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Research Article

The Complexity of Urban CO_2 Emission Network: An Exploration of the Yangtze River Middle Reaches Megalopolis, China

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With their focus on human production and consumption activities, cities incur massive energy consumption and CO_2 emissions. An intercity connection is a typical complex system in which the interaction between cities is crucial for developing low-carbon outputs within the urban agglomeration. This paper presents the construction of the CO_2 emission network of an urban agglomeration in the Yangtze River middle reaches megalopolis, based on the gravity model. Combined with social network analysis (SNA), a multilevel analysis framework is proposed to deal with the complexity, spatiality, and visualization of the CO_2 emission network with reference to the network features, structural equivalence, and the rich-club phenomenon. The following results emerged: firstly, the spatial structure of the CO_2 emissions was characterized by low robustness and compactness, indicating disunity among the studied cities. Secondly, there was found to be a strong correlation between regionalism and intercity connections, with geographically close cities playing a similar role in the network. Thirdly, the "rich-club" cities, including Wuhan, Changsha, Xiaogan, and Zhuzhou, dominated the connections, covering more than 87.1% of the network in the Yangtze River Middle Reaches Megalopolis.

1. Introduction

tGiving rise to ecological and environmental changes owing to human activities, global warming has become the world's greatest challenge, caused by the greenhouse effect. The amount of CO_2 emissions has increased dramatically in China, transforming the country into the greatest contributor to energy consumption and carbon emissions in the world since joining the WTO in 2002 and accounting for about 30% globally of global emissions [1]. Considering China's current urban patterns, involving the Wuhan metropolitan area in Hubei Province, the Chang-Zhu-Tan urban agglomeration in Hunan Province, and the Poyang Lake city group in Jiangxi Province, the Yangtze River middle reaches megalopolis is not only a major pillar of the Yangtze River Economic Belt but is also a new growth area in China's economic development [2]. Moreover, the Yangtze River middle reaches megalopolis is a cross-regional urban agglomeration, connecting eastern and western as well as northern and southern China when viewed from a geospatial perspective and is a key area in the efforts to conserve energy and reduce emissions in China [3]. Currently, based on the goal of reaching peak carbon emissions by 2030 while actively building a resource-saving and environmentally friendly society (two-oriented society), the Yangtze River middle reaches megalopolis is separated two subgroups, including "national comprehensive reform pilot areas of two-oriented society construction" and "eco-economic zone" [3]. At present, given that this is a major area of interest within the energy conservation and emission reduction field, covering various aspects such as sustainable development, ecological carrying capacity, ecological efficiency, and CO_2 emissions [4–7], numerous achievements have been noted in the Yangtze River middle reaches megalopolis in terms of CO_2 emissions, including estimating the regional CO_2 emissions, their influencing factors, and a low-carbon development strategy [8–11]. However, since the influence of population migration, the movement of capital, industrial transfer, and even the atmospheric cycle [12], the regional urban CO_2 emissions exist spatial correlation rather than being limited to a certain administrative region [13]. At the same time, the flows of material and information among cities are greatly frequent, as well as the closer connections rather than being isolated, profited by the rapid development of transportation and informatization [14]. A complex system was constructed with a mutual role as an important aspect [15]. With a focus on two fundamental issues, the current study constructs the CO_2 emission network of the Yangtze River middle reaches megalopolis and explores its complex structure, as well as how to promote integrating urban agglomeration between geographical locations and “space of flow” from a network perspective, based on the given context.

Given the large gaps that exist between the economic level and resource structure in diverse regions of China that cover a vast territory [16], more energy-intensive industries and backward productivity remain in underdeveloped areas than developed areas, making the kernel areas of CO_2 emissions and the economy continually shift in an opposite direction [17], in turn further generating regional diversity and inequality in carbon emissions [18]. With a high degree of spatial correlation, the regional CO_2 emissions locally manifest a certain degree of spatial aggregation, that is, the outwardness of the regional disparity and spatial correlation of CO_2 emissions [19], which is beneficial for the implementation of targeted policies to reduce urban CO_2 emissions that respond to differences among diverse regions and cities [20]. Furthermore, accompanied by the growing society and economy, the denser China’s transportation network becomes, the closer the connection among cities [21, 22], meaning that regionally coordinated emission reduction policies will effectively lower regional CO_2 emissions [23]. There is a limitation of geographical proximity even though spatial econometrics can be used to verify the spatial correlation [24]. In conclusion, the research on urban CO_2 emissions that is based on spatial econometrics is of great significance to understanding both urban CO_2 emissions and the consensus around spatial differences and spatial correlations in regional CO_2 emissions. Nevertheless, compared with the social network analysis, spatial econometrics can only reveal a modicum of spatial correlation, especially in terms of spatial interaction and network complexity.

