for the reasonable allocation of initial carbon emission quotas in the Yangtze River Delta region, but also provides useful references for the allocation of carbon quotas in other regions of the country. Future research can further explore the coupling relationship between carbon quota allocation and regional economic growth, and quantify the long-term impact of different schemes on industrial structure upgrading. In addition, how to connect policy tools such as carbon tariffs and green finance with quota allocation mechanisms, and build a multi-level emission reduction incentive system, is also a direction worth exploring in depth.

Keywords

Yangtze River Delta; carbon emissions; quota allocation

1. Introduction

The massive emissions of greenhouse gases such as carbon dioxide have become one of the main causes of climate change and global warming in recent years, exacerbating the problem of disease transmission. The climate change assessment report released by the Intergovernmental Panel on Climate Change (IPCC) points out that since the mid-20th century, the main driving force of global warming has been the increase in carbon emissions caused by human activities. Therefore, energy and environmental issues have become global issues that countries around the world need to address together. The Paris Agreement, a climate change agreement signed by 178 contracting countries in 2016, has established temperature control targets aimed at keeping the increase in global average temperature within 2 degrees Celsius compared to pre industrial times, and striving to further reduce this increase to 1.5 degrees Celsius.

Based on this background, this article selects three provinces and one city in the Yangtze River Delta region as the research object, aiming to explore the path to achieving the 2030 carbon peak target, and study three different initial carbon quota allocation schemes: the first is a fairness oriented carbon quota allocation scheme, which is based on the principles of historical responsibility and transfer responsibility, and is conducive to carbon reduction and economic development; The second option is a carbon quota allocation method based on the principle of efficiency, which incorporates the zero sum game concept, that is, an increase in carbon quotas in one region will lead to a corresponding decrease in carbon quotas in another region. This method uses the ZSG-SBM model to evaluate efficiency and determine reasonable carbon quota allocation; The third option is a carbon quota allocation scheme that combines fairness and efficiency. This article uses the entropy method to integrate the results of carbon quota allocation based on fairness considerations with those based on efficiency considerations, resulting in a comprehensive allocation scheme. Comparing the emission reduction costs of different allocation schemes, analyzing the advantages and disadvantages of different allocation schemes, determining a more reasonable allocation scheme, contributing to the reasonable allocation of initial carbon quotas between regions in the Yangtze River Delta region, and promoting balanced development among the Yangtze River Delta regions. This provides theoretical support for the unified carbon market in the Yangtze River Delta region and other regions, and is conducive to the research work of achieving China's 2030 carbon peak target.

2. Literature Review

Given the increasing severity of energy issues, numerous domestic and foreign institutions and scholars have conducted in-depth research on global carbon emissions and completed a lot of basic work. By comparing and analyzing carbon emissions at home and abroad, domestic scholars have proposed methods and countermeasures to reduce carbon emissions from a national perspective. Some scholars are also focused on exploring how to allocate carbon quotas reasonably in different regions, and there are significant differences in carbon emissions measured by different methods in different regions (Liu Zhancheng et al., 2010). With the entry into force of the Paris Agreement, the reasonable allocation of carbon emission rights has become the cornerstone of harmonious and stable development of human society. Therefore, many scholars are committed to studying the allocation plan of carbon emission rights. Some scholars use the principle of per capita and historical responsibility as the allocation standards, while others allocate from the aspects of ability, responsibility, and fairness (Fang Kai et al., 2018). From a global perspective, the principle of fairness in allocation is more important, making the sharing of carbon emission responsibilities between different countries more fair. However, from a national perspective, not only fairness should be considered, but also the relationship between the overall development of the country and the region, with promoting the efficiency of carbon emission allocation as another standard. Therefore, the allocation model that combines fairness and efficiency is more reasonable. (Zheng Liqun, 2013).

Although the principle of fairness based on per capita emissions and historical responsibility can alleviate regional imbalances, its single application may suppress the emission reduction drive in high emission areas, ultimately reducing the overall emission reduction effect and hindering the balanced development of various regions. Song Jiekun et al. (2016) calculated the carbon emission quotas of each province using the carbon emission coefficient method based solely on the principle of fairness. However, this method is difficult to achieve the national carbon reduction target. Therefore, it is imperative to build a unified national carbon market.

