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Research Article

Modeling Intercity CO_2 Trading Scenarios in China: Complexity of Urban Networks Integrating Different Spatial Scales

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Today, cities account for the majority of global energy consumption and CO_2 emissions. The interaction between cities is critical for regional low-carbon development. At this time, China has turned to the full opening of the carbon trading market as an important policy tool for achieving its ambitious emission reduction goals. This paper attempts to explore the spatial relationships among cities from the perspective of carbon trading. A "multiscenarios across different spatial scales" analysis framework applied to the allocation and trading of CO_2 emission quotas among cities in China is proposed. Based on this framework, the carbon trading networks of 182 cities in China are specifically simulated under four different scenarios, with a comparative analysis of the networks' complexity made from different perspectives. The results of the study are as follows: firstly, significant spatial network correlations exist between the cities' carbon trading under each scenario. Secondly, on a national scale, there are more inner connections in carbon trading networks, with stronger correlations and robustness, while the degree of connection of intercity carbon trading is higher overall on a regional scale. Thirdly, on a national scale, no obvious core nodes exist in the network, while core nodes do exist in the overall network and in each region under the regional scale. Fourthly, cities in the central region have the highest core position overall. Finally, based on the research results, practical guidance in using the framework for achieving carbon reduction, promoting economic growth, and balancing regional development, as well as the important inspiration for policy formulation, is further discussed.

1. Introduction

Economic development and human activities have led to a sharp rise in greenhouse gas emissions; carbon emissions now account for approximately 75% of total emissions [1]. It is projected that, by 2030, global carbon emissions will be 30% higher than they were in 2010 [2]. In the context that climate change has threatened human survival and sustainable development [3], reducing carbon emissions has become a consensus priority for all countries in the world. Under the guidance of the United Nations, governments have made and implemented corresponding emission reduction policies, such as the carbon emissions trading systems in China and Europe. These systems have proven to be an effective way to achieve emission reduction targets [4]. Furthermore, rapid urbanization has resulted in cities becoming major consumers of energy and the main emitters of CO_2 all across the world [5]. Cities account for more than 80% of China's energy consumption and carbon emissions, meaning that cities are a key area for implementing carbon reduction policies [6]. With the rapid development of urbanization and industrialization, there will inevitably be more big cities in China. Developing low-carbon cities is an inevitable choice if China is to implement its ambitious goals and meet the low-carbon commitments as promised at international conventions [7]. Therefore, learning how to effectively reduce urban carbon emissions is an urgent need and a key challenge for the implementation of climate change mitigation and carbon emission reduction policies.

China is the world's largest energy consumer and CO_2 emitter, generating 20% of the world's primary energy consumption and 30% of its CO_2 emissions [8, 9]. As a responsible nation of power, China has made a series of solemn commitments to climate change mitigation [10]. China pledged to reduce CO_2 emissions per unit of GDP by 60%–65% by 2030 (compared to 2005) and increase the proportion of nonfossil energy in primary energy consumption to 20%. China announced to peak carbon emissions by 2030 and achieve carbon neutrality by 2060. Studies on carbon emission and reduction, as well as China's integration into global environmental protection, have received increasing attention from the academic community. Existing research on carbon emission has mainly focused on carbon emission accounting [11], carbon emission efficiency [12], and the factors that influence and drive carbon emissions [13]. Previous research on carbon emission reduction has mainly included examining the impact [14], strategy, and path analysis of carbon emission reduction [15]. One of the most significant achievements in the implementation of China's carbon emission reduction is the establishment of the pilot carbon trading system [16]. The operation of the pilot carbon markets has led to a remarkable reduction in carbon emissions in the pilot areas [17]. It has also accumulated valuable experience for the construction of China's national carbon market [18]; it was on this basis that the national carbon market came into being. Research on carbon trading has gradually become a hot topic. Such studies mainly include the review of and prospects for the carbon trading market [16], the evaluation of carbon trading pilot programs [19], the impact of carbon markets on the economy, energy and the environment [20], and the design and optimization of carbon trading system [21]. In the final topic, the allocation of carbon emission quotas [22] and the prediction of carbon prices [23] have received most of the attention. However, China's carbon market is still in its infancy, with many flaws [24]; related research is also quite limited and mostly conducted on the national or provincial level. To ensure that China's carbon emission reduction targets are successfully achieved, the total carbon emission control targets must be distributed to each province, city, and even smaller economic and social unit [25]. Under the premise of controlling the total amount of regional emissions, allowing carbon trading among different areas will be conducive to achieving a win-win situation for carbon emission reduction and economic development [26]. Several studies have simulated interregional carbon trading and identified buyers and sellers of carbon quotas at the regional and provincial scales [26, 27]. With the growing importance of cities in carbon reduction and the increasing interconnectedness of cities, some of the key topics that urgently need to be studied include how to allocate carbon quotas among cities, how to promote city cooperation and regional collaboration in carbon reduction through intercity carbon trading, how to promote interregional linkages and coordinated development, and how to make this process adaptable to different policy scenarios.

In recent years, focus has gradually turned to the construction of urban spatial networks. The development of transportation and information technology has prompted modern cities to present a polycentric and networked spatial development pattern [28]. To understand a region, it is necessary to understand not only its internal constituent cities, but also the intricate structure of intercity relationships [29]. Taylor refers to the relationships and interactions between cities as the "second nature of cities" [30]. The methods used to depict spatial correlations mainly include the gravity model [31] and the vector autoregression (VAR) model [32]. Social network analysis is an effective tool used to analyze the relationships and structural characteristics of networks between nodes, the continuous development of which has drawn the attention of the research field of urban spatial relations. Social network analysis has been used to study population migration [33], urban structure [34], and urban ecological relationships [35]. Empirical studies of traffic flow [36], Internet flow [37–39], trade flow [40], and carbon flow [41] have also been used to depict urban networks. The study of urban networks has broken through the limitation of simply understanding the complexity of urban spatial relationships via physical space and location [42]. An urban network is effectively a representation of urban spatial relationships. The current situation of China's unbalanced regional development has led to significant differences in carbon emissions across regions. Thus, research on carbon emissions is mainly conducted from the perspectives of individual city, province, and regional scales. However, carbon emissions will shift with the spatial movement of air currents and even other elements, such as population and capital [43]. As such, the spatial correlation of carbon emissions is gradually becoming a new research hotspot [44]. The spatial correlation of carbon emissions has been explored through spatial econometrics approach [45]. Spatial econometrics approach is prominent in studying the spatial factors of carbon emissions. However, it has the limitation of geographical proximity and generally ignores the influence of the relationship between carbon emission entities on carbon emissions [46]. Compared with social network analysis, only a small amount of spatial correlation can be revealed [47]. Social network analysis can reveal the interactions and global structure features between individuals within a network in a more comprehensive way. Moreover, it can give insight into the changes in spatial interactions [32]. The increasing interconnection between cities means that regional synergistic carbon reduction policies will effectively reduce regional carbon emissions; this is more beneficial to mitigating global warming [48]. A comprehensive understanding of the spatial relationship of carbon emissions and the structure of the interregional carbon emission association network will virtually guarantee achieving the goal of regional synergistic carbon emission reduction [46]. The spatial association characteristics of carbon emissions have previously been studied using social network analysis [49]. The scope of current carbon emission network research covers only certain areas [50]; the research content is also relatively shallow. The operation of carbon trading markets will promote the spatial correlation of carbon emissions to a certain extent and will also provide a basis for the further development of urban network research

under a new perspective. The contributions of this paper are as follows. First, previous studies have mostly examined the carbon emission quota allocation at the national and provincial levels. We conduct the allocation of carbon emission quotas at the city level and identify potential buyers and sellers to simulate intercity carbon trading. Such research will make the energy saving and emission reduction work more targeted and make the promotion of carbon trading market construction more operable. Moreover, exploring the spatial relationships among cities from the perspective of carbon trading can help the formulation of regional carbon reduction policies. This will also provide a new analysis perspective for the study of urban networks and the study of carbon trading decisions under multiple scenarios of decision objectives.