Originating from social psychology, social network analysis (SNA) is a tool used to analyze the interaction between nodes [25], highlighting the effect of group organization on individual perception [26]. The continuous development of SNA has drawn attention in the field of urban spatial studies, and SNA is of sprawling application for the interactive structure between regional cities and urban agglomerations [27]. Underlining the significance of network, flow, and dynamic evolution, repeating the theory of complexity and considering the relationships and interactions among cities as a core aspect of comprehending cities [28], “New Urban Science” has broken through the limitations of simply understanding urban complexity via physical space and location [29, 30]. So, as the second essence of intercity, the connection and interaction between cities preferably grasp and depict the urban system. In fact, a major area of interest within empirical studies has arisen from the various visible traffic flows among cities, such as air traffic flow [31] and the road traffic flow [32] to the invisible Internet flows [33] and the cooperative flow of patent innovation [34], which portray the intercity network and its traits while further explore the intercity interaction. Thus, it can be said that research on urban networks reconstructed the urban spatial relationship.

One of the most crucial challenges for urban network studies is how to describe the complexity of urban networks through quantitative methods and then effectively visualize this [35]. Recent studies have further expounded upon the complexity of urban network structures, in addition to common social network indicators, such as density [36], degree [37], and hierarchy [38]. As models for studying network locations and measuring structural equivalence, blockmodels that have gradually evolved into stochastic blockmodels have been introduced to engage with specific issues in the remit of social network analysis [39, 40], such as the global economic system [41] and the structural relationship among enterprises [42]. Inspired by the Pareto principle, the rich-club coefficient [43] is mainly used to discuss the existence of rich nodes in complex networks and test the interaction between prominent elements [44], such as brain networks [45, 46]. A few studies focus on China’s population flow network [47] and national trade network [48]. Regarded as effective tools for characterizing network features, both blockmodels and the rich-club coefficient, respectively, excel at detecting network locations and identifying rich nodes, which can aid in exploring the spatial network complexity of the Yangtze River Middle Reaches Megalopolis, viewed from the perspective of subgroups and nodes. Besides, GIS provides an effective platform for spatial analysis as well as visualization, which has the advantage to describe the complex spatial morphology of urban [49].

Building on integrating GIS and complex network analytical tools, a spatial network analysis framework for the Yangtze River Middle Reaches Megalopolis is here proposed to explore the complexity of the urban CO_2 emission network. On the basis of the framework, the urban CO_2 emission network of the Yangtze River middle reaches megalopolis is constructed first by using CO_2 emission data and the gravity model, whose characteristics are analyzed. The structural equivalence and rich-club phenomenon in this urban CO_2 emission network is considered through blockmodels and the rich-club coefficient, under the subgroups and nodes of urban agglomerations. Following that, a geovisual analysis was conducted using GIS. The rest of this paper is structured as follows: Section 2 describes the main research areas, basic data, analytical framework, and research methods. Section 3 reports the spatial characteristics of the urban CO_2 emission network, including the overall characteristics, structural equivalence, and rich-club coefficient. Section 4 discusses the findings and presents the conclusions.

2. Materials and Methods

2.1. Study Area. In this paper, the study area of the Yangtze River middle reaches megalopolis consists of the Wuhan metropolitan area, the Chang-Zhu-Tan urban agglomeration, and the Poyang Lake city group, as clarified by the Development Planning for the Yangtze River middle reaches megalopolis by China's central government in 2015. To promote the Wuhan city circle, the Changsha-Zhutan urban agglomeration, and the Poyang Lake urban agglomeration through green-driven and innovative development, China's central government further supplied the strategy for developing the Yangtze River middle reaches megalopolis, which had gradually upgraded to the national level. As a region of national priority connecting the east and the west, as well as the north and the south of China, the Yangtze River middle reaches megalopolis, which has even been called the fourth economic increase pole of China [50, 51], straddles three regions, including nine provinces and two municipalities (see Figure 1(a)). The megalopolis also radiates outwards as the dual-center structure of "Wuhan-Changsha," to promote new urbanization, exploit the interprovincial adjacent cities, and form a multicenter and networked development pattern [52, 53]. In 2017, the total economic output of the megalopolis was 7.9 trillion yuan, the population was 153 million, and the land area was 317 thousand km^2, respectively, accounting for 9.6%, 11.1%, and 3.3% of the country as a whole, demonstrating that this area is one of the most important locations in the Yangtze River Economic Belt. Accordingly, the Yangtze River middle reaches megalopolis is not only the major development zone of national land space, but also the gathering area of rivers and lakes, as well as an important ecological shelter. Low-carbon development is of great significance to the Yangtze River middle reaches megalopolis and even the whole country [54, 55].

For the purposes of this study, the CO_2 emission data were obtained from 182 regions across the country from China's CO_2 emission database (http://www.ceads.net/), covering cities in the Yangtze River middle reaches megalopolis. Complying with the administrative-territorial management method of the Intergovernmental Panel on Climate Change (IPCC), we classify the 46 socioeconomic sectors and fossil fuels according to China's national accounting system [56]. Therefore, these data are not only accurate but also comparable among cities. Figure 1(b) shows that Wuhan has the highest CO_2 emissions, while Fuzhou has the lowest, in the Yangtze River middle reaches megalopolis, roughly incarnating a phenomenon in descending order of circle layers.

2.2. Analytical Framework. To explore the network structure and complexity of the CO_2 emission network in the Yangtze River middle reaches megalopolis, we designed an analytical framework (Figure 2) in which a CO_2 emission network was constructed based on the gravity model. We then analyzed the complexity of the CO_2 emission network structure at three levels (global, subgroup, and node), acquired the network features (density, efficiency, hierarchy, rich-club phenomenon, and structural equivalence), employed GIS for visualization purposes, and successfully detected the network complexity of CO_2 emissions in the Yangtze River middle reaches megalopolis.

