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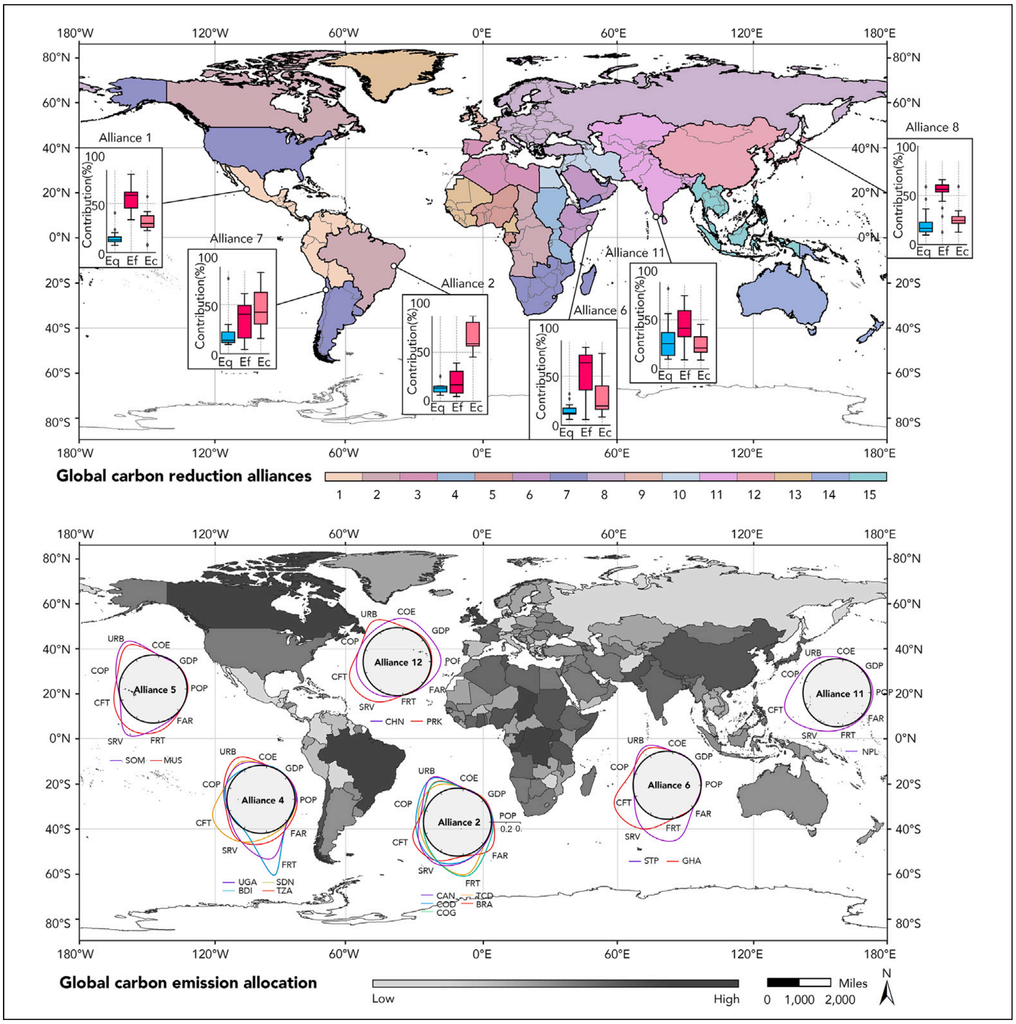

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Highlights

Framework for global carbon reduction and equitable rights distribution

Alliances focus on technology sharing and resource optimization for emissions

Intra and inter-alliance strategies boost global carbon trading

Strong-to-strong union and leadership-driven union cooperation strategies are gained

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Mapping carbon reduction: A cross-continental study of alliance strategies

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SUMMARY

Addressing the equitable distribution of global carbon emission rights is critical for sustainable development. Our research develops a detailed framework for a Global Carbon Reduction Alliance based on regional cooperation strategies, identifying key modes of intracontinental proximity and intercontinental distance collaboration. It emphasizes alliances formed among high carbon emission right countries and leadership-driven models propelling low carbon emission right countries, offering insights for optimizing emission reduction efforts. The analysis highlights the strategic role of developing nations in Africa and Asia, as well as developed regions in Europe and North America, advocating for the adoption of clean energy, enhancement of forest economic value, acceleration of urbanization, and an increased contribution of the service sector to the economy as essential pathways to achieving net-zero emissions. Our approach advocates for a comprehensive model of global carbon reduction cooperation, aiming at the equitable distribution of carbon emission rights and supporting the sustainable development goals.

INTRODUCTION

The Sustainable Development Goals (SDGs), integral to the 2030 Agenda for Sustainable Development, represent a collective call to global action for nurturing prosperity while safeguarding our planet. Endorsed unanimously in 2015 by all member states of the United Nations, these 17 goals embody a comprehensive blueprint for addressing a spectrum of global challenges.[1] Presently, we are navigating through the crucial United Nations Decade of Action 2020–2030, an initiative underscoring the need for globally concerted efforts and innovative solutions to fulfill the SDGs.[2] In concordance with the Paris Agreement's ambitious mandate[3] to achieve net-zero emissions in the latter half of the century, a growing contingent of countries is actively incorporating this objective into their national agendas, thereby charting pathways toward a carbon-neutral future. Data from the Energy & Climate Intelligence Unit as of 2023 indicate that 159 countries and regions have now pledged to "zero carbon" or "carbon neutrality" commitments.[4] Addressing carbon emissions, an issue that inherently transcends national frontiers, necessitates a synergistic approach within the international community, entailing coordinated strategies and actions at multiple levels.

Management of carbon emission rights, defined as the legal entitlements allocated to countries or entities to emit a specific amount of carbon dioxide, represents a critical mechanism in the global endeavor to regulate carbon emissions.[5] On one hand, this domain involves the quantification of emission objectives, thereby facilitating state and government-level oversight and control over carbon emissions.[6] On the other hand, the judicious allocation of these carbon emission credits is instrumental in promoting the efficient allocation and utilization of resources, a step crucial for achieving energy sector transformation and environmental preservation.[7] The distribution of these rights, directly linked to the extent of developmental latitude afforded to respective nations,[8] encompasses a series of complex challenges. Foremost among these is the principle of equitable distribution, a contentious and longstanding debate given the disparate economic development levels and carbon reduction responsibilities across varying nations and regions.[9] Furthermore, ensuring that the allocated carbon emission quotas do not unduly impede economic and social advancement, while concurrently catalyzing a societal transition to low-carbon models, represents a multifaceted issue, entangled with diverse influencing factors.[10] Lastly, the economic implications of reducing carbon emissions, which often necessitate a comprehensive overhaul of existing energy infrastructures and industrial frameworks, imply substantial financial commitments.[11] The aim of this research is to investigate a more equitable and effective framework for global carbon emission rights allocation, tackling the pressing challenges of worldwide carbon emissions. This study emphasizes the pivotal issues encountered by various nations and regions in allocating carbon emission rights, encompassing the equity of allocation principles, the integration of economic and societal growth, and the equitable distribution of carbon mitigation costs.