The 182 cities in China selected for this study straddle the eastern, central, and western regions of China. These cities cover 73.2% of cities in China's major urban agglomerations, such as the Yangtze River Delta urban agglomeration and the urban agglomeration in the middle reaches of the Yangtze River. In 2019, the total economic volume of these cities is 77.77 trillion yuan; the total population is 935.23 million, accounting for 78.48% and 66.8% of the country's economic volume and population, respectively. The two central questions that this study focuses on are as follows: (1) how does intercity carbon trading work? (2) How do the effects generated by intercity carbon trading and the complexity of carbon trading networks differ across scenarios? Around these questions, this study proposes a "multi-scenarios across different spatial scales" framework for the allocation and trading of CO_2 emission quotas. Next, the allocation of urban CO_2 emission quotas and the calculation of urban carbon trading volume under multiple scenarios are carried out. Then, the carbon trading networks of 182 cities in China are constructed by using carbon trading volume data and the gravity model. A comparative analysis of the complex characteristics of the networks under each scenario is then performed using global indicators, such as network density and node indicators, such as centrality. Following that, geographic visualization is conducted using GIS. The remainder of this paper is structured as follows: Section 2 describes the study area, basic data, and analysis framework. Section 3 introduces the methodology and the spatial characteristics indicators of urban carbon trading networks. Section 4 reports the analysis results, and Section 5 presents this paper's discussion and conclusions.

2. Study Area and Framework

2.1. Study Area. Carbon trading is a market mechanism used for buying and selling CO_2 emission quotas, which are regarded as a commodity, in order to promote global greenhouse gas emission reduction. In China, a cap-and-trade mechanism is being used in the current stage of the carbon trading system [4]. The government sets the emission cap and then allocates the carbon emission rights to each emission unit in the form of quotas. Excess quotas can be sold in the market, while insufficient quotas can be purchased from the market. The transaction volume and transaction amounts of quotas in China's carbon trading market have been on a growing trend since their establishment. The cumulative transaction volume had reached 480 million tons, with a cumulative transaction amount of 11.4 billion yuan by June 2021. Significant differences exist among the pilot carbon markets; the vastly different approaches to total determination and quota allocation schemes in each region have led to large differences in carbon prices (b and *c* in Figure 1). Since the launch of the national carbon market in July 2021, the cumulative transaction volume had reached 22.17 million tons at the time of this study, and the cumulative transaction amount had reached 990 million yuan. The running of the national carbon market will comprehensively accelerate the progress of China's carbon peaking and carbon neutrality.

In this study, 182 cities in the carbon emission data are used as the study area. According to the city levels classified by China's administrative system [51], these cities include municipalities directly led by the nation (MD) (four cities), subprovincial cities (15 cities), other provincial cities (five cities), and prefecture-level cities (158 cities). There are 66 cities in the eastern region (a1 in Figure 1), 92Figure 92 cities in the central region (a2 in Figure 1), and 24Figure 24 cities in the western region (a3 in Figure 1). The selected cities differ significantly in terms of population and socioeconomic development. For example, in 2019, the cities range from a population of 0.66 million in Altay, to 31.24 million in Chongqing, and from a GDP of 34 billion yuan in Altay, to 3815.5 billion yuan in Shanghai. Significant differences also exist in the cities' carbon emissions, ranging from a minimum of 1.6 million tons to a maximum of 194 million tons. Due to the huge number of study subjects, the difficulty of acquiring city-level data, and the consideration of the research focus, the calculation of carbon emissions is not included as part of our research. The CO_2 emission data of the 182 selected cities were obtained from China's CO_2 emissions database (www.ceads.net/). The database complies with the administrative-territorial management method of the Intergovernmental Panel on Climate Change (IPCC) and can provide strong and transparent data support for China's city-level emissions control and nationwide emissions trading mechanisms [52]. The reasonable allowable emissions for each city will be obtained by reallocating the total actual carbon emissions of all cities, based on the population and economic status of each city. On this basis, the actual total emissions are set as the total quota. The GDP and resident population data of each city were obtained from the annual socioeconomic statistics, which are publicly released by each level of government.

2.2. The Design of, Allocation, and Trading of CO2 Emission Quotas in a "Multiscenarios across Different Spatial Scales" Framework. China, as the world's largest CO_2 emitter, considers carbon trading to be an important initiative in its energy conservation and emission reduction strategy. At the present stage, China's carbon trading is mainly concentrated within regions. The practice of interregional carbon trading is relatively closed, resulting in some problems such as the

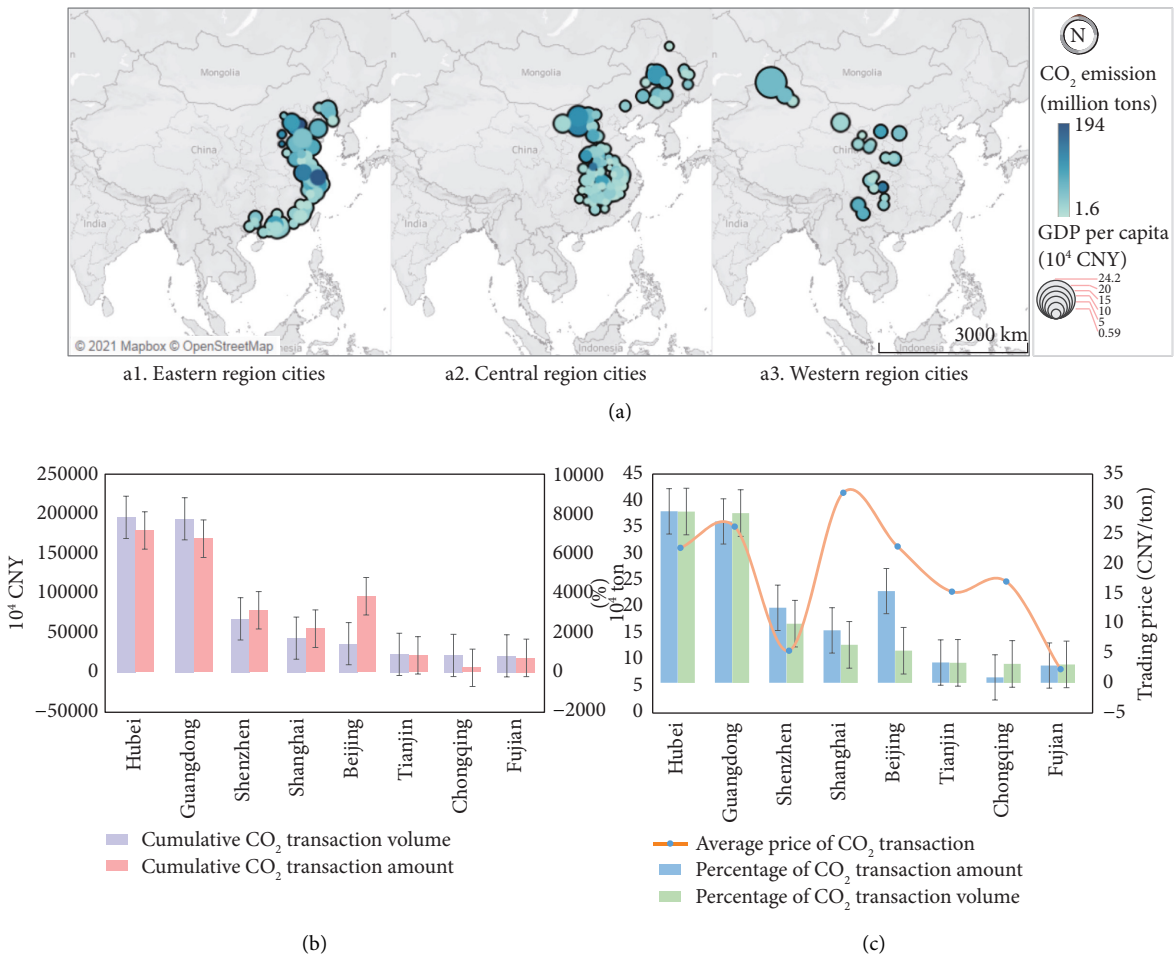

Figure 1: Basic statistics of China's carbon trading pilots. Notes: The deeper the color of the bubbles in a1, a2, and a3 in Figure 1, the higher the carbon emissions; the larger the size of the bubbles, the higher the GDP per capita.

imbalance between the supply and demand of quotas and inactive trading. As such, China is deviating from the open concept of mature global carbon trading. The cross-regional flow of CO_2 emission quotas will be an inevitable requirement in dealing with environmental problems [53]; the development of cross-regional carbon trading in the Beijing-Tianjin-Hebei region has provided experience of this practice. However, the current situation of unbalanced regional development in China means that regional carbon trading still occupies an important position. Reasonable regional carbon trading, cross-regional carbon trading, and national carbon trading policies will all effectively promote carbon emission reduction. But the applicability of these policies varies at different stages of development of carbon emission reduction in China. In the near term phase, China focuses on regional carbon trading and gradually transitions from regional pilot carbon markets to a national carbon market. In the far-term phase, the national carbon market will dominate. The two complement and supplement each other. Based on the above, we set different spatial scales. The regional scale is applicable to the near term phase, and the national scale is applicable to the far-term phase. In addition, the reasonable allocation of carbon emission quotas is the core issue of carbon trading. We set two different allocation principles to improve the multiapplicability and optionality of the policy scenarios. These are the principle of affordability and the principle of equality, respectively, which are more widely accepted and applied. Different allocation principles will bring different socioeconomic effects. The principle of affordability emphasizes that economically, relatively developed areas should bear more responsibility for emission reduction, while the principle of equality emphasizes the equal rights of each citizen in the use of public resources.