2.3. Constructing a Spatial Association Network of Carbon Emissions. What keeps the most frequently utilized on urban spatial interactions is the classical gravity model, which was introduced into the social sciences by Carey, who argued that both social phenomena and physical phenomena follow the same laws [57]. Gliding with the further summarization by Stewart [58] and Zip [59], the gravity model has been promoted, explained, revised, supplemented, modified [60–62], and then widely used for urban problems, such as immigration [63], trade flows [64], and archaeology and linguistics [65]. In light of Zipf's hypothesis, the interaction force W_{ij} is proportional to the population size F_i and F_j between city i and city j, while inversely proportional to the distance d. Soon afterward, F_i *and* F_j were more generally replaced by other indicators such as GDP and trade scale to describe the "attractiveness" of cities in other literature studies [66, 67], which partially modifies the gravity model to achieve a more precise quantifying of the gravity between cities. So as to better characterize the correlation of CO_2 emissions between cities, the current study constructed a revised gravity model to measure the spatial relationships of CO_2 emissions in the Yangtze River middle reaches megalopolis, as shown in the following equation:

$$W_{ij} = k_{ij}\frac{\sqrt[3]{P_iC_iG_i}\sqrt[3]{P_jC_jG_j}}{\left(d_{ij}/g_i - g_j\right)^2},\qquad k_{ij} = \frac{C_i}{C_i + C_j}, \tag{1}$$

where i and j represent different provinces; W_{ij} represents the gravity of CO_2 emissions between city i and city j; and P_i and P_j show the total population of city i and city j at year-end. In the case of different regions, C_i and C_j depict the total CO_2 emissions, G_i and G_j represent the total product value of cities, d_{ij} denotes the geographic distance, and $g_i - g_j$ is the difference value in per capita GDP. k_{ij} represents the contribution rate of different cities in terms of CO_2 emissions. Among them, the year-end total population, GDP, and per capita GDP of each city were all taken from the China City Statistical Yearbook of each city in 2019.

Given that the relationship of CO_2 emissions between cities was here determined through the gravity model, a spatial correlation network of CO_2 emissions was constructed of the Yangtze River middle reaches megalopolis. The CO_2 emission spatial correlation network was rendered as a set, that is $A = (N, E)$, where E represents the city node in the network, and it reveals the connecting strength