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Numerous countries and regions have formulated carbon emission rights allocation plans. The EU's carbon emission rights have been transformed from independent setting by member states to centralized allocation by the European Commission.[12] This has prompted the total carbon emission quotas to decrease year by year, and the cost of carbon emissions has gradually reduced.[13] The EU's allocation plan is based on the overall situation, but it will inevitably cause dissatisfaction among some member states. The United States does not have a unified national carbon emission rights allocation plan. Each state mainly distributes through auctions based on its own actual condition.[14] This can easily lead to different regions working independently, and there can also be issues such as compatibility. Due to the lack of accurate and reliable data, China's current allocation of carbon emission rights adopts an "ex post allocation" method,[15] which involves allocating carbon emission rights based on past emissions data rather than projected future emissions, highlights challenges in effective carbon emission control. It is difficult to control global carbon emissions at a macro level through national or regional control, and it is difficult to unify standards for various allocation plans. Therefore, some scholars conduct research on the distribution of global carbon emission rights based on principles such as emission reduction responsibility,[16] economic capacity,[17] and ecology.[18] The negotiation process for these allocations often encounters resistance from nations and regions that perceive the distribution as inequitable, a significant barrier to the progression of global emissions reduction dialogues. In this context, allocation strategies that integrate multiple principles, particularly those emphasizing fairness, are seen as enhancing both the flexibility and practicability of global carbon emission rights management.[19] This study transcends the perspective of individual nations or regions, proposing a global framework for carbon emission rights allocation, aimed at comprehensively addressing the challenges of global carbon emission management.

Commonly used carbon emission rights allocation methods include the Grandfathering and the Benchmarking. Under the Grandfathering, those to be allocated make vertical comparisons. Initially, the allocated carbon emission quotas are only based on the historical baseline annual carbon emission records,[20] and are further developed to superimpose emission reduction coefficients on historical emission levels to control the total amount of carbon emissions.[21] This method obviously violates the principle of fairness and in disguise rewards countries with high historical carbon emissions.[22] Under the Benchmarking, quota benchmark value is based on the industry's benchmark carbon emissions, according to the industry's technical level, emission reduction potential, emission control objectives and other comprehensive factors.[23] This method is fairer but may not accurately reflect diverse industry standards due to limited data and imperfect calculations, making it more suitable for industries with a single type of energy product.[24] Related research shows that multilateral cooperation can promote effectiveness in global energy governance.[25] It ensures participation in energy governance activities to a certain extent and can effectively promote cooperation between countries. In addition, Liu et al. proposed that the use of regional cooperative game strategy, which can strengthen cooperation and resource sharing between game subjects, and can also improve the effectiveness of scheduling between subjects.[26] It is conducive to raising the allocation of carbon emission rights to global considerations and reflecting the synergy between different regions. Therefore, relevant research on multilateral cooperation and cooperative games provides us with new ideas for conducting global carbon emission reduction research.

This study proposes the idea of building a carbon emissions alliance on a global scale in response to the problem that the lack of cooperation among countries and regions in reducing carbon emissions. The construction of the alliance can mainly (1) strengthen international cooperation to promote technological innovation, financial support and experience sharing; (2) on the basis of maximizing the protection of the development interests of member states, reasonably share emission reduction tasks and implement the principle of fairness; and (3) integrate the resources of member countries and fully tap the potential of carbon reduction. This study specifically studies the division of global carbon emission alliances, aiming to form a global carbon reduction cooperation network. In addition, by allocating the carbon emission rights within the alliance and each alliance, the carbon emission rights of each major country (region) are obtained. This approach positions the carbon alliance as a pivotal instrument for the equitable and effective distribution of carbon emission rights, ultimately leading to the development of a comprehensive global carbon emission rights map. The contribution of this research lies in offering an integrated framework that not only considers economic development but also addresses environmental protection, while presenting a viable approach for the equitable distribution of global carbon emission rights.

THEORETICAL FRAMEWORK

Principles of carbon emission rights allocation

The global climate crisis stems mainly from historical emissions of industrialized nations.[27,28] Recognizing differences in historical carbon emissions and economic conditions, equity demands a balanced carbon rights allocation.[29] The finite nature of carbon allowances necessitates their efficient allocation for optimal resource use. Countries must adopt cost-effective emission reduction measures, guided by efficiency.[30] Additionally, ecological principles call for economic growth that preserves ecosystems and biodiversity, integrating environmental conservation with development.[31]

This study employs fairness, efficiency, and ecology principles, as per the Sixth Report (AR6)[32] criteria of the Intergovernmental Panel on Climate Change (IPCC), to guide global carbon right allocation. It assesses sustainability across social, economic, and environmental dimensions, reflecting the carbon reduction resources and costs of nations, thus forming a comprehensive framework (Table 1).

(1) Fairness Principle: Emphasizing per capita equality, this principle ensures equal carbon rights worldwide,[33,34] often based on national population.[35] It also includes the ability-to-pay principle, where economically advanced regions bear more emission reduction responsibility.[36] GDP is used as an indirect capacity indicator for climate action.[37] The historical responsibility principle indicates that developed countries, with significant historical carbon emissions, should accordingly bear responsibility.[29,38] Therefore, under the fairness principle, a country's historical cumulative population, GDP, and historical cumulative carbon emissions serve as critical indicators.

Table 1. Indicator system of carbon emission rights allocation

Dimensions	Equity (Eq)	Efficiency (Ef)	Ecology (EL)
Society (Sc)	POP (x_1): Population (million individuals) is based on the *de facto* definition of population, which counts all residents regardless of legal status or citizenship.	URB (x_4): Urbanization (% of total population) refers to the proportion of the total population living in urban areas, as defined by national statistical offices.	SRV (x_7): The service employment percentage (% of total employment) is the share of working-age people working in sectors like retail, restaurants, and hotels.
Economy (Ec)	GDP (x_2): GDP (current US$) is the total value added by producers plus product taxes, minus excluded subsidies.	COP (x_5): Carbon productivity (US$/ton CO2) refers to the economic value generated per unit of carbon dioxide emitted.	FRT (x_8): Forest rents (% of GDP) are the economic value of forests based on the harvested timber amount.
Environment (Ev)	COE (x_3): Carbon dioxide emissions (kg per PPP $ of GDP) come from burning fossil fuels and making cement, including the use of solid, liquid, and gas fuels.	CFT (x_6): Access to clean fuels and technologies for cooking (% of population) means the percentage of people using clean fuels and technologies.	FAR (x_9): Forest area (sq. km) refers to land with natural or planted trees over 5 m tall, excluding trees in agricultural settings and urban areas.