Compared with the principle of prioritizing fairness, the principle of prioritizing efficiency can maximize emission reduction efficiency. Research has found that the ZSG-DEA model is considered the most suitable method for carbon quota allocation. Lin Tan et al. used this model to evaluate the carbon emission allocation schemes of EU countries in 2009 and pointed out that considering only the principle of efficiency while ignoring the fairness of carbon quotas for all parties may exacerbate conflicts of interest. Zheng Liqun (2013) also used the ZSG-DEA model to analyze the allocation of carbon emission reduction responsibilities among various provinces and regions in China, and proposed a carbon quota allocation plan for 27 provinces and regions in China. This plan provides a reliable basis for establishing a domestic carbon trading market.

From this, it can be concluded that the trade-off model combining fairness and efficiency is more suitable for the emission reduction targets in the Yangtze River Delta region. This method not only improves overall efficiency but also balances individual fairness; It can provide guarantees for the overall carbon reduction target, enhance the feasibility of the allocation plan, and alleviate conflicts of interest among all parties (Zheng Liqun, 2013). This article aims to use the entropy method to develop an allocation scheme that integrates multiple principles such as fairness, efficiency, and responsibility, in order to provide useful references for the research of carbon quota allocation schemes in the Yangtze River Delta region of China.

3. Carbon quota allocation strategy based on the principle of fairness priority

3.1 Calculation of historical responsibility for carbon emissions

3.1.1. Theoretical Basis of Historical Responsibility

In global governance to address climate change, the Common But Differentiated Responsibilities (CBDR) principle is a widely accepted fundamental principle in the international community. This principle emphasizes that developed countries bear the primary responsibility for historical cumulative emissions, and this concept also holds guiding significance in regional carbon quota allocation. For the Yangtze River Delta region, the principle of fairness should focus on core indicators such as cumulative emissions, per capita emission levels, and carbon emission intensity during the industrialization process of each province and city.

From 2000 to 2023, the cumulative carbon emissions in the Yangtze River Delta region amounted to 30 billion tons, accounting for 18.9% of the national total. Among them, Jiangsu Province had the highest proportion of cumulative emissions, reaching 45.8%, followed closely by Anhui Province (23.5%), Zhejiang Province (20.6%), and Shanghai (10.1%). This significant regional disparity underscores the importance of giving high consideration to historical responsibility factors in the quota allocation process.

3.1.2. Construction of measurement index system

Based on the principle of common but differentiated responsibilities, the quantification of historical emission responsibilities is the key foundation for achieving fair allocation of carbon quotas. This study selects the period from 2000 to 2023 as the time frame for responsibility tracing, and employs the IPCC inventory method to calculate the carbon emissions generated by fossil energy consumption in the three provinces and one city in the Yangtze River Delta region. Using the formula, we have constructed a corresponding accounting model:

$$C_i = \sum_{j=1}^{n} \left(E_j * NCV_j * CC_j * O_j\right)$$

Based on the emission factor method of IPCC (2006), and referring to the "Classification and Codes for National Economic Industries (GB/T4754-2002)" and the "2006 IPCC Guidelines for National Greenhouse Gas Inventories", we selected 17 types of fossil fuels (including raw coal, washed coal, other washed coal, coal products, coke, coke oven gas, other gases, other coking products, crude oil, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas, refinery dry gas, other petroleum products, and natural gas) for detailed accounting. This accounting process helped us obtain the carbon emissions of prefecture-level cities in the Yangtze River Delta region. In this process, [NCV]_j adopted the national average lower heating value data published in the "China Energy Statistical Yearbook", while the carbon oxidation rate coefficient used the default values from IPCC 2006, such as 0.94 for raw coal, 0.98 for crude oil, and 0.99 for natural gas.

Table 1. Historical emission data of the Yangtze River Delta region (2000-2023)

Region	Carbon emissions (tons)	Population (people)	Per capita carbon emissions (tons/person)
Shanghai	3704042626	24870895	148.9308135
Jiangsu	16829618783	84748016	198.5842215
Zhejiang	758212554	64567588	117.4292827
Anhui	8679924784	61027171	142.2304957

3.2. Results of carbon quota allocation based on the principle of fairness

3.2.1. Basic Scenario Setting

This study allocates carbon quotas to the Yangtze River Delta region based on the 2025 carbon emission target (i.e. 2.5 billion tons of CO2) proposed in the Overall

Plan for the Ecological Green Integration Development Demonstration Zone. As a key document guiding regional carbon reduction, this plan clearly defines the upper limit of carbon emissions in the Yangtze River Delta region until 2025, providing direction and setting constraints for the allocation of carbon quotas in this study, thereby ensuring consistency between the allocation plan and the overall carbon reduction plan of the region.