In summary, a spatial scale and socioeconomic binary dimension is designed, and the core of the intersection of the binary dimension is the Urban CO_2 Trading Network. The spatial scale includes "National" and "Regional" dimensions; the socioeconomic dimensions include "Affordability" and "Equality." Four scenarios are obtained by combining two of the dimensions from those two groups, namely, "National-Affordability," "National-Equality," "Regional-Affordability," and "Regional-Equality." To ensure that all cities under each scenario can participate in carbon trading, and to further improve the multiapplicability and reference value of the policy scenarios, an economic complementary trading

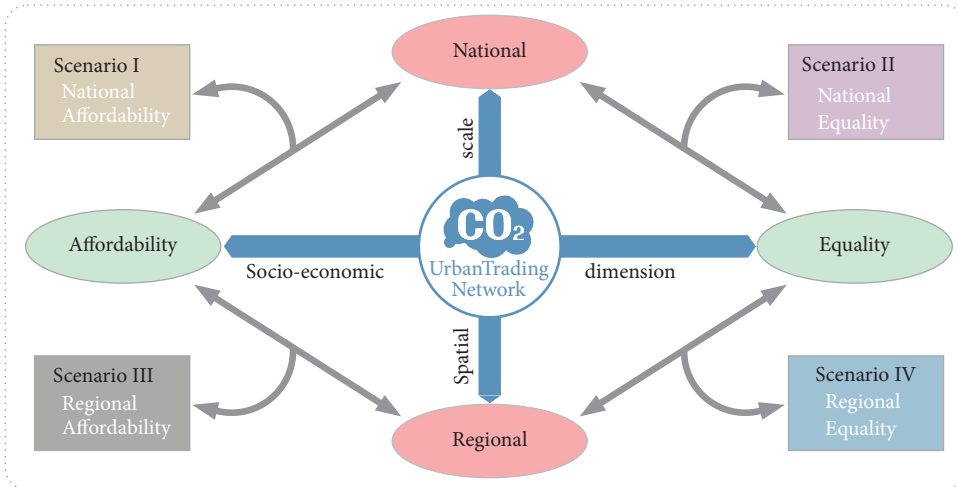

Figure 2: Design of the scenario framework for allocation and trading of CO_2 emission quotas.

scenario has been added to the regional scenarios. To a certain extent, this scenario also responds to China's policy of regional linkage between developed and underdeveloped areas. The later steps of the allocation of urban CO_2 emission quotas, the calculation of urban carbon trading volume, construction of urban carbon trading networks, and comparative analysis of the networks' complex characteristics will be conducted in the framework of these four scenarios (Figure 2).

The specific descriptions of the four scenarios are listed as follows: (1) "National-Affordability" refers to the allocation of quotas under a nationwide scale, according to the principle of affordability. In this scenario, all buyers and sellers trade with each other. (2) "National-Equality" refers to the allocation of quotas under a nationwide scale, according to the principle of equality. In this scenario, all buyers and sellers again trade with each other. (3) "Regional-Affordability" refers to quotas being allocated individually within the eastern, central, and western regions, according to the principle of affordability. In this scenario, buyers and sellers within adjacent areas trade with each other, while buyers with higher (or lower) GDP per capita trade with sellers with lower (or higher) GDP per capita. (4) "Regional-Equality" refers to quotas being individually allocated within the eastern, central, and western regions, according to the principle of equality. In this scenario, buyers and sellers within adjacent areas trade with each other, while buyers with higher (or lower) GDP per capita trade with sellers with lower (or higher) GDP per capita. Under the national scale, cities do not have trading preferences that are due to interregional differences; rather, the promotion of coordinated development across regions is valued. Quotas flow cross-regionally, with resources and wealth being distributed and transferred on a national scale. Free-form, open and holistic development features are presented. Under the regional scale, on the one hand, the similarity of natural environments, resource conditions, and humanistic and social conditions inside a region leads cities to prefer to cooperate with adjacent areas in economic activities. Meanwhile, promoting the coordination within the region and ensuring the relatively stable development of each region are both things that are emphasized. A portion of the quotas flows within the region, with resources and wealth distributed and transferred on a regional scale. On the other hand, in order to promote regional linkage between developed and underdeveloped regions, developed and underdeveloped cities will trade with each other. A portion of the resources and wealth are distributed and transferred across regions. This is characterized by relatively interventionist, relatively closed and partial development.

3. Methods

3.1. Allocation of Urban CO2 Emission Quotas. The allocation of CO_2 emission quotas is the single most important element in the design of a carbon trading system; it plays a fundamental role in determining the responsibility for emission reduction. The allocation principle can be summarized as efficiency and equity principles [54], and the allocation methods mainly include the indicator method and data envelopment analysis (DEA) technology [55]. Indicator method, the most commonly used emissions allocation method, means that emission permits or reduction targets are allocated based on certain indicators [26]. Here, we use the indicator method for quota allocation from the perspective of equity. Different spatial scales and principles of quota allocation are considered in the above four scenarios, expressed by the following equations.

Scenario 1. "National-Affordability." Under this scenario, quotas are allocated among all cities, according to the principle of affordability. In practice, GDP per capita has been positively correlated with the ability to reduce emissions [56]. Therefore, under this principle, the ratio of emissions reduction to GDP is equal across cities.

$$A_i = A_t \times \frac{P_i \left(G_i/P_i\right)^{-a}}{\sum_{i=1}^{182} P_i \left(G_i/P_i\right)^{-a}}, \tag{1}$$

where A_t represents the total quota of 182 cities; P_i represents the resident population of city i; G_i represents the total product value of city i. If $a < 1$, this means that the amplitude of the increase (or decrease) of quotas is smaller than the amplitude of the decrease (or increase) of GDP per capita. This assumption ensures that a city's quotas do not decrease significantly in line with the increase of GDP per capita. Through comparative analysis, the allocation result obtained by a being set at 0.5 is better. The result is also in line with theoretical expectations and realistic situations. Therefore, a is taken as 0.5 in this study.

Scenario 2. "National-Equality." Under this scenario, quotas are allocated among all cities, according to the principle of equality. All citizens have the right to share resources equally; population numbers are also positively related to emissions demand [22]. As a result, the total CO_2 emissions are allocated according to the proportion of each city's population out of the total population under this principle.

$$A_i = A_t \times \frac{P_i}{\sum_{i=1}^{182} P_i}, \tag{2}$$

where A_t represents the total quota of 182 cities, and P_i shows the resident population of city i.

Scenario 3. "Regional-Affordability." Under this scenario, quotas are allocated among regional cities following the principle of affordability. Compared with Scenario I, the spatial scale is changed from national to regional. Therefore, we have slightly improved the formula of Scenario I, and the total quota and the number of cities will change with regions.

$$A_i = A \times \frac{P_i \left(G_i/P_i\right)^{-a}}{\sum_{i=1}^{n} P_i \left(G_i/P_i\right)^{-a}}. \tag{3}$$

In the above formula, when cities are located in the eastern region, A is taken as A_e, the total quota of cities in the eastern region; n is taken as 66, the number of cities in the eastern region. When cities are located in the central region, A is taken as A_c, the total quota of cities in the central region; n is taken as 92, the number of cities in the central region. When cities are located in the western region, A is taken as Aw, the total quota of cities in the western region; n is taken as 24, the number of cities in the central region. P_i represents the resident population of city i; G_i represents the total product value of city i, and a is taken as 0.5.