(Note: The description of indicators is the same as the definition of the World Bank database).

(2) Efficiency Principle: Central to this principle is the optimization of the input-output ratio, where carbon emissions per unit of economic output serve as a critical efficiency metric.[39,40] This approach aligns carbon management with societal developmental imperatives. In parallel, the principle of feasibility is rigorously applied,[41] taking into account factors such as urbanization rates, energy infrastructure, and data accessibility. This ensures that emission reduction initiatives are economically viable. Indicators like the rate of urbanization, carbon productivity, and the share of clean energy usage are employed, striking a strategic balance between developmental goals and ecological sustainability. This methodology encapsulates a sophisticated approach to harmonizing economic growth with environmental stewardship.

(3) Ecological Principle: This principle prioritizes the sustainability of societal development, typically employing the proportion of the tertiary sector as a benchmark.[42] It extends beyond a human-centric approach in carbon emission rights allocation, advocating for the primacy of ecosystem rights. This approach demands the protection of ecosystem diversity and the maximization of ecological value in the allocation process. Drawing on the global valuation of ecosystem services as calculated by Costanza et al.,[43] Ferraro proposes the realization of market pricing and environmental benefits for emission rights through compensatory mechanisms.[44] Consequently, the ecological principle employs indicators such as the service employment percentage, forest rents, and forest area.

Theoretical models for carbon emission rights allocation

The global carbon reduction alliance involves various forms of collaboration like technology transfer, joint research, carbon trading, policy sharing, and financial aid among countries. It focuses on prioritizing and quantifying carbon reduction efforts among nations to collectively tackle climate change challenges by leveraging global resources and expertise. The likelihood of such cooperation increases with a nation's abundant carbon reduction resources and lower costs.[45] Developed countries with high emissions are now more likely to engage in sustainable technology and practice collaborations with developing nations, aiming not just to reduce emissions but also to foster sustainable growth in these countries. However, factors like geographical distance[46] and high labor costs[47,48] can increase the costs of carbon reduction, potentially reducing the feasibility of international cooperation. The probability of collaboration decreases with increasing distance and economic burdens. To address this, we propose the 'carbon reduction gravity model', an evolution of the traditional gravity model that incorporates labor costs alongside distance. This model aims to offer a more comprehensive view of international carbon reduction cooperation, considering socio-economic, environmental, and logistical factors, and providing insights into the complex dynamics of global climate governance.

The essence of global carbon emission rights allocation is the game of national interests.[49,50] Countries can play a greater role in reducing carbon emissions by forming cooperative alliances, making the overall interests better than without cooperation. Allocation with the help of cooperative game theory can not only guarantee collective rationality and pursue efficiency, fairness and justice in the allocation of carbon emission rights, but also avoid vicious competition that may be caused by non-cooperative game in multi-country situations,[51,52] that is, countries sacrifice global interests for independent interests. The allocation of carbon emission rights based on each country's contribution to the global carbon reduction target is considered to be theoretically justified.[53–55]

RESULTS

Division of global carbon emission reduction alliance

This study reveals two primary patterns of carbon reduction cooperation among nations (Figure 1). The first pattern involves geographically adjacent countries collaborating, such as Poland, Belarus, and Romania with Ukraine in Europe; Ethiopia, Kenya, and Tanzania with Somalia in Africa; and Thailand, Laos, and Myanmar with Vietnam in Asia. This proximity-based cooperation helps in minimizing the costs associated with

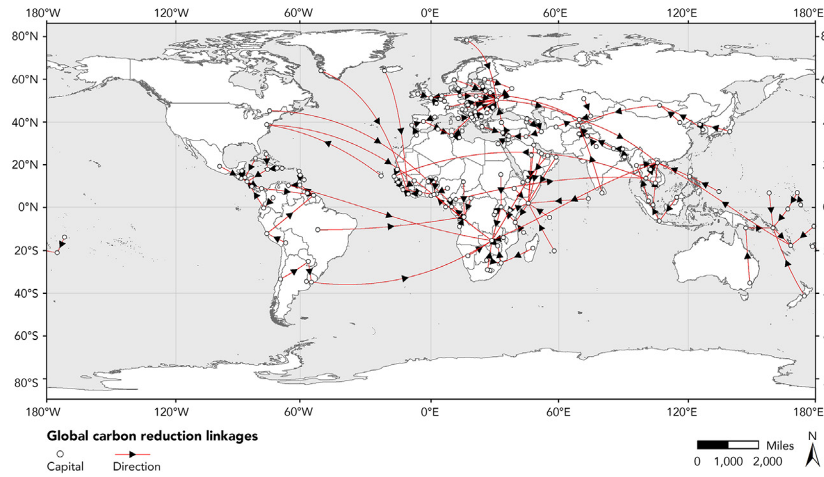

Figure 1. Vector map of carbon reduction linkages

Substitute the index weight into the improved carbon reduction gravity model to obtain the carbon emission reduction linkage of each country with other countries. The maximum of the linkage between each country is taken to get the country that is most likely to cooperate in carbon reduction in each country. The relationship is mapped to the map to get the vector map of national carbon reduction cooperation, the red line represents the linkage between countries, and the arrow represents the direction of carbon reduction cooperation.

carbon reduction efforts. The second pattern is transcontinental cooperation, exemplified by Brazil in South America partnering with the Democratic Republic of Congo in Africa, the United States in North America with Mali in Africa. This indicates that factors like carbon reduction capacity and associated costs also play a pivotal role in shaping these alliances, beyond just geographical proximity. This study, therefore, suggests that the decision-making process in establishing carbon reduction collaborations is influenced by a strategic assessment of these interrelated factors, rather than being predominantly dictated by geographical closeness.

The boundaries of the Carbon Emission Reduction Alliance delineate a unique framework that diverges from traditional political, geographical, economic, cultural, and ecological divisions. This alliance emerges from a multilateral perspective on carbon reduction cooperation, factoring in the costs, resources, and potential for collaboration among countries, thereby forging a more efficacious pattern of carbon emission reduction (Figure 2).

The composition of each alliance varies, reflecting the varying intensity of carbon reduction linkages among countries. Alliance 8 boasts the highest number of participating countries, totaling 29, predominantly located in Europe, including Germany, Italy, Poland, Sweden, and Switzerland. Conversely, Alliance 12 encompasses the smallest group, limited to just five East Asian nations: China, Japan, South Korea, North Korea, and Mongolia. Interestingly, some alliances possess enclave-like characteristics; for instance, Alliance 2 spans across seven countries in Africa, North America, and South America, Alliance 7 includes 18 countries distributed over South America, North America, Africa, and Asia, and Alliance 13 comprises 12 countries across Africa, Europe, and North America.