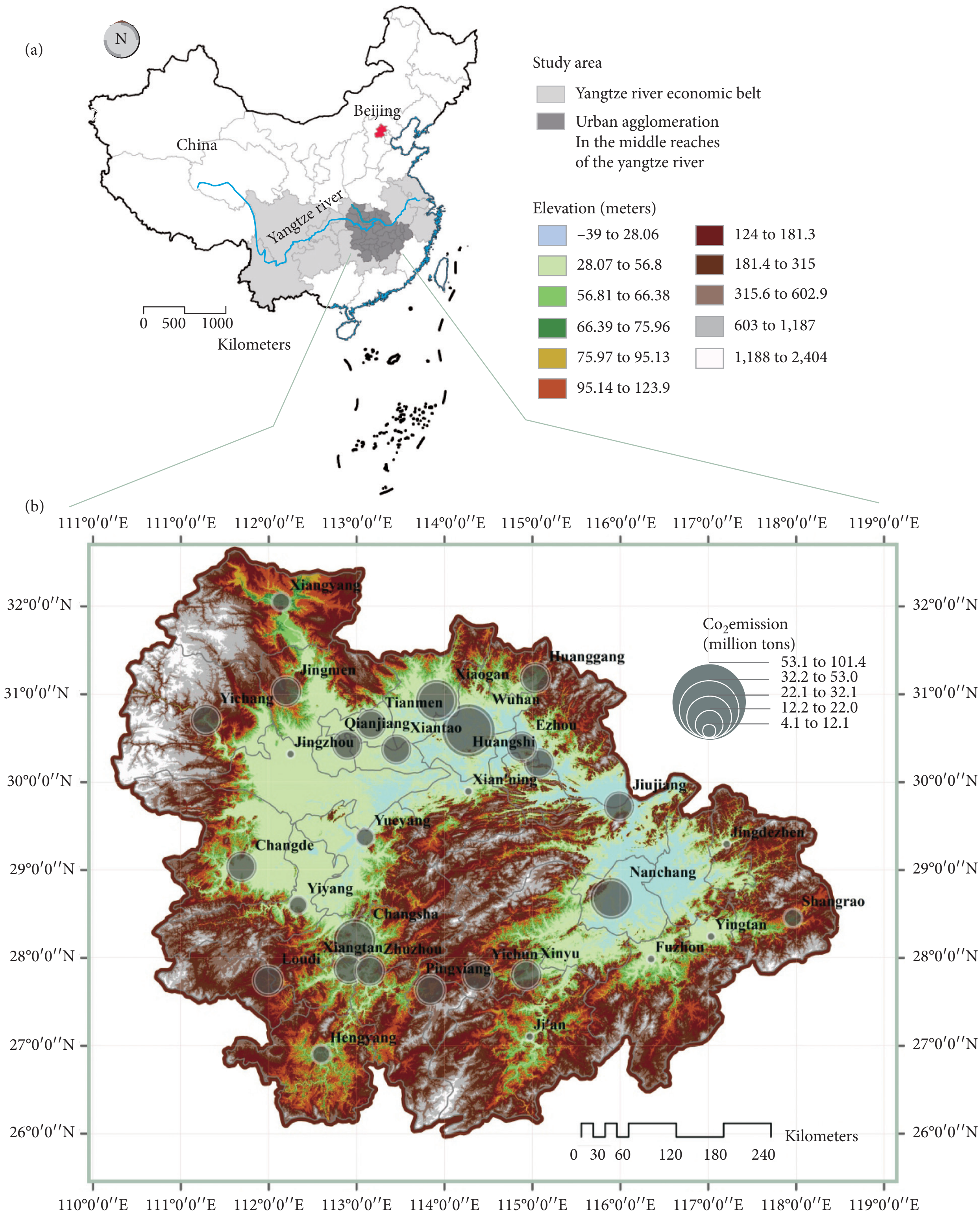


Figure 1: Location of the Yangtze River middle reaches megalopolis (a) and the cities' CO_2 emissions (b). Note: the data in Figure 1(b) show the CO_2 emission data in the Yangtze River middle reaches megalopolis, provided by the China CO_2 emission database (http://www.ceads.net/).

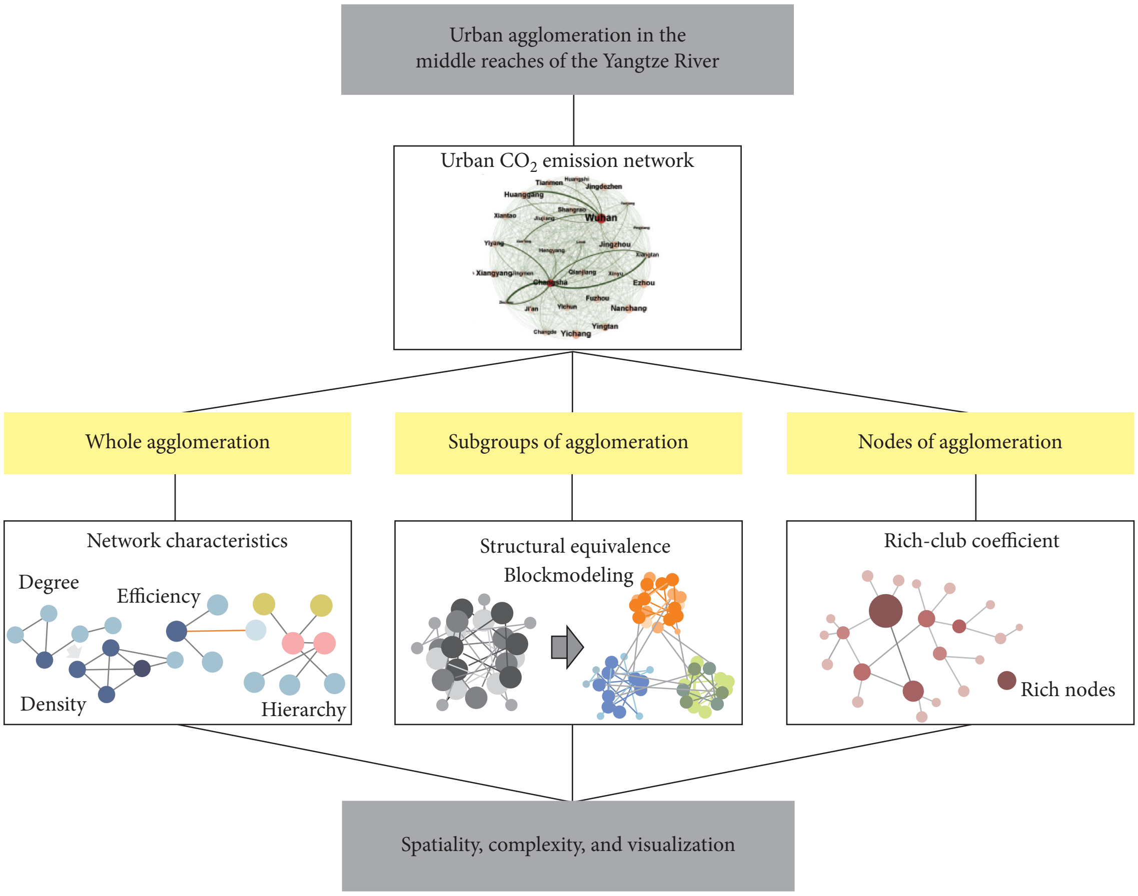


Figure 2: Analytical framework.

between nodes (whereby N represents the network nodes and the association intensity sets E as the network edges):

$$E = \begin{cases} 1, & W_{ij} > \text{the mean of matrix row}, \\ 0, & \text{otherwise}. \end{cases} \tag{2}$$

2.4. Characterizing Structure of the Spatial Association Network of Carbon Emissions. After above describing the correlation characteristics of the spatial correlation network in this paper, we use the density, hierarchy, efficiency, and degree to analyze the global identities of the spatial correlation network and utilize the convergence of iterated correlations (CONCOR) and rich-club coefficient to expose the network space structure based on the plates and nodes:

(1)Density is an index that reflects the closeness of network members' associations, whereby the higher the density, the closer the connection between network members, and the greater the network's influence on the actors' attitudes and behaviors.