Scenario 4. "Regional-Equality." Under this scenario, quotas are allocated among regional cities, following the principle of equality. Compared to Scenario II, the spatial scale is changed from national to regional. Therefore, we have made the same improvements to the formula of Scenario II as above, and the total quota and the number of cities will change with regions.

$$A_i = A \times \frac{P_i}{\sum_{i=1}^{n} P_i}. \tag{4}$$

In the above formula, when cities are located in the eastern region, A is taken as A_e, the total quota of cities in the eastern region; n is taken as 66, the number of cities in the eastern region. When cities are located in the central region, A is taken as A_c, the total quota of cities in the central region; n is taken as 92, the number of cities in the central region. When cities are located in the western region, A is taken as Aw, the total quota of cities in the western region; n is taken as 24, the number of cities in the central region. P_i represents the resident population of city i.

3.2. Construction of Urban CO2 Trading Network. The gravity model is an effective method that can be used to measure the spatial forces between cities and can also quantitatively describe the attraction between cities [57]. The basic gravity model assumes that the spatial connection between two cities is proportional to the size of each city and inversely proportional to the distance between the two cities [58]. The size of a city is measured by some indicators such as population, GDP, and trade scale [59]. In this paper, the size of a city is measured by the carbon trading volume of a city. The equation for the calculation of city carbon trading volume is as follows:

$$T_i = \left|A_i - C_i\right|, \tag{5}$$

where A_i represents the city's CO_2 emission quotas, and C_i represents the city's actual carbon emissions. When $A_i > C_i$, i is a seller, and T_i is the selling volume. When $A_i < C_i$, i is a buyer, and T_i is the buying volume.

Since only buyers and sellers trade with each other, the gravity model is improved by adding a dummy variable. The improved urban CO_2 trading gravity model is specified as follows:

$$W_{ij} = \frac{\alpha\left|A_i - C_i\right| \times \left|A_j - C_j\right|}{d_{ij}^2}, \tag{6}$$

$$\alpha = \begin{cases} 1 & \left(A_i - C_i\right) \times \left(A_j - C_j\right) < 0 \\ 0 & \left(A_i - C_i\right) \times \left(A_j - C_j\right) > 0 \end{cases} \tag{7}$$

where W_{ij} represents the gravity of CO_2 trading between city i and city j; $|A_i - C_i|$, $|A_j - C_j|$ denote the carbon trading volumes of city i and city j; and d_{ij} represents the geographic distance between city i and city j. When the signs of $A_i - C_i$ and $A_j - C_j$ do not coincide, $\alpha = 1$, ensuring that an attraction exists between the buyer and the seller. Conversely, no attraction exists between cities with the same demand. The above model is applied to the "National-Affordability" and "National-Equality" scenarios.

Under the "Regional-Affordability" and "Regional-Equality" scenarios, one rule is that buyers and sellers within adjacent areas trade with each other. Based on this rule, another dummy variable is added to the model, using the following equation:

$$\beta = \begin{cases} 1\, d_{ij} \in \text{near distance}, \\ 0\, d_{ij} \notin \text{near diatance}, \end{cases} \tag{8}$$

$$\alpha = \begin{cases} 1\left(A_i - C_i\right) \times \left(A_j - C_j\right) < 0, \\ 0\left(A_i - C_i\right) \times \left(A_j - C_j\right) > 0, \end{cases} \tag{9}$$

$$\alpha = \begin{cases} 1\left(A_i - C_i\right) \times \left(A_j - C_j\right) < 0 \\ 0\left(A_i - C_i\right) \times \left(A_j - C_j\right) > 0 \end{cases} \tag{10}$$

where W_{ij} represents the gravity of CO_2 trading between city i and city j; $|A_i - C_i|$, $|A_j - C_j|$ denote the carbon trading volumes of city i and city j; and d_{ij} represents the geographic distance between city i and city j. The difference, compared to the national scale, is the addition of the distance restriction. Buyers and sellers will trade with each other only when the distance between each other is relatively short. When this occurs, then $\beta = 1$. After consideration of the reasonableness of intercity commuting time and cost, and the search of the distance between cities within each region [60], the *near* distance is set at 800 km.

Another rule is that the buyers with higher (or lower) GDP per capita trade with the sellers with lower (or higher) GDP per capita. The equation based on this rule is as follows:

$$A_i \in D_n, A_j \in D_m, \tag{11}$$

$$W_{ij} = \frac{\left|A_i - C_i\right| \times \left|A_j - C_j\right|}{d_{ij}^2}, \tag{12}$$

where A_i represents buyer city i, A_j represents seller city j, $|A_i - C_i|$ and $|A_j - C_j|$ represent the carbon trading volumes of buyer city i and seller city j, respectively; d_{ij} represents the geographic distance between city i and city j; D_m, and D_n represent the city classes of buyer cities and seller cities, respectively, which are in turn divided equally by GDP per capita in descending order. Cities are divided into four classes here, with first- (or second-, third-, or fourth-) class buyer cities trading with fourth- (third-, second-, or first-) class seller cities. The results obtained based on the above two formulas of the gravity model are aggregated together, and then the duplicate results are eliminated to obtain the final relationships of carbon trading between cities.

3.3. Characteristic Indicators of Urban Carbon Trading Spatial Association Network. After the construction of the spatial association network, indicators such as network density are used to characterize the overall characteristics of the network. Indicators like degree centrality are also utilized to indicate the centrality of each node. Since the calculation of these indicators is commonly found in other literature, and reliable calculation tools are available (e.g., Ucinet and Pajek), their detailed formulas are not presented in this paper, due to space limitations.

Characteristic indicators of the overall network: the number of association relations refers to the actual number of CO_2 trading relationships in the carbon trading association network, namely, the number of edges [61]. Network density is the ratio of the actual number of association relationships between nodes to the maximum possible number of association relationships [49]. The higher the density is, the closer the association between the nodes is, and the greater the influence of the network structure on the nodes' attitudes and behaviors is. The number of association relations and the network density are used to measure the robustness and tightness of the spatial association network. The higher the number of association relations and network density there are, the stronger the robustness and tightness of the network will be. The degree is used to measure the number of edges of each node that connects to other nodes in the whole network [57]. Characteristic indicators of nodes: degree centrality (DC) is used to measure the degree to which a node is away from the network center [46], which directly reflects the position of the node in the network. A node with high DC is at or close to the center of the overall network. Closeness centrality (CC) is used to measure the degree to which a node is out of the control of other nodes [62]. The higher the CC of a node is, the more direct the connection between the node and other nodes will be, and then the node is a central participant in the network.

4. Results

4.1. Allocation and Trading of CO2 Emission Quotas among Cities under Multiple Scenarios. The statistical characteristics of urban CO_2 emission quotas and trading volume under the four scenarios are shown in Table 1. In terms of CO_2 emission quotas, under "Affordability" scenarios, the city given the least amount of quotas is Karamay, which is an oil industry city with the highest GDP per capita in China. Under "Equality" scenarios, Altay, the city in the western region with the smallest population of the 182 cities in this study, receives the least quotas. The quotas they have received are both less than 0.1% of the total. Chongqing is located in the western region and is the largest mountain city in China. Chongqing consistently obtains the largest amount of quotas under the four scenarios, accounting for about 3.55% of the total. The results show that cities with lower GDP per capita and larger populations bear less responsibility for emissions reduction and are granted more opportunities for economic development. The mean value of CO_2 emission quotas is the same under each scenario, but the standard deviation is different. The highest deviation occurs under the "Regional-Affordability" scenario; the lowest occurs under the "National-Equality" scenario. In terms of carbon trading volume, significant differences exist among cities under the four scenarios. The largest carbon trading volumes are all more than five times the average trading level; the smallest carbon trading volumes are all less than 1% the average trading level. The mean and standard deviation of carbon trading volume are different under each scenario, with the largest occurring under the "National-Affordability" scenario and the smallest occurring under the "Regional-Equality" scenario. The mean and standard

Table 1: Basic statistics of CO_2 emission quotas and trading volume under each scenario.