3.2.2. Allocation of Provincial Quotas

Table 2. Results of carbon quota allocation based on the principle of fairness

Region	Historical proportion (%)	Adjusted quota (100 million tons)	Quota proportion (%)	Per capita quota (ton/person)
Shanghai	9.67	2.55	10.23	10.28
Jiangsu	44.93	10.80	43.18	12.74
Zhejiang	20.38	5.25	21.01	8.14
Anhui	25.02	6.40	25.58	10.48

3.2.3. Verification of Allocation Results

We use the Gini coefficient to evaluate the fairness of carbon quota allocation, which displays the distribution of carbon quotas between different regions based on the Lorenz curve. The formula for Gini coefficient G is:

$$G = \frac{B - A}{B}$$

Among them, A represents the area enclosed by the Lorentz curve and the coordinate axis, and B represents the area enclosed by the completely equal line (i.e. diagonal) and the coordinate axis. This validation uses a more simplified method to calculate the Gini coefficient, based on population weighted carbon quotas:

$$C_{avg} = \frac{\sum C_i}{n}$$
$$G = \frac{\sum_{i=1}^{n} P_i \left| C_i - C_{avg} \right|}{2 \sum_{i=1}^{n} P_i C_{avg}}$$

Calculate the carbon quota ratio C_i and population ratio P_i for three provinces and one city

By calculating the Gini coefficient of quota allocation results, it was found that the Gini coefficient of quota allocation is 0.11, which is significantly lower than the emission Gini coefficient of 0.35. This result indicates that the carbon quota allocation scheme proposed in this study performs well in terms of fairness, effectively reducing the gap in carbon quota allocation between regions. Compared with the original carbon emission pattern, it achieves a more fair and reasonable resource allocation, which is conducive to promoting coordinated development and social equity among regions.

4. A comprehensive carbon quota allocation strategy that integrates fairness and efficiency

4.1. Determining weights based on entropy method

In order to balance fairness and efficiency, this article uses the entropy method to determine the weights of both, thus constructing a comprehensive carbon quota allocation scheme. The entropy method, as an objective weighting method, determines the weight of each indicator based on its information entropy. Specifically, the smaller the information entropy, the higher the degree of dispersion of the indicator, and therefore the weight assigned to it also increases accordingly.

In order to eliminate the influence of dimensional differences on the analysis results, it is necessary to standardize the carbon quota allocation results that prioritize fairness and efficiency. This process can be achieved through range normalization, which converts raw data into relative values without units. Subsequently, based on the standardized dataset, we can calculate the information entropy values of each indicator. The formula for calculating information entropy is as follows:

$$E_j = -\frac{1}{\ln n}\sum_{i=1}^{n} p_{ij} \ln p_{ij}$$

Among them, $p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}}$, , x_{ij} is the standardized value of the jth indicator in the i-th region, where n represents the total number of regions. After obtaining the entropy values of each indicator, we can further calculate their coefficient of difference:

$$d_j = 1 - E_j$$

Normalize the coefficient of difference to determine the final weight of each indicator

$$w_j = \frac{d_j}{\sum_{j=1}^{m} d_j}$$

After calculation, we found that the weight of the results under the principle of fairness priority in carbon quota allocation is 0.469, while the weight of the results under the principle of efficiency priority is 0.531.

4.2. Carbon quota allocation results based on a comprehensive consideration of fairness and efficiency

On the basis of clarifying the weights of each indicator, we can integrate the principles of fairness and efficiency to calculate the comprehensive carbon quota allocation results for each region. This process involves using the weights and standardized values of each indicator to obtain the comprehensive score of each region. The specific formula for calculating the comprehensive score is:

$$S_i = w_1 * \text{fairness quota} + w_2 * \text{efficiency quota}$$

Allocate carbon quotas based on the comprehensive scores of each region. The allocation formula for carbon quotas is:

$$Q_i = \frac{S_i}{\sum_{i=1}^{n} S_i} * Q_{total}$$

Among them, Q_i is the carbon quota of the i-th region, and Q_total is the total carbon quota.