A broad overview of the 15 alliances indicates that those in Asia, Europe, and Oceania have more cohesive boundaries with higher national aggregation. In contrast, alliances in Africa, North America, and South America exhibit more fragmented boundaries with pronounced enclaves, reflecting an imbalanced distribution of carbon reduction resources and costs among member countries (e.g., Alliances 1, 2, 7, etc.). This necessitates transcontinental cooperation with distant countries to maximize carbon reduction efficacy.

Global distribution of carbon emission rights

Allocation in alliances

In the global context, Alliance 8 has secured the highest proportion of carbon emission rights, accounting for 10.88%, approximately 2.5 times greater than that of Alliance 9, which holds the lowest at 4.27% (Table 2). Notably, the distribution of carbon emission rights among alliances does not exhibit a direct correlation with the number of constituent countries. For instance, Alliance 1, comprising 25 countries, allocates only 6.89% of carbon emission rights, whereas Alliance 2, with merely 7 countries, surpasses this with an allocation of 9.78%. Under a cap-and-trade system, the formation of cooperative alliances for the distribution of carbon emission rights proves advantageous in maximizing the utilization of existing carbon credit pools, ensuring that the collective benefit of the alliance surpasses the sum of individual gains of the member countries.

Regarding carbon emission rights, the total carbon emission rights of alliances 8, 2, 7, 6, 11, and 1 account for more than half (51.10%) of the world's total, making them high carbon emission rights alliances. The contribution of the fairness, efficiency and ecological principles of carbon emission rights allocation to the high-carbon emission rights alliance is shown in Figure 2. The efficiency and ecological allocation principles play a greater role in the current international carbon reduction. These alliances can be roughly divided into efficiency-oriented, ecological-oriented and efficiency-ecological co-oriented. The efficiency-oriented type is represented by alliances 8, 6, 11 and 1. The carbon

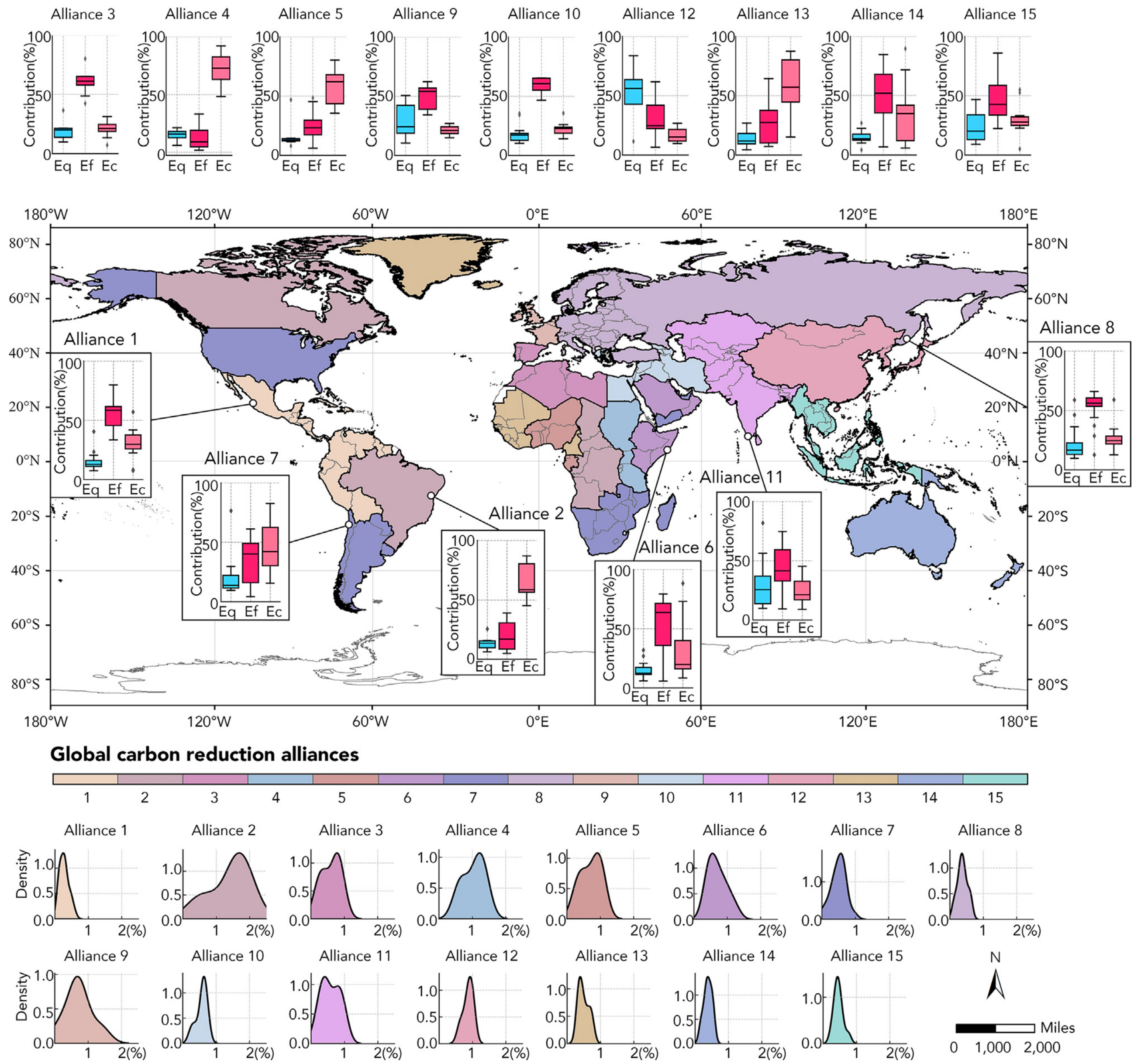

Figure 2. Global Carbon Reduction Alliances Distribution Map

This map clusters countries into 15 global 'carbon reduction alliances' based on their maximum carbon reduction linkage. Around the global map, boxplots represent the contribution of carbon emission rights allocation principles (equality (Eq), efficiency (Ef), and ecological (Ec)) for Alliances 8, 2, 7, 6, 11, and 1. These plots illustrate how each principle contributes to the allocation of high-carbon emission rights, with the horizontal axis indicating the principles and the vertical axis showing the proportion of each principle's contribution. Additionally, the kernel density estimation curves for each alliance are presented under the chart to explore the distribution structure of carbon emission rights within the alliances. The horizontal axis denotes the carbon emission rights allocation rate, indicating the proportion of rights allocated to each country in an alliance. The vertical axis represents the distribution density of these rates, with higher values indicating a higher frequency of a particular rate in the dataset, reflecting a greater number of countries in the alliance with that specific carbon emission rights allocation rate.

emission rights contributed by the efficiency principle account for 56.14%, 63.51%, 41.46% and 58.40%, while the contributions of the fairness and ecological principles are slightly lower and both are in Between 10% and 30%, these alliances play a major role in the allocation of carbon emission rights, such as urbanization rate, carbon productivity and proportion of clean energy use that symbolize the country's carbon reduction efficiency. The ecologically oriented type is represented by Alliance 2, whose ecological principle contributes significantly, reaching 58.75%, while the fairness and efficiency contribute less, only 13.53% and 16.97%. In the carbon reduction of the alliance, the indicators

Table 2. Analysis of carbon alliance for countries (regions)

Alliance	Number of countries (regions)	Countries (regions)	Allocation (%)
1	25	Antigua and Barbuda, Bahamas, Barbados, Belize, Bolivia, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Peru, Suriname, Trinidad and Tobago, Venezuela	6.89
2	7	Angola, Brazil, Canada, Central African Republic, Chad, Republic of the Congo, Democratic Republic of the Congo	9.78
3	9	Algeria, Andorra, Kiribati, Libya, Malta, Morocco, Portugal, Spain, Tunisia	5.36
4	6	Burundi, Comoros, Rwanda, Sudan, Tanzania, Uganda	6.19
5	9	Benin, Burkina Faso, Equatorial Guinea, Gabon, Ghana, Niger, Nigeria, São Tomé and Príncipe, Togo	6.39
6	11	Bahrain, Ethiopia, Kenya, Kuwait, Maldives, Mauritius, Oman, Qatar, Saudi Arabia, Seychelles, Somalia	7.70
7	18	Argentina, Botswana, Cape Verde, Chile, Djibouti, Lesotho, Madagascar, Malawi, Mozambique, Namibia, Paraguay, South Africa, United Arab Emirates, United States, Uruguay, Yemen, Zambia, Zimbabwe	8.87
8	29	Albania, Austria, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Finland, Germany, Hungary, Italy, Latvia, Lithuania, Moldova, Montenegro, Norway, Poland, Romania, Russia, Serbia, Slovakia, Slovenia, Svalbard and Jan Mayen, Sweden, Switzerland, Turkey, Ukraine	10.88
9	6	Belgium, France, Ireland, Luxembourg, Netherlands, United Kingdom	4.27
10	12	Armenia, Azerbaijan, Cyprus, Egypt, Georgia, Greece, Iran, Iraq, Israel, Jordan, Lebanon, Syria	6.77
11	12	Afghanistan, Bangladesh, Bhutan, India, Kazakhstan, Kyrgyzstan, Nepal, Pakistan, Sri Lanka, Tajikistan, Turkmenistan, Uzbekistan	6.98
12	5	China, Japan, South Korea, North Korea, Mongolia	4.34
13	12	Cameroon, Côte d'Ivoire, Gambia, Greenland, Guinea, Guinea-Bissau, Iceland, Liberia, Mali, Mauritania, Senegal, Sierra Leone	5.97
14	12	Australia, Fiji, Federated States of Micronesia, Nauru, New Zealand, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, Vanuatu, Marshall Islands	4.58
15	11	Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Palau, Philippines, Singapore, Thailand, Vietnam	5.05

Calculate the carbon reduction marginal contribution of each alliance through the Shapley value of the cooperative game model to obtain the alliance's carbon emission rights distribution ratio.

symbolizing carbon reduction ecology such as the economic proportion of the tertiary industry, forest lease income and forest area play an important role. The efficiency and ecology co-leading type is represented by Alliance 7, with high efficiency and ecological principles, 40.20% and 42.25% respectively. The carbon reduction efficiency and ecology of this alliance play a synergistic role in the carbon reduction process.

The kernel density estimation curves of alliances 1, 7, 8, 10, 12, 13, 14, and 15 show the characteristics of small span, high peak value and left-skewed distribution (Figure 2), indicating that the distribution of carbon emission rights is relatively average and lower than the average value, that is, the carbon emission rights of all countries in the alliance are lower. For example, the carbon emission rights allocation rate of the 29 countries in Alliance 8 is mostly concentrated at 0.37%, and the carbon emission rights allocation rate of the 25 countries in Alliance 1 is mostly concentrated at 0.28%. The kernel density curves of alliances 2, 3, 4, 5, 6, 9, and 11 have the characteristics of large spans and low peaks, indicating that there are large differences in the allocation of carbon emission rights among countries within these alliances. Among them, the curve distribution of alliances 2 and 4 is skewed to the right and concentrated at 1.65% and 1.23%, indicating that these two alliances contain more countries with high carbon emission rights allocation. In addition, distribution differences within alliances can be seen from the uni-modal or multi-modal characteristics of the curve. For example, the carbon emission rights allocation rates of Alliances 3, 4, 5, 11 and 13 show a bimodal distribution, which means that there are two different extreme values of carbon emission rights within the alliance. For example, in Alliance 4, the carbon emission rights of some countries are concentrated at 0.65%, the other part is concentrated at 1.23%. The results of the kernel density estimation curve show that the carbon emission rights of countries in the alliance are not necessarily positively correlated with the alliance's carbon emission rights, but depend on the carbon emission rights allocation structure within the alliance.

Allocation in countries (regions)

The geographic spatial distribution of global carbon emission rights exhibits a pronounced polarization pattern, with notable polarization centers in Northern North America, Eastern South America, Western Europe, Central Africa, and Eastern Asia (Figure 3A). There exists a substantial disparity in carbon emission rights among nations, with Canada (CAN) holding the highest carbon emission rights (indicated by the darkest color in the figure), which is 172 times greater than that of Zimbabwe (ZWE) (represented by the lightest color in the figure).

In order to analyze the characteristics of countries and regions where carbon emission rights are concentrated, representative countries with the top 10% of global carbon emission rights allocation rates were analyzed (Table 3). The allocation of carbon emission rights for these countries ranges from 0.96 percent to 2.02 percent. Geographically, these countries are mainly concentrated in Africa (Chad, Congo, Uganda, Burundi, Somalia, Sudan, SAO Tome and Principe, Tanzania, Mauritius, Ghana, Tunisia) and Asia (China, North Korea, Nepal and Tunisia), with the remaining three countries located in North America (Canada), South America (Brazil) and Europe (United Kingdom). This suggests that the main geographical areas for cooperative carbon reduction in the future are located in Africa and Asia.