Scenario	Carbon	Maximum	Minimum	Mean	S.E	Mean		
						Eastern	Central	Western
National-affordability	Emission quotas	272.61	0.93	41.81	35.48	41.48	42.06	41.78
	Trading volume	163.11	0.27	30.96	28.68	29.91	31.47	31.85
National-equality	Emission quotas	269.25	2.06	41.81	34.54	48.05	37.25	42.15
	Trading volume	150.35	0.10	25.41	24.99	25.64	24.10	29.81
Regional-affordability	Emission quotas	268.82	0.92	41.81	37.80	51.94	34.70	41.20
	Trading volume	160.62	0.05	30.26	27.86	31.17	28.19	31.51
Regional-equality	Emission quotas	263.17	2.02	41.81	35.66	51.94	34.70	41.20
	Trading volume	148.52	0.04	25.23	24.98	26.76	23.07	29.33

deviation of carbon trading volume under "Affordability" scenarios are larger than those under "Equality" scenarios.

From a regional perspective, in terms of CO_2 emission quotas, under the "National-Affordability" scenario, the mean value of quotas is larger in the central and western regions. However, under other scenarios, the mean value of quotas is larger in the eastern and western regions. Compared with the regional scale, the central and western regions receive more quotas under the national scale, while the eastern region receives fewer quotas under the national scale. Comparing the "Affordability" scenario and the "Equality" scenario at the national scale, the eastern and western regions are allocated more quotas under the "National-Equality" scenario; the central region is allocated more quotas under the "National-Affordability" scenario. In terms of carbon trading volume, the mean value of carbon trading volume in the western region is always the largest under each scenario, followed by the eastern region. Under the "Regional-Affordability" scenario, the mean value of carbon trading volume in the eastern region reaches its maximum, while the mean value of carbon trading volume in the central and western regions reaches the maximum under the "National-Affordability" scenario.

4.2. Characteristics of Intercity CO2 Trading Networks and Their Visualization under Multiple Scenarios. The carbon trading networks of 182 cities in China under four different scenarios, according to formulae (6) to (12), are presented in a1, b1, c1, and d1 in Figure 3. Significant spatial network correlations exist among the carbon trading of cities under the four scenarios; the shape of the network is also stable, with typical network structure characteristics. When comparing the national scale and the regional scale, the number of network correlations is greater under the national scale, and a gap exists between the actual number of network correlations and the maximum possible number of network correlations under the regional scale. There is still room to improve the spatial correlation, which is caused by the carbon trading rules under the "Regional" scenarios. Under the same spatial scale, the number of network correlations is greater under the "Affordability" scenarios than under the "Equality" scenarios. Looking at the mean value of gravity, the degree of connection of intercity carbon trading is higher overall under the regional scale. This stronger degree of connection provides opportunities for both city cooperation and regional economic integration. Looking at each region, under the "National-Affordability" scenario, the degree of connection of intercity carbon trading in the central region is the highest overall; under the other scenarios, the degree of connection is highest in the eastern region. The western region is always the lowest. From a cross-regional perspective, the degree of connection of carbon trading between cities in the eastern and central regions is always the highest and is always the lowest between cities in the eastern and western regions. As seen in a2, b2, c2, and d2 in Figure 3, the distribution of distance values under the same spatial scale is similar, although some subtle differences do exist, because the role of the cities (buyer or seller) changes somewhat (but not to any significant degree) under different allocation principles. The frequency of distance values under the regional scale is lower than that under the national scale, with lower frequency of high distance values. This is due to the fact that trading happens mainly inside regions. In Figure 3, a3, b3, c3, and d3 show that the frequency of high gravity values is higher under the regional scale than that under the national scale. Under the same spatial scale, the frequency of high gravity values is higher under the "Affordability" scenario than that under the "Equality" scenario.

Figure 4 and Table 2 provide the CO_2 trading characteristics networks of the 182 sampled cities under the four scenarios, and the basic statistical characteristics of network characteristic indicators, respectively. The numbers of association relations for the network are 8256, 8160, 3991, and 3840 in the four scenarios, and the network densities are 0.251, 0.248, 0.121, and 0.117, respectively. These findings suggest that, under the national scale, there are more network inner connections, and the robustness and closeness of the network are stronger. The greater robustness and tightness can lead to one city's carbon trading practices having a greater impact on other cities. Under the national scale, the cities' degrees present only two colors, and no obvious core nodes exist in the network. Under the regional scale, however, the cities' degrees are quite different, with core nodes found in the overall network and in each region. Such differences are caused by the different carbon trading rules under each scenario. The cities' degrees and intercity gravity index, respectively, indicate that the number of intercity connections is higher under the national scale than the regional scale; the degree of intercity connections is higher overall under the regional scale than the national scale. The sum of the degrees of all cities in each region

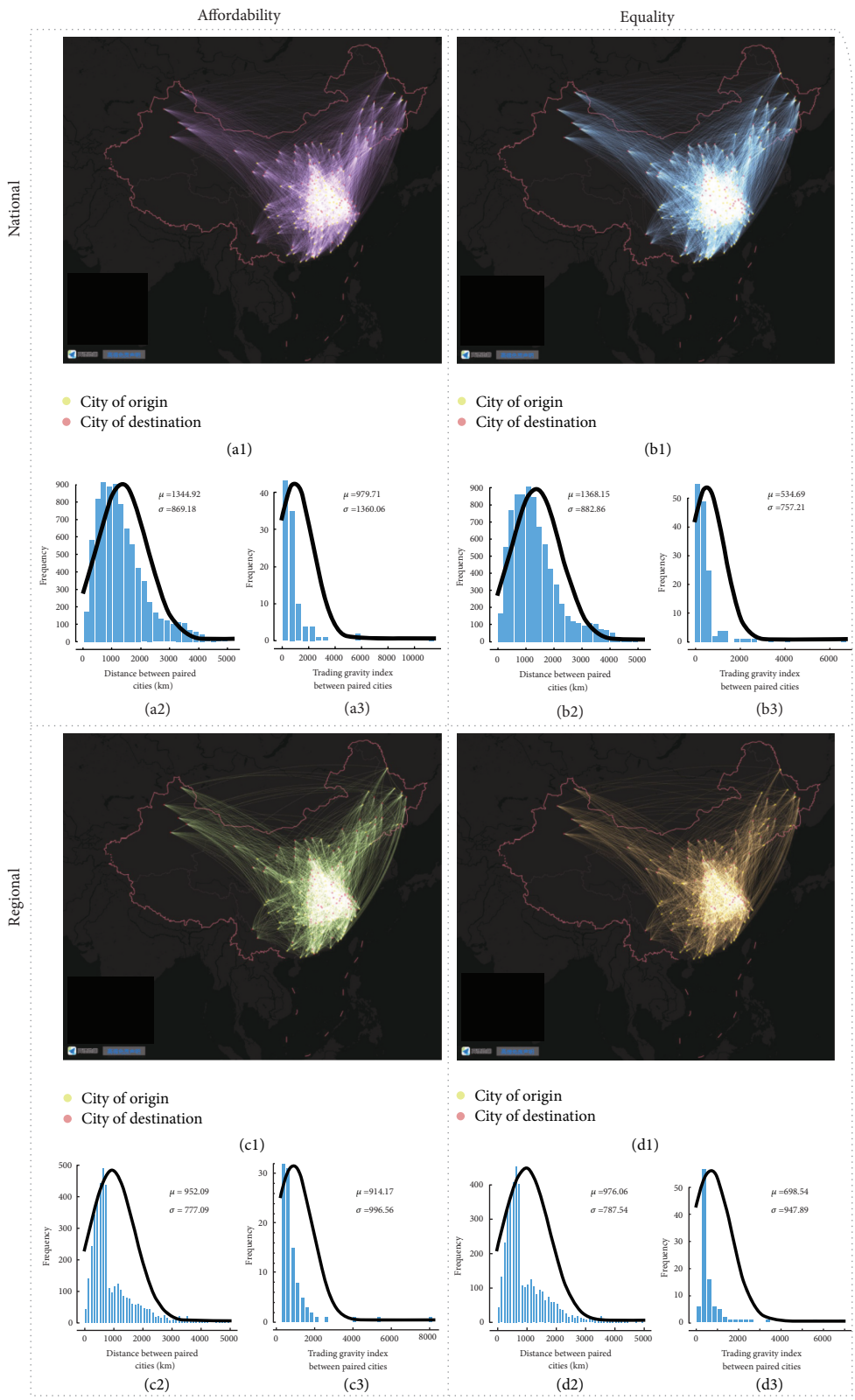

FIGURE 3: CO_2 trading network of 182 cities under different scenarios. Notes: Figures a1, b1, c1, and d1 represent the visualization of the intercity CO_2 trading networks under the four scenarios, and they are produced online on the Gaode Map open platform (https://lbs.amap.com/). Figures a2, b2, c2, and d2 show the distribution of distances between all paired cities under the four scenarios. The distributions of the trading gravity index (top 100) between all paired cities under the four scenarios are shown in Figures a3, b3, c3, and d3, respectively.