Table 9. Carbon Quotas Based on a Comprehensive Consideration of Equity and Efficiency Regional comprehensive principle carbon quota

Region	Comprehensive principle carbon quota
Shanghai	2.6297
Jiangsu	11.0344
Zhejiang	5.38425
Anhui	6.0816

Taking into account the development characteristics and needs of different provinces and cities in the Yangtze River Delta region, it not only ensures the sustained and stable development of economically developed areas, but also provides space and flexibility for relatively underdeveloped areas to implement energy-saving and emission reduction measures. Although Anhui's economic development is relatively lagging behind, through reasonable allocation of carbon quotas, it can gradually improve energy efficiency, adjust and optimize industrial structure while ensuring economic development, in order to gradually reduce the development gap with developed regions.

5. Conclusion and Policy Analysis

5.1. Research Conclusion

This study focuses on three provinces and one city in the Yangtze River Delta region, systematically exploring carbon quota allocation schemes under the principles of fairness priority, efficiency priority, and comprehensive consideration. The results show that

The equity priority plan is based on historical responsibility, and by introducing dynamic adjustment mechanisms and carbon debt transfer mechanisms, it significantly reduces the Gini coefficient of quota allocation between regions, from 0.35 to 0.11, reflecting strong fairness. However, this plan may suppress the emission reduction enthusiasm of high emission areas, resulting in insufficient overall emission reduction efficiency.

The efficiency priority plan is based on the ZSG-SBM model, which optimizes resource allocation through zero sum game theory, allowing efficient regions such as Jiangsu and Shanghai to obtain more quotas, and reducing the province's emission reduction costs by about 12.8% compared to the fairness plan. But its Gini coefficient reaches 0.40, exacerbating the quota gap between northern Anhui and coastal cities, and posing a risk of Matthew effect.

The comprehensive allocation scheme adopts the entropy method to integrate the principles of fairness and efficiency, with weights of 0.469 and 0.531, respectively. The results show that the Gini coefficient of this plan is 0.17, and the emission reduction cost is reduced by 19% -28% compared to a single plan. It not only guarantees the low-carbon transformation space of economically strong cities such as Shanghai and Jiangsu, but also reserves development rights for underdeveloped areas such as Anhui, achieving a coordinated optimization of efficiency and fairness.

5.2. Policy Suggestions

Based on research findings, the following policy recommendations are proposed:

Implementing a comprehensive quota allocation mechanism: It is recommended that the Yangtze River Delta region use the entropy based weighting scheme as the core framework, and dynamically adjust the weight parameters based on the differences in industrial structure, energy endowment, and emission reduction potential among provinces and cities. For example, increasing efficiency weights appropriately for efficient regions such as Shanghai and Jiangsu, and increasing fairness compensation coefficients for underdeveloped regions such as Anhui and Zhoushan, can alleviate regional development imbalances.

Building a collaborative mechanism for regional carbon markets: It is recommended to establish a cross regional carbon trading market mechanism to promote the transfer of carbon emission rights between quota surplus areas and industrial intensive areas through market-oriented means, in order to optimize resource allocation. Simulation shows that if the regional carbon price stabilizes at 30-60 yuan/ton CO_2, the total cost of emission reduction can be reduced by 25% -76%, while stimulating technological innovation and energy structure transformation of enterprises.

Strengthen dynamic monitoring and flexible adjustment: Introduce a carbon quota reserve pool system, reserving 5% -10% of quotas annually to cope with sudden emission fluctuations. Combining Monte Carlo simulation to regularly evaluate the robustness of allocation schemes, ensuring that the impact of parameter changes on quota structures is controllable.

Exploring ecological carbon sink compensation mechanism: incorporating the carbon sequestration capacity of natural ecosystems such as wetlands and forests in the Yangtze River Delta region into the carbon quota allocation consideration system. For example, for ecological functional zones such as Qiandao Lake in Zhejiang Province and Mount Huangshan in Anhui Province, quota incentives can be converted according to carbon sequestration to balance the demand for economic development under the industrial emission limitation policy and promote the dual realization of ecological protection and emission reduction goals.

Deepen cross regional governance cooperation: Establish a carbon data sharing platform in the Yangtze River Delta, unify carbon emission accounting standards and monitoring technologies, and avoid allocation disputes caused by differences in data caliber. At the same time, a low-carbon technology collaborative innovation fund will be established to focus on supporting clean energy substitution and energy efficiency improvement projects in the northern Anhui region, narrowing the regional cost gap in emissions reduction.

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