Upon examining carbon emission rights allocations within specific carbon reduction alliances, it emerges that among countries with high allocation rates, five are members of Alliance 2, and four are part of Alliance 4. This pattern indicates that the collaborative efforts within these alliances are particularly effective, demonstrating alliances formed amongst high carbon emission right countries. In contrast, other alliances such as 5, 6, and 12 each encompass two countries with significant emission rights, while Alliances 3, 9, and 11 have one such country each. This suggests that in these alliances, individual countries play a pivotal role in driving the overall carbon reduction efforts, embodying a leadership-driven model propelling low carbon emission right countries.

In terms of developmental status, among these countries, 16 are classified as developing nations, with only Canada and the United Kingdom being developed countries. This highlights a growing trend where more developing countries, possessing larger potential for carbon emission allowances, are expected to take on increased responsibilities in carbon reduction, integrating more actively into global carbon mitigation strategies.

In analyzing high carbon emission right countries, we observed a distinct pattern of indicators driving carbon emission rights allocation (Figure 3B). Key indicators, such as FRT and CFT, significantly influence these allocations. For example, Burundi, Uganda, and the Republic of Congo predominantly rely on FRT, while Mauritius, Nepal, and Tunisia are guided by CFT. Some countries exhibit mixed influences from multiple indicators. Canada and São Tomé and Príncipe are shaped by URB and SRV indicators; Somalia by FRT and SRV; Sudan by CFT and SRV; and the United Kingdom by URB, CFT, and SRV. This pattern highlights the importance of clean energy, forest value, urbanization, and service sector growth in acquiring higher carbon emission rights.

Notably, in high carbon emission right countries, POP, GDP, and COE generally have a minimal impact under equity principles. However, China is an exception, with these indicators each contributing around 20%. This highlights China's large population, rapid economic growth, and significant historical carbon emissions, factors that collectively influence its global carbon emission rights allocation. China's role reflects its importance in global carbon mitigation efforts and its critical responsibility toward achieving the global net-zero emission target.

DISCUSSION

In this study, we have explored the intricacies of global carbon reduction cooperation, identifying two primary modes: intraregional, based on geographical proximity, and intercontinental, driven by resource optimization. These models echo existing frameworks like the EU ETS and the UNFCCC's CDM, fostering international collaboration and efficiency in carbon reduction.

In response to the unique challenges of each carbon emission alliance, tailored strategies are essential to enhance global carbon reduction efforts. High carbon-emitting alliances, such as Alliances 8, 2, and 7, should prioritize sharing advanced technologies and resources, particularly in clean energy and carbon capture, to improve overall reduction efficiency. Alliances with evenly distributed carbon rights, like Alliances 1 and 8, would benefit from enhanced cooperative mechanisms, including carbon trading systems within the alliance, to maximize the reduction potential of each member. For alliances with uneven carbon rights distribution, such as Alliances 2, 4, 5, 6, 9, and 11, differentiated strategies are needed to address the diverse reduction capacities, balancing economic growth with environmental sustainability. Moreover, alliances with a bimodal distribution of carbon rights, such as Alliances 3, 4, 5, 11, and 13, require internal balancing strategies, potentially involving financial support or technical assistance to bolster the reduction capabilities of lower-emitting countries.

The study presents a unique contribution by detailing carbon rights allocation strategies, particularly focusing on precise intra-alliance cooperation and inter-alliance carbon rights exchange. This fosters global carbon trading, creating a unified platform for carbon finance, technology, and resources. For instance, intra-alliance collaboration ensures effective circulation of carbon rights, while inter-alliance trading promotes two-way flow of carbon rights and technology. These strategies not only improve the fairness and efficiency of carbon right allocation but also offer new insights into the equitable distribution of global carbon resources.

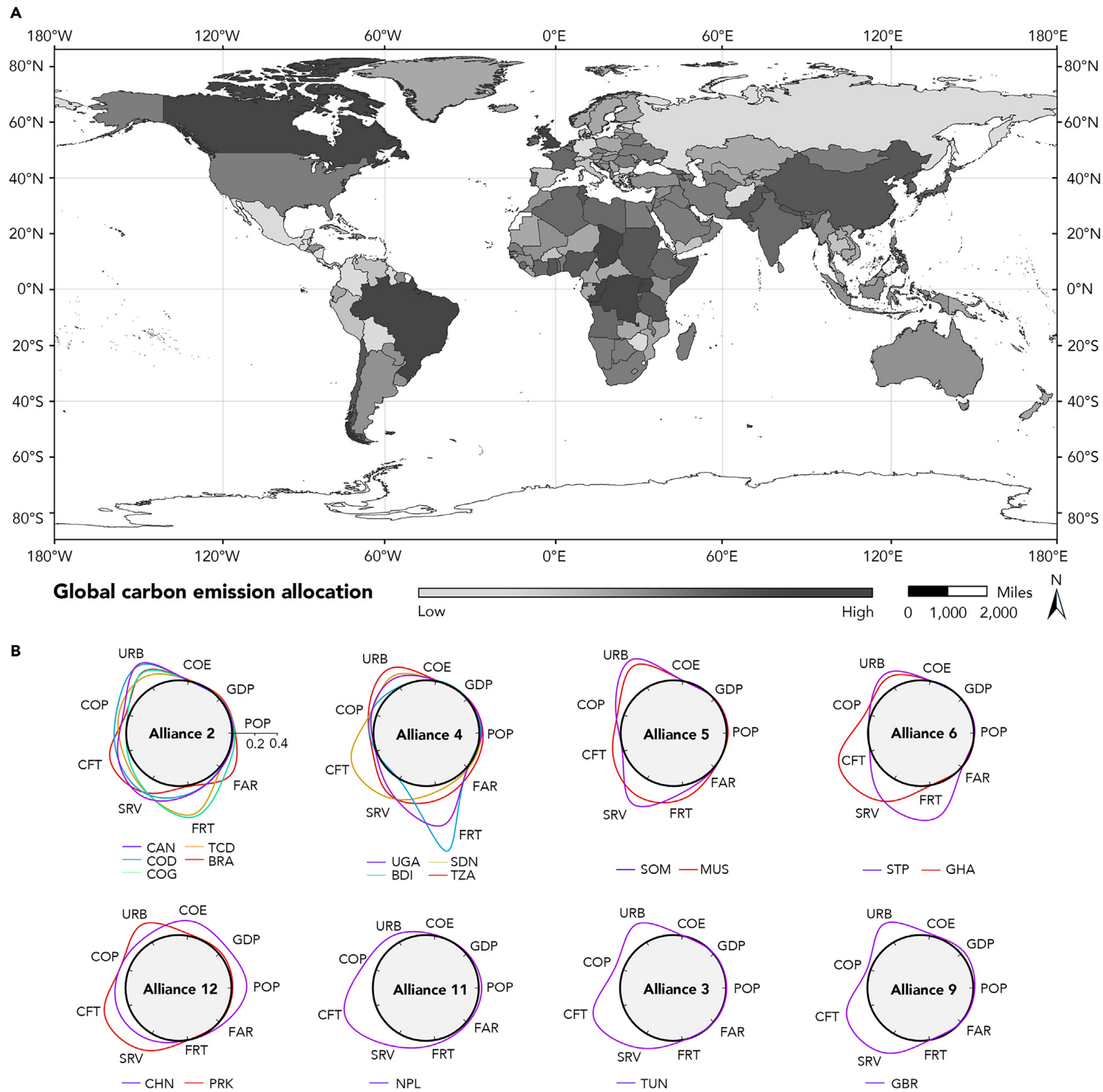

Figure 3. Map of global carbon emission allocation

(A)The Shapley value calculation is performed on each alliance to obtain the carbon emission rights allocation results of countries around the world.