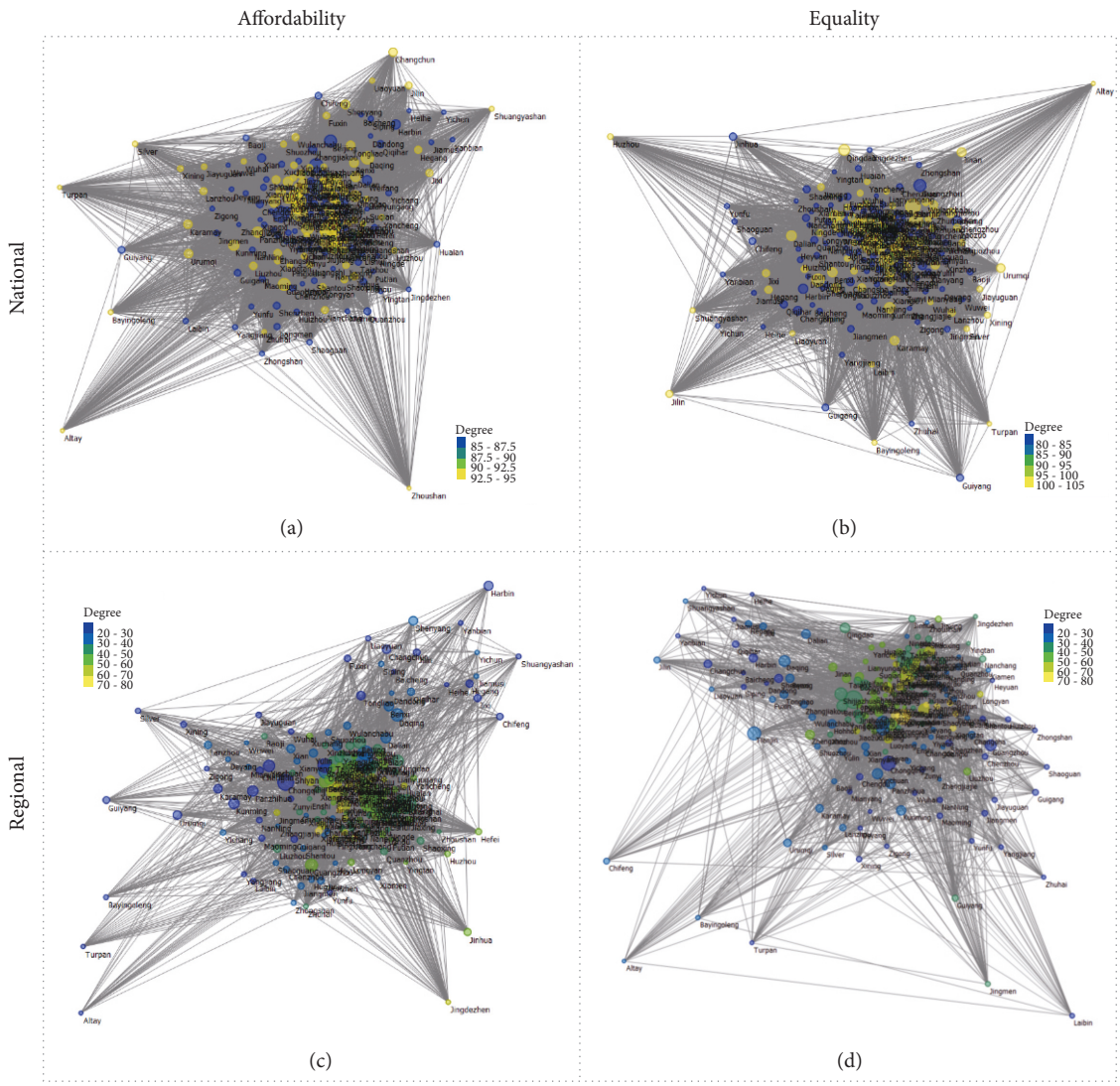

Figure 4: Spatial distribution of the CO_2 trading network of 182 cities under different scenarios. Notes: the color of the node represents the size of the degree, and the size of the node reflects the amount of emissions. The larger the node is, the more emissions there are.

Table 2: Basic statistics of characteristic indicators of CO_2 trading network under each scenario.

Scenario	Indicator	Maximum	Minimum	Mean	S.E	Mean		
						Eastern	Central	Western
National-affordability	Degree	96	86	91	4.99	91	90	91
	Degree centrality	0.53	0.48	0.50	0.03	0.50	0.50	0.51
	Closeness centrality	6.63	0.59	4.34	1.62	4.16	4.19	5.39
National-equality	Degree	102	80	90	10.9193	90	89	92
	Degree centrality	0.56	0.44	0.50	0.06	0.50	0.49	0.51
	Closeness centrality	23.88	2.79	14.81	5.48	14.70	14.01	18.17
Regional-affordability	Degree	74	23	44	12.91	44	47	30
	Degree centrality	0.41	0.13	0.24	0.07	0.24	0.26	0.16
	Closeness centrality	3.68	0.25	2.60	0.94	2.38	2.68	2.86
Regional-equality	Degree	79	21	42	14.23	42	45	31
	Degree centrality	0.44	0.12	0.23	0.08	0.23	0.25	0.17
	Closeness centrality	7.92	0.37	5.61	1.98	5.64	5.47	6.04

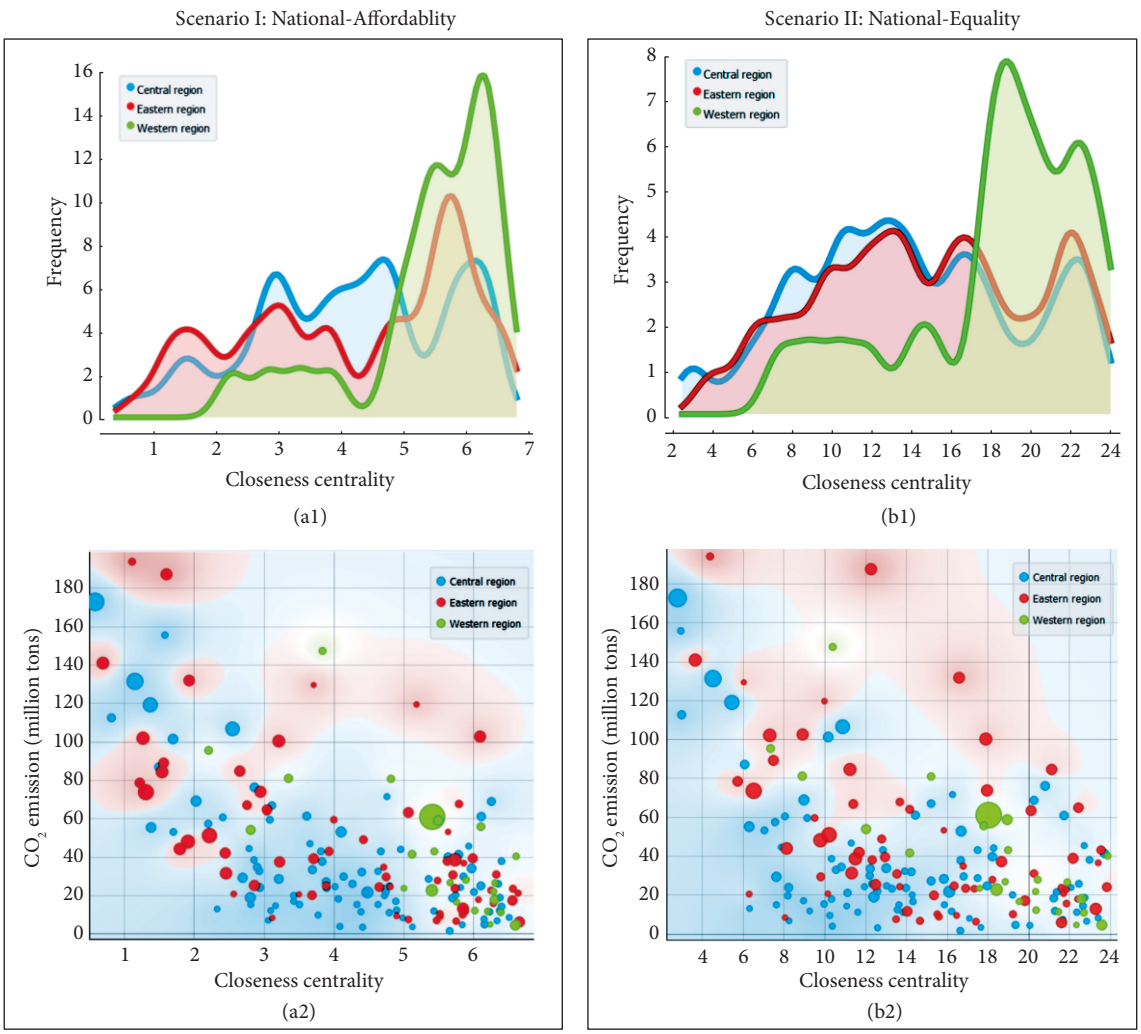

Figure 5: Statistical chart based on the results of node indicators. Notes: the size of the bubbles represents the amount of carbon emissions.