(2)The hierarchy is an indicator reflecting each member's hierarchical structure in the space network, which usually reflects whether the hierarchical structure of the overall network is prominent.

(3)Apart from reflecting the extent to which redundant lines occur in the network, the lower overall network efficiency is uncertain in the overall network, which may imply the existence of a network with sufficient overflow channels and a stable associated network.

(4)The degree is used to measure the number of edges connecting to nodes in the entire network, while the in-degree reflects the strength of the node's aggregation, and the out-degree mirrors the size of the node's diffusion, in directed networks.

(5)As an approach used to detect the relationship between various positions in the network, the blockmodeling performs cluster analysis on actors according to the structural equivalence, in turn, mapping the relationship onto the positional connections among the actors [40]. When continually using the convergence of iterated correlations (CONCOR) and hierarchical clustering, six standards are, generally, applied to determine the value of each block: perfect fit, zero block, one block, α-density criterion, maximum value, and mean value [36], in which the most commonly employed is the alpha-density index (α-density index). According to Wasserman and Faust, the roles in the plate are divided into four categories: the first category is the "bidirectional spillover," the second is "agent," the third is the "main in-flow," and the last is "main out-flow." Different roles represent different associations between plates. For example, the "bidirectional spillover" plate is equivalent to more spillover relationships between members inside and outside the plate; the "agent" plate means that their members are the bridge for other plates, with the loose internal connection [36]. In this paper, we analyze the CO_2 emission network of the Yangtze River middle reaches megalopolis through the CONCOR algorithm [68] and reveal the role of each sector and its members in the associating network of CO_2 emissions, based on the correlation between the internal and external sectors.

(6) It is well known that numerous nodes exist in the network, holding large amounts of resources and tending to link with one other. The rich-club coefficient defines the extent to which a network displays a topological organization characterized by the presence of a node rich-club. This coefficient is crucial for the investigation of internal organization and network functions arising in systems of disparate fields such as transportation, social, communication, and neuroscience [69]. There are generally two ways to define rich nodes: one is the number of edges connected to the nodes (i.e., $r = k$), and the other is the total external connecting strength of the nodes (both $r = s$) [44]. Since the CO_2 emission network in this paper is constructed based on the gravity model, rather than the traditional O-D network, the rich-club coefficient was measured by the total external intensity of the nodes $(r = s)$. The calculation of the rich-club coefficient includes the global rich-club coefficient and the local rich-club coefficient, where the former is used to determine whether the rich-club phenomenon occurs in the network and to define the rich nodes, and the latter to measure the connecting tendency between each node and rich nodes, as well as the riches' influence in the network [44]. To provide an in-depth description of the network traits of the "rich-club" in this paper, we calculate the global rich-club coefficient of the CO_2 emissions' network in the Yangtze River middle reaches megalopolis in further, as well as the local rich-club coefficient.

3. Result

3.1. Global Spatial Network Structure of the Urban Agglomeration. Figure 3 shows the CO_2 emission network constructed for the Yangtze River middle reaches megalopolis according to formulae (1) and (2), in which Wuhan and Changsha are the two core nodes, while Nanchang is inconspicuous. Simultaneously, Wuhan, Changsha, and Nanchang are the respective centers in the Wuhan urban agglomeration, the Changsha-Zhuzhou-Xiangtan urban agglomeration, and the urban agglomeration around Poyang Lake network. However, the degree of the inner connection between the Wuhan urban agglomeration and the Changsha-Zhuzhou-Xiangtan urban agglomeration is higher than that of the urban agglomeration around Poyang Lake. Wuhan and Changsha affect the spatial distribution of CO_2 emissions when they are the economic and commercial centers in the Yangtze River middle reach megalopolis. With reference to the indicators related to the overall characteristics of the CO_2 emission network, network density, network hierarchy, and network efficiency measure only 0.1462, 0.083, and 0.84, respectively, in the Yangtze River middle reaches megalopolis. The network density indicates that further enhancements are found in the regional linkages and coordinated emission reductions of the Yangtze River middle reaches megalopolis. The network-level shows that the CO_2 emission network does not have an obvious hierarchical structure, in which the core cities are weak in terms of influence power. The network efficiency finds excellent small regional features in the CO_2 emission network, lacking structural stability. Specifically, the network density of urban agglomeration around Poyang Lake (0.30) is slightly lower than that of the Wuhan urban agglomeration (0.32) and Changsha-Zhuzhou-Xiangtan urban agglomeration (0.32), but the overall difference is not apparent.