(B) Radar map of the contribution of high carbon emission rights countries' alliances and carbon emission rights allocation indicators. The contribution of all carbon emission allocation indicators is normalized to 0–1, where the maximum contribution of each indicator is re-scaled to 1, and 0 remains 0. The different colors in the figure represent different countries within the same alliance.

In response to the global distribution of carbon emission rights, the following potential solutions are proposed to augment global carbon reduction efficiency: African and Asian nations, such as Tanzania, Mauritius, China, and Nepal, are urged to strengthen renewable energy collaborations, particularly in solar and wind power, leveraging their vast potential. Developed countries, notably Canada and the UK, are advised to initiate carbon capture and storage (CCS) technology transfer projects with these regions, harmonizing advanced technology with local emission reduction needs. For nations predominantly influenced by FRT and CFT indicators like Uganda and Congo, forest conservation and sustainable management practices are essential to enhance carbon sequestration capabilities. Additionally, countries such as Canada and the UK should be supported in implementing sustainable urbanization and

Table 3. Carbon emission rights allocation rate of top 10% countries (regions)

Ranking	Country (Region)	Alliance	Allocation (%)	Continent	Developed or not
1	Canada	2	2.02	North America	True
2	Democratic Republic of the Congo	2	1.67	Africa	False
3	Congo	2	1.67	Africa	False
4	Chad	2	1.63	Africa	False
5	Brazil	2	1.61	South America	False
6	United Kingdom	9	1.37	Europe	True
7	Uganda	4	1.37	Africa	False
8	Burundi	4	1.27	Africa	False
9	Somalia	6	1.23	Africa	False
10	Sudan	4	1.21	Africa	False
11	São Tomé and Príncipe	5	1.06	Africa	False
12	Tanzania	4	1.05	Africa	False
13	Mauritius	6	1.02	Africa	False
14	Ghana	5	1.00	Africa	False
15	China	12	0.99	Asia	False
16	North Korea	12	0.99	Asia	False
17	Nepal	11	0.98	Asia	False
18	Tunisia	3	0.96	Africa	False

In order to reveal the driving factors of high carbon emission rights, an indicator correlation analysis was conducted on the countries with the top 10% of global carbon emission rights allocation rates.

service sector strategies to facilitate a low-carbon economic transition. Lastly, for multi-indicator-driven countries, collaborative reduction incentives, including participation in carbon trading markets, are recommended to fully realize their comprehensive reduction potential.

Limitations of the study

Addressing the challenges such as policy alignment and technical transfer difficulties in global carbon reduction cooperation is crucial. Future research should focus on developing more effective international cooperation mechanisms, ensuring equitable and effective collaboration between developed and developing countries. This entails a comprehensive approach considering economic, political, and environmental factors to realize long-term global carbon reduction objectives. However, the limitations of this study lie in its inability to delve into specific strategies and methods to overcome these challenges. For instance, coordinating policies across different countries and regions, overcoming specific hurdles in technical transfer, and quantifying and assessing the effectiveness of cooperation mechanisms are areas that need further exploration in future research. Moreover, given the urgency of global climate change, research must also identify and promote effective emission reduction measures more swiftly to address this global challenge.

STAR★METHODS

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AUTHOR CONTRIBUTIONS

C.Z., B.Z., and Z.W. designed research; C.Z. and B.Z. performed research; X.X. contributed new reagents/analytic tools; C.Z., B.Z., and X.X. analyzed data; and C.Z. and B.Z. wrote the paper.

DECLARATION OF INTERESTS

The authors declare no competing interest.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Global population data	World Bank	https://data.worldbank.org
Global GDP data	World Bank	https://data.worldbank.org
Global carbon dioxide emissions data	World Bank	https://data.worldbank.org
Global urbanization data	World Bank	https://data.worldbank.org
Global carbon productivity data	World Bank	https://data.worldbank.org
Global access to clean fuels and technologies for cooking data	World Bank	https://data.worldbank.org
Global service employment percentage data	World Bank	https://data.worldbank.org
Global forest rents data	World Bank	https://data.worldbank.org
Global forest area data	World Bank	https://data.worldbank.org
Global labor costs data	World Bank	https://data.worldbank.org
Software and algorithms		
Grasshopper	RHINO	https://www.grasshopper3d.com
ArcGIS	ESRI	https://www.arcgis.com/index.html

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Bifeng Zhu (512126134@qq.com).

Materials availability

This study did not generate any new physical materials.

Data and code availability

- Data: This paper uses existing publicly available data. These datasets are listed in the key resources table.
- Code: This paper does not report original code.
- All other requests: Any additional information required to reanalyze the data reported will be shared by the lead contact upon request.

EXPERIMENTAL MODEL AND SUBJECT DETAILS

This article does not contain any studies with all the experimental models (animals, human subjects, plants, microbe strains, cell lines, primary cell cultures) performed by any of the authors.

METHOD DETAILS

This research is structured into two segments: forming carbon emission alliances and assigning emission rights. It starts with the collection of data for 184 countries from sources like the world bank (Table 1). The entropy weight method is used to calculate weights for social, economic, and environmental indicators of each nation, aiming for an objective approach. An advanced carbon reduction gravity model then assesses the carbon reduction linkages between countries, considering factors like economic capacity, environmental resources, geographical proximity, and labor costs. This model guides the formation of optimal carbon alliances (Figure 2) by pairing countries based on their maximum linkage (Figure 1), indicating potential for effective collaboration in carbon reduction. Following this, the study utilizes the Shapley Value method from game theory to allocate carbon emission rights within these alliances, taking into account each country's contribution and potential in reducing carbon emissions (Figure 3).