reveals that the central region has the most inner connections, followed by the eastern region. The mean value of the cities' degrees in each region shows that cities in the central region are always in the most central position overall, followed by the eastern region.

4.3. Centrality Characteristics of Nodes in CO_2 Intercity Trading Network Structure. To further characterize the structural features of the CO_2 intercity trading network under different scenarios, degree centrality and closeness centrality are used to evaluate the centrality of each city in the network. The results, as shown in Table 2, indicate that no obvious central node exists in the network under the national scale. Also, the degree centrality of the buyer cities is higher than that of the seller cities. Under the "Regional-Affordability" scenario, Nanchang is the central city in the central region (and even in all of China), followed by Ezhou and Xiangtan. These cities have a strong capability to radiate to the surrounding areas and show a strong spatial spillover effect to other regions in terms of carbon trading. The central city in the eastern region is Suqian; the central city in the western region is Baoji. Due to its remote location, few trading objects, and small trading volume, Jiayuguan is weakly spatially correlated with other cities. Under the "Regional-Equality" scenario, Huangshi is the central city in the central region (and even in the whole country), followed by Pingxiang, Ezhou, and Xiangtan. The central city in the eastern region is Nanjing; the central city in the western region is Guiyang. Overall, the carbon trading of cities in the central region has the greatest impact on other regions. The sizes and distributions of the closeness centrality of each city under the four scenarios are presented in a2, b2, c2, and d2 in Figures 5 and 6. The closeness centrality of cities is generally highest under the "National-Equality" scenario. Under the "National-Affordability" scenario, the top three cities are Zhoushan, Laibin, and Guiyang. The findings show that 53% of the eastern cities, 49% of the central cities, and 83% of the western cities are above the mean value. Under the "National-Equality" scenario, the top three cities are Guiyang, Huzhou, and Jilin, while 48% of the eastern cities, 41% of the central cities, and 79% of the western cities are over the mean value. Under the "Regional-Affordability" scenario, the top three cities are Jingdezhen, Shenyang, and Zhoushan; 53% of

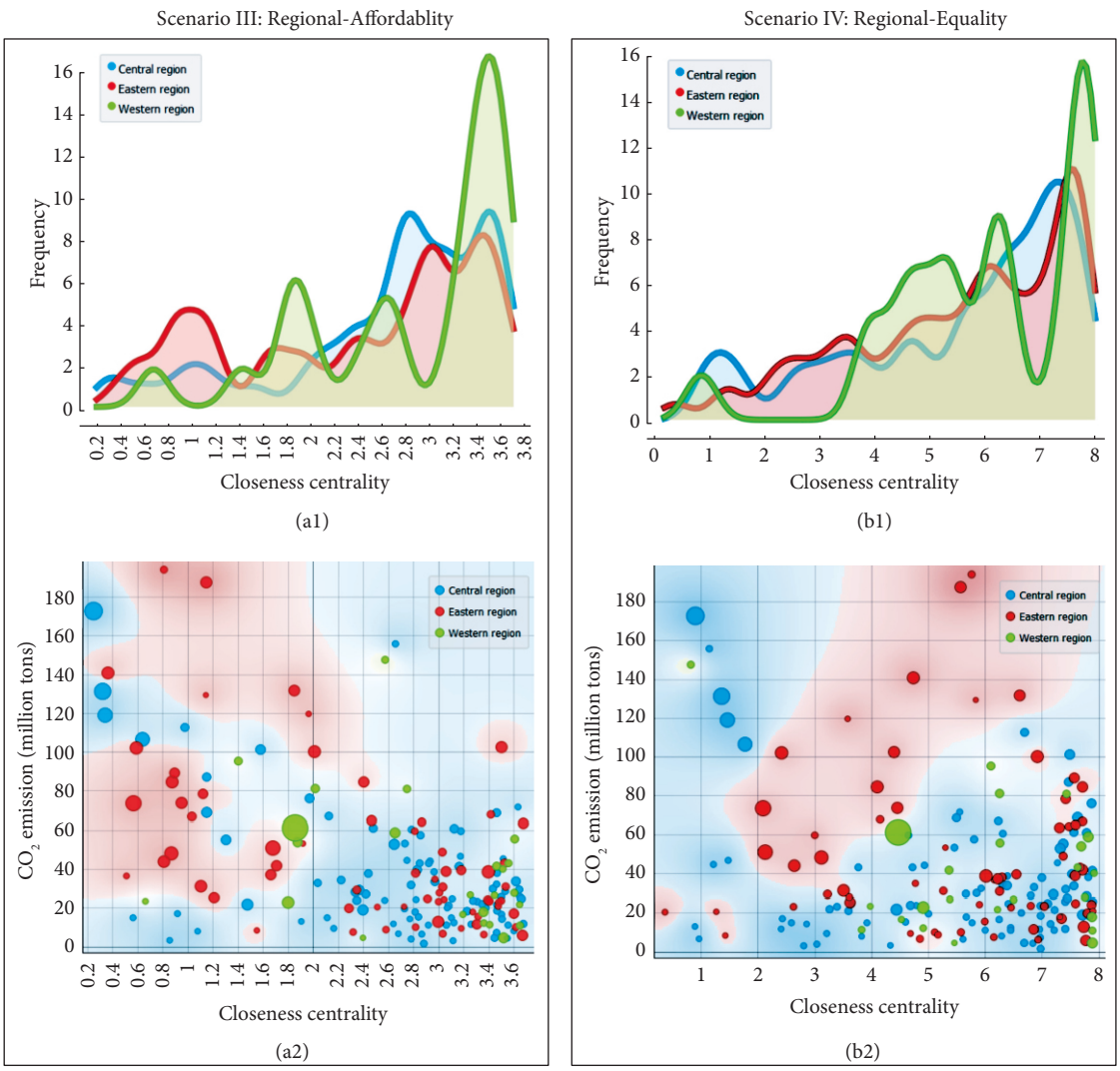

Figure 6: Statistical chart based on the results of node indicators. Notes: the size of the bubbles represents the amount of carbon emissions.

the eastern cities, 68% of the central cities, and 67% of the western cities are over the mean. Under the "Regional-Equality" scenario, Guiyang, Jingmen, and Laibin are the top three cities; 58% of the eastern cities, 61% of the central cities, and 58% of the western cities are above the mean value.