The force in Figure 4 uses the Fruchterman–Reingold algorithm [70]. Concerning the degree of all cities in the Yangtze River middle reaches megalopolis, Wuhan and Changsha hold the core position in the network (Figure 4), in which the centrality of Wuhan is higher than that of Changsha, while that of Nanchang, one of the three provincial capitals, is significantly lower than Wuhan and Changsha. Given the directed network properties, the degree of the CO_2 emission network in the middle reaches of the Yangtze River can be further divided into in-/out-degrees, namely, 71% and 12.4%, respectively, with regard to network centralization. The gap in terms of the out-degree between each city in the CO_2 emission network is not marked, but the difference of the in-degree between Wuhan and Changsha is much greater than the others, as the same as the in-degree and out-degree between them.

3.2. Measuring Structural Equivalence. To cluster the CO_2 emission network on the basis of blockmodels of the Yangtze River middle reaches megalopolis, the CONCOR algorithm was applied, taking 2 and 0.2 as the maximum segmentation depth and convergence criteria, respectively, and dividing 31 cities into 4 sections. The classification standard achieves a good fitting effect and ensures that the number of cities in each plate is greater than three [71]. As can be seen in Figure 5, the first plate contains six cities such as Wuhan, Ezhou, Yichang, Qianjiang, Xiantao, and Xiangyang, while eight cities, such as Tianmen, Xianning, Huangshi, Xiaogan, Huanggang, Changde, Jingzhou, and Jingmen, comprise the second plate. The third plate includes eight cities: Yueyang, Yiyang, Zhuzhou, Pingxiang, Loudi, Hengyang, Xiangtan, and Changsha. Finally, there are Jiujiang, Yichun, Fuzhou, Xinyu, Ji'an, Nanchang, Shangrao, Jingdezhen, and Yingtan on the fourth plate. Here, it can be seen that the urban structural equivalence on the same plate is virtually identical. Based on the cluster results, there emerges a stronger correlation between regionalism and the subgroup; that is,

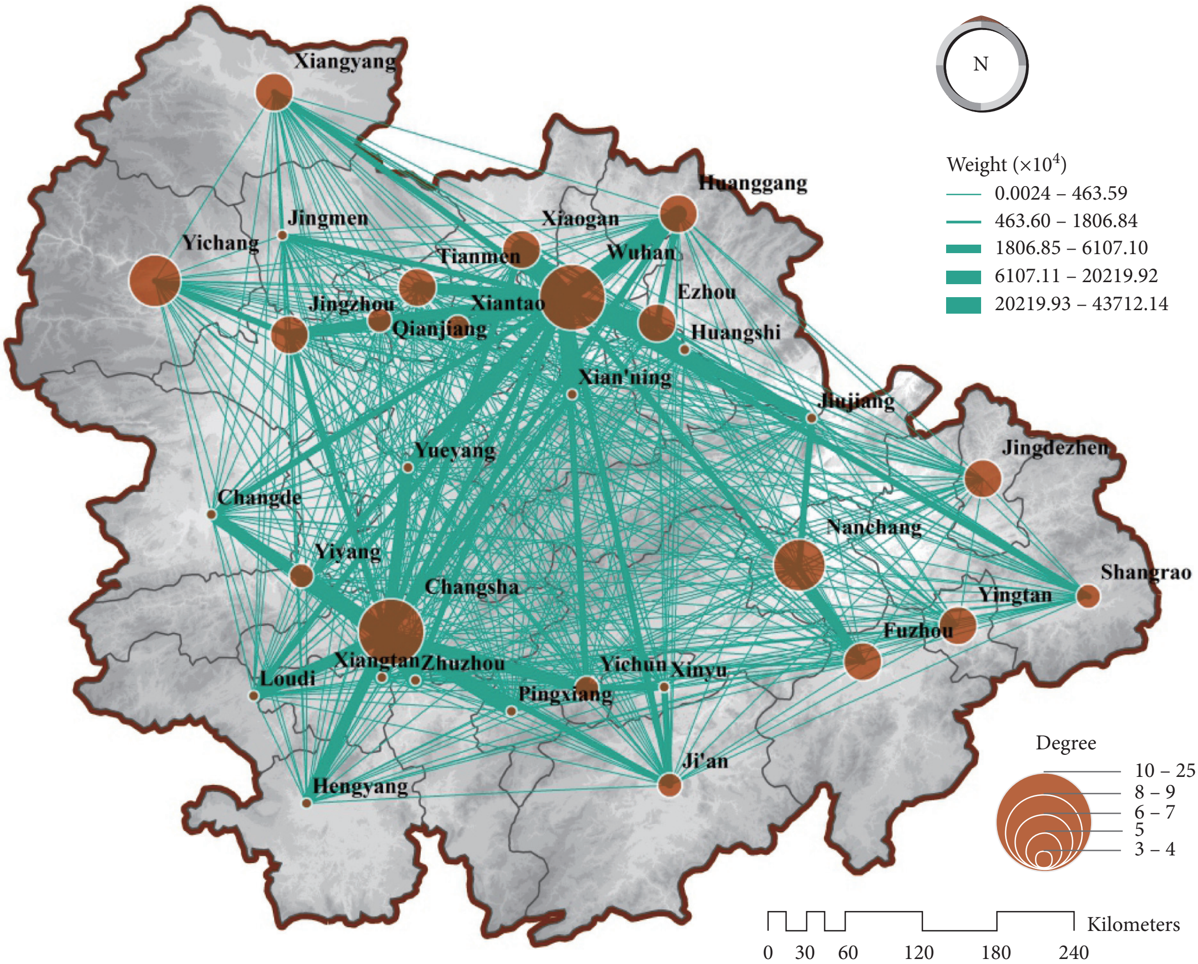


FIGURE 3: CO_2 emission network of the Yangtze River middle reaches megalopolis in China.

geographically close cities possess the same structural equivalence, thus proving the spatial dependence of CO_2 emissions.

Based on calculating the density matrix of the spatial correlation on network plates, the image matrix was obtained and is shown in Table 1. The α-density index, that is, the average density of the entire network, is the most frequently used to determine the value of each section. It can be seen from the image matrix that the links between the plates mainly exist within the plates, while the links between the plates are not close. The CO_2 emission spatial correlation network was further analyzed by dividing the positional scale and the plate's attributes in the network, with these results presented in Table 2. The role of the plate is mainly determined by the value of the expected proportion of internal relationship and actual proportion of internal relationship. Seen in detail, the actual internal relationship ratio of the first sector is 16.7%, which is equal to its expected internal relationship ratio. Given that the total spillover value is 36, the total revenue value is 39, but the number of external acceptance relationships is 33, and the external issue relationship number is 30, the first sector falls under the "agent" section. Given that the actual internal relationship ratio is 10%, less than the expected internal relationship ratio of 23.3%, the number of external acceptance relationships is 26, and the number of external issues is 27, the second sector also can be classified within the "agent" sector. When viewing the 3rd and 4th plate together, their actual internal relationship ratios are both greater than those expected. However, compared to the 4th plate, the number of external acceptance relations on the 3rd plate is much larger than that on the 4th, making the 3rd plate the "main in-flow" section, while the 4th is the "bidirectional spillover" section. In terms of the classification of plates, the first and second types, as the main part in the Yangtze River middle reaches megalopolis, play the role of bridges and influencing other sectors in the entire network. The cities in the third sector show a "main in-flow," relying to some extent on nonregional energy and high-carbon products due to the regional economic development. The reason why the fourth plate is "bidirectional spillover" is that it has abundant natural resources, which are not only for itself but also be delivered to other provinces.

3.3. The Rich-Club Coefficient.

The result of the global rich-club coefficient is shown in Figure 6(a), which delivers plentiful information: on the one hand, the $p_w(s)$ curve

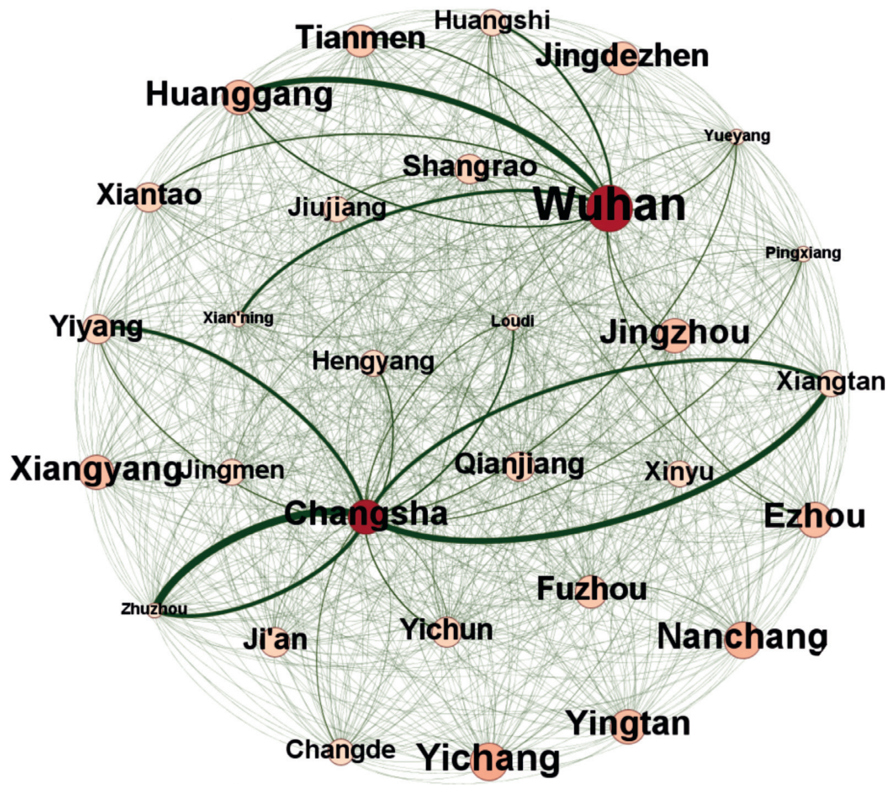
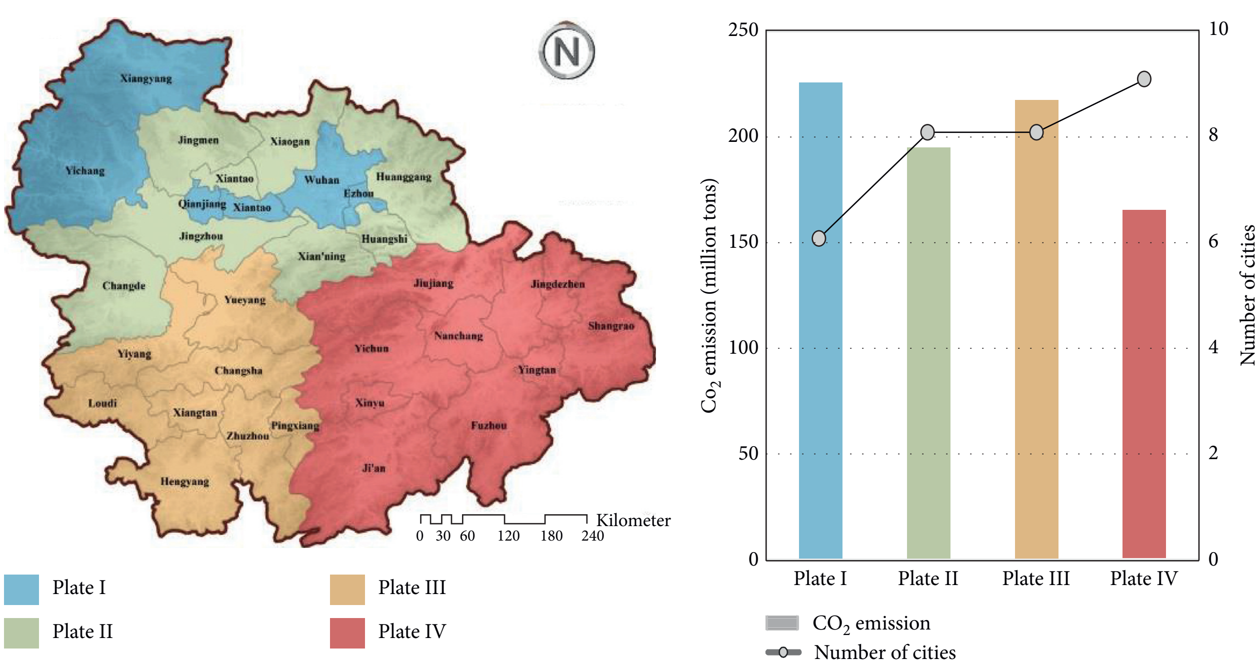


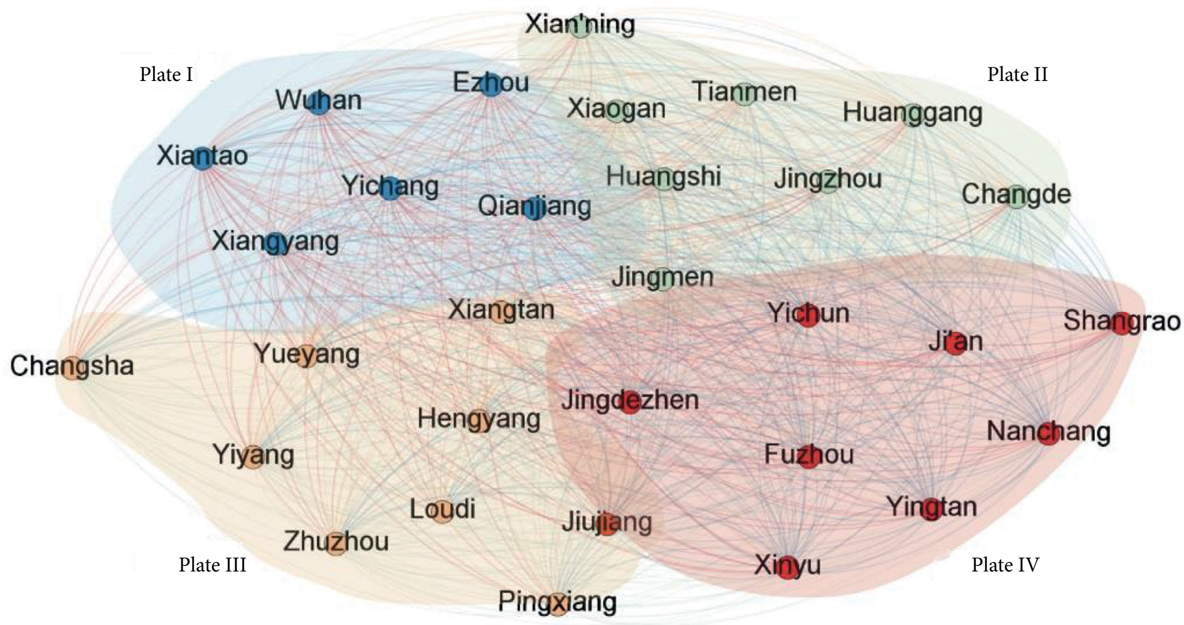
FIGURE 4: The force-directed layout of CO_2 emission network. Note: the force uses the Fruchterman–Reingold algorithm.



(a)

(b)

FIGURE 5: Continued.



(c)

Figure 5: Spatial distribution of the subgroup in the urban CO_2 emission network. Note: (a, c) the spatial distribution of different plates within the geographical space and cyberspace, respectively, and (b) the parameter attribute and CO_2 emissions of each plate.

Table 1: Density matrix of the CO_2 emissions on spatial correlation network plate and image matrix.