EWM (ENTROPY WEIGHT METHOD)

In order to avoid the interference of subjective factors, this study uses the entropy weight method[56] to calculate the weights of the nine indicators related to carbon emission rights. The calculation process is as follows:

a. data normalization. Establishing 9 indicators (x_{1-9}) matrix X for 184 countries. V_{ij} represents the normalized result of j indicators of the i-th country, x_{ij} represents the original value of the j-th indicator of the i-th country. x_{max} represents the maximum raw value of this indicator in all regions, x_{min} represents the smallest original value of this indicator in all regions.

$$X = \begin{bmatrix} x_{1,1} & \cdots & x_{1,j} \\ \vdots & \ddots & \vdots \\ x_{1,j} & \cdots & x_{i,j} \end{bmatrix} (\mathrm{i} = 1, 2, 3, \ldots\ldots, 184;\ \mathrm{j} = 1, 2, 3, \ldots\ldots, 9) \quad \text{(Equation 1)}$$

$$V_{ij} = \frac{x_{ij} - x_{min}}{x_{max} - x_{min}} \quad \text{(Equation 2)}$$

b. index normalization. Probability of indicators p_{ij}.

$$p_{ij} = \frac{V_{ij}}{\sum_{i=1}^{n} V_{ij}} \ (i = 1, 2, 3, \ldots, n; j = 1, 2, 3, \ldots, 9) \quad \text{(Equation 3)}$$

c. entropy value calculation of each indicator. E_j represents the information entropy value of the j indicator。

$$E_j = -\frac{1}{\ln n} \sum_{i=1}^{n} p_{ij} \times \ln p_{ij} \ (j = 1, 2, 3, \ldots, 9) \quad \text{(Equation 4)}$$

d. weighting calculation. g_j represents the Information utility value of the j indicator， ω_j represents the weight of the j indicator，W is the target weight vector for all indicators.

$$g_j = 1 - E_j \ (j = 1, 2, 3, \ldots, 9) \quad \text{(Equation 5)}$$

$$\omega_j = \frac{g_j}{\sum_{j=1}^{m} g_j} (j = 1, 2, 3, \ldots, 9) \quad \text{(Equation 6)}$$

$$W = (\omega_1, \omega_2, \ldots, \omega_9)^T \quad \text{(Equation 7)}$$

CARBON REDUCTION GRAVITY MODEL

To calculate the linkage of carbon reduction capacity, resources, and costs between countries, we have enhanced the traditional gravity model. Our proposed carbon reduction gravity model comprehensively takes into account the carbon reduction capabilities and resources of each country (or region) across social, economic, and environmental dimensions, as well as the carbon reduction costs related to geographical proximity and labor costs. The model posits that the carbon reduction linkage between countries is directly proportional to their carbon reduction abilities and existing resources, and inversely proportional to the geographical distance and labor costs of each country. For details, see Equation 8.

$$CRL_{ij} = \frac{\sqrt[3]{Sc_i Ec_i Ev_i} \times \sqrt[3]{Sc_j Ec_j Ev_j}}{D_{ij}^2 \times L_i L_j} \quad \text{(Equation 8)}$$

In Equation 8, CRL_{ij} (Carbon Reduction Linkage) represents the carbon reduction linkage between country i and country j. *Sc*、*Ec*、*Ev* represent the carbon emission reduction capacity and resources of social, economic and environmental dimensions respectively, which are obtained by summing the index by multiplying the weight; D_{ij} stands for the distance of countries i and j, usually the geographical distance between capitals; L_i and L_j represent the labor costs of countries i and j.

SHAPLEY VALUE

Multilateral cooperation among countries is needed to exert the synergistic effect of carbon reduction. In this study, Shapley Value method[57] in game theory is adopted to calculate the contribution of each country to the global carbon reduction goal, and the allocation ratio of carbon emission rights is determined according to the degree of contribution. This game theory has some advantages in dealing with our research problem, it can integrate the principles of equity, efficiency and ecology by taking into account synergies between different regions,[58] and many studies have concluded that collaborative emissions reductions bring more benefits than emissions reductions alone.[58–60]

This study includes two stages of allocation, the first is to allocate 15 alliances around the world, and then the second allocation is to the countries included in each alliance, and finally the carbon emission rights allocation ratio of each country is obtained. This study uses the $\sum CRL_{ij}$ (Carbon Reduction Linkage) and $\sum ACI_i$ (Abatement Capacity Index)[61] (Equation 9) of countries in each carbon reduction alliance to determine the (Characteristic function) $v(s)$ (Formula 10) of allocation of carbon emission rights of each country in the carbon reduction alliance., that is, cooperation between countries with greater carbon emission reduction potential and higher carbon emission reduction linkage can play a greater role in carbon reduction. In the formula, Eq_i、 Ef_i、 El_i represents the carbon reduction equity, efficiency and ecological index of country i in the carbon reduction alliance, which is obtained by summing up the corresponding indicators multiplied by the weight; $v(s)$ is a characteristic function of multilateral cooperation and represents the marginal contribution of each country in cooperative carbon reduction.

$$ACI_i = Eq_i + Ef_i + El_i \quad \text{(Equation 9)}$$

$$v(s) = \sum_{i \in s} ACI_i \sum_{i,j \in s} CRL_{ij} \quad \text{(Equation 10)}$$

Then the Shapley value is calculated, as shown in Equations 11, 12, and 13. $\omega(|s|)$ in the formula represents the weighting factor; n represents the total number of carbon reduction alliances (countries); $|s|$ represents the number of countries in each subset; $\varphi_i(v)$ represents the Shapley value of the Carbon Reduction Alliance (country) i; Q_i represents the proportion of country i in the global carbon emission quota.

$$\omega(|s|) = \frac{(n - |s|)!(|s| - 1)!}{n!} \quad \text{(Equation 11)}$$

$$\varphi_i(v) = \sum_{s \in S_i} \omega(|s|)[v(s) - v(s \backslash \{i\})] \quad \text{(Equation 12)}$$

$$Q_i = \frac{\varphi_i(v)}{\sum_i \varphi_i(v)} \quad \text{(Equation 13)}$$

QUANTIFICATION AND STATISTICAL ANALYSIS

We take the distribution of global carbon emission rights as the research content, and take 184 countries as the research objects, which cover almost all the major economies and land areas except the Arctic and Antarctic, and can reflect the global carbon emission reduction situation. The data of the carbon emission rights allocation indicator system mainly comes from the public World Bank database, including the cumulative total population, GDP, carbon dioxide emissions, urbanization rate, carbon productivity, access to clean fuels and technologies for cooking, service employment percentage, forest rents, forest area and labor costs. Population and carbon emission data are selected from 1990 to 2020, because 1990 is a key year for studying greenhouse gases, and the national structure has been relatively stable since then, making it easier to trace emission responsibilities. Because the remaining indicators need to reflect the latest situation of the country, 2020 is used as a reference and the average value of the data of each indicator in the past five years (2016–2020) is taken. The relative distances between countries are obtained by calculating the distances between the capitals of the countries using ArcGIS software.

ADDITIONAL RESOURCES

This study did not generate additional resources.