Kernel density estimation for each region was performed to further understand the distribution characteristics and spatial evolution features of the cities' closeness centrality (a1, b1, c1, and d1 in Figures 5 and 6). With kernel density estimation, the distribution of data is not attached to any assumption; rather, its characteristics are studied from the sample itself [63]. As can be seen, firstly, there are multiple peaks of the nuclear density curves in each region under each scenario. This shows a staged aggregation of the closeness centrality of cities. Secondly, the western region's nuclear density curve is overall closest to the right under each scenario, with the highest closeness centrality of cities overall. Thirdly, under each scenario, the rightmost wave peak of the kernel density curve of the western region is always the highest, with the largest area underneath. This finding means that the western region accounts for the largest share in the high-value cities. Specifically, under the "National-Affordability" scenario, the closeness centrality of cities in the central and eastern regions is relatively evenly distributed. In the interval 5–7, the western region's nuclear density curve exhibits the steepest wave peak and the highest values, with the highest degree of aggregation of closeness centrality in this region. The variations between cities in each region are smaller, with the smallest being in the western region. In the interval 0–5, larger variations are seen between cities in each region, with the largest in the western region. Under the "National-Equality" scenario, the closeness centrality of cities in the central and eastern regions remains relatively evenly distributed. In the interval 18–24, the highest degree of agglomeration is in the western region, as indicated by that region's highest wave peak. In the interval 2–18, the degree of agglomeration is higher in the central and eastern regions than in the western region. The variations between cities in each region are larger in the interval 2–18 and smaller in the interval 18–24. Under the "Regional-Affordability" scenario, the closeness centrality of cities in the western region is mainly clustered in the interval 3.2–3.8;

in the central region in the interval 2.6–3.8, and in the eastern region in the interval 2.8–3.8. Under the "Regional-Equality" scenario, the closeness centrality of cities in each region is mainly clustered in the interval 6–8; a fault appears in the western region in the interval 1–3.8. In the interval 3.8–8, the largest variations between cities are found in the western region.

5. Concluding Discussions

A market-based emissions trading system is a promising cost-effective policy instrument for achieving its long-term targets for emission reduction in China. The realization of interregional carbon trading policy in China will effectively promote a win-win situation for carbon reduction and economic development. The vast size of China means that cities vary greatly in terms of economy, population, and resources. The allocation of urban carbon emission control targets not only directly affects the achievement of overall emission reduction targets, but also relates to the sustainable development of economy and society. Meanwhile, the continuous improvement of the total carbon emission control system requires that carbon emission reduction targets must be allocated to the city level. On this basis, this study first allocates carbon emission quotas at the city level. Then, potential buyers and sellers are identified with reference to the carbon trading operation mechanism to simulate national and regional intercity carbon trading. Such simulation breaks free of the restrictions imposed in the current situation, whereby carbon trading is spatially limited within province. It realizes intercity and interregional cooperation in carbon emission reduction, and the multiple effects of promoting regional coordinated development and regional economic integration, as well as driving the development of underdeveloped regions, are generated. Finally, the spatial relationships and interactions between cities are explored from the perspective of carbon trading. Currently, there is still relatively little research and practice on city-level carbon trading, but it has great research significance and development possibilities. When cities are given emission reduction targets, then they will have a surplus or deficit of quotas and will inevitably trade with other cities. Intercity carbon trading is the trading of total carbon emission control targets. Different from real carbon markets, intercity carbon trading is essentially a horizontal financial transfer to achieve the optimal allocation of carbon emission targets among cities, providing more options for cities to achieve their carbon emission reduction targets.

A "multiscenarios across different spatial scales" framework, which is applicable for the allocation and trading of intercity CO_2 emission quotas in China, is proposed in this study. In this framework, the allocation of city carbon quotas and the calculation of carbon trading volume are carried out. Then, based on the carbon trading volume data and the gravity model, the carbon trading networks of 182 cities in China under different scenarios are constructed and comparatively analyzed. Firstly, under the "National" scenarios, the central and western regions are given more quotas and economic development opportunities. In addition, connections and cooperation between regions are promoted via urban cross-regional trading. Carbon trading is more conducive to promoting regional coordinated development and improving the unbalanced status of regional development in China. Under the "Regional" scenarios, the carbon trading pays more attention to promoting the cooperation between cities inside the region as a means to reduce emissions. A wise move would be to vigorously promote high-quality integration development through the establishment and optimization of regional carbon trading markets and regional comprehensive collaborative management platforms. This approach would help achieve the rational utilization of resources in different regions. Secondly, under the "Affordability" scenarios, cities with smaller and wealthier populations bear more responsibility for emission reduction. Meanwhile, underdeveloped cities are granted more opportunities for economic development, and the gaps between cities are narrowed. Economically developed cities should actively introduce and develop high level emission reduction technologies and optimize the energy economic structure. Under the "Equality" scenarios, cities with larger populations received larger quotas, and their emission needs for the survival and economic development of large-scale populations are met. Thirdly, significant spatial network correlations exist between the carbon trading of cities under each scenario. Under the national scale, there are more inner connections in carbon trading networks, with stronger correlations and robustness. Regional cooperation should be emphasized, especially between underdeveloped cities in the western region and cities in other regions. This would ensure that carbon emission quotas from underdeveloped regions are exchanged with resources from developed regions, in order to achieve an equitable redistribution of resources and wealth and thereby promote regional coordinated development. Under the regional scale, the degree of connection of intercity carbon trading is higher overall. In addition, reducing cooperation barriers and promoting city cooperation and regional integration can effectively promote carbon emission reduction. Fourthly, under the national scale, no obvious core nodes exist in the network, while core nodes do exist in the overall network and in each region under the regional scale. The role of national core cities, regional core cities, and the central region in terms of radiating and driving other cities should be fully played. In fact, geographically close cities play a similar role in the network. Most of the cities with higher core positions are from the urban agglomeration in the Middle Reaches of the Yangtze River, which is a cross-regional urban cluster that connects the east, west, north, and south of China. This is also a key region for energy conservation and emission reduction in China. Thus, it would be both meaningful and worthwhile to strengthen the cooperation between this region and other regions in carbon emission reduction and carbon trading. Furthermore, based on strengthening the complementary functions and dislocation competition among cities with high core status, China's central government should also consider promoting the relatively weaker core position of some megacities and provincial capitals. The government should also facilitate the

flow of technology and funds related to energy saving and emission reduction.

In urban networks, a visible flow between cities is presented in this paper through scenario simulations of the allocation and trading of CO_2 emission quotas. This approach provides a new perspective for urban network research. With the continuous development of pilot carbon markets and a national carbon market, the study of the complexity of urban carbon trading networks will have great development prospects. At present, research on urban networks in the field of carbon emissions mainly focuses on the study of carbon emission spatial association networks. However, previous authors have rarely, if ever, considered carbon trading networks, especially the kind of carbon trading networks found in a "multiscenarios across different spatial scales" framework. The framework reflects differences in both spatial scales and socioeconomic effects, with characteristics of multiapplicability and simple computation. This framework can also provide potential multischeme support for policy decisions. In carbon trading, China is gradually transitioning from pilot carbon trading to national carbon trading. As such, several different varieties of the carbon trading schemes designed in this study have some reference value. In addition, the transaction subjects of realistic carbon trading are mainly enterprises. Some studies have analyzed the impact of carbon trading policies on enterprises [64], such as how such policies incentivize enterprises to carry out low-carbon technology innovations. However, this study takes an innovative approach to the trading subject and proposes the concept of intercity carbon trading. Although the concept does not quite accord with reality, it still reflects the idea of realistic carbon trading. This carbon trading concept is also expected to bring more direct and profound incentives to the low-carbon development of cities. Policy makers could be motivated to formulate macro carbon reduction policies for the sustainable development of cities and the improvement of cities' competitiveness. Policy makers should also promote carbon reduction from all aspects of every city, rather than just focusing on the enterprise level. Finally, cooperation with other cities should be strengthened, in order to comply with the trend of regional collaboration on carbon reduction. In the analysis of complex characteristics, kernel density estimation is used in this study to further reveal the distribution and evolutionary features of the results. This approach differs from most studies in that the evolution and differences in space are highlighted here. However, this study has several limitations. Firstly, the availability and timeliness of data are limited; there remains great potential to develop the analysis of the complex features of carbon trading networks. A valuable research direction in the future would be to explore the change law about the urban carbon trading networks on a spatial and temporal scale, using panel data. Moreover, urban agglomerations have now become the most dynamic regions for economic development in China. The complexity of the spatial structure of carbon trading networks in different urban agglomerations could be comparatively analyzed in the future. Secondly, the results of the study are mainly simulated. In addition, a gravity model is adopted to construct the networks in this paper, which may not match well with reality. Finally, the networks are simply depicted, with only a few indicators. Some studies include rich club coefficients in the indicator system and use block models and the CONCOR algorithm to reveal the role of each member in the network. This is also a direction we could develop in future research. The balance of efficiency and equity in quota allocation, the improvement of the gravity model, the further optimization of the scenario framework–with more consideration given to realistic factors, the design of a more rational scheme for the allocation, and trading of CO_2 emission quotas, along with the improvement of its scientific and reference value, can all be conducted in the future.

Data Availability

The sources of all data used in the study have been described in the paper. If readers are interested in the data after the paper is published, they can contact the authors.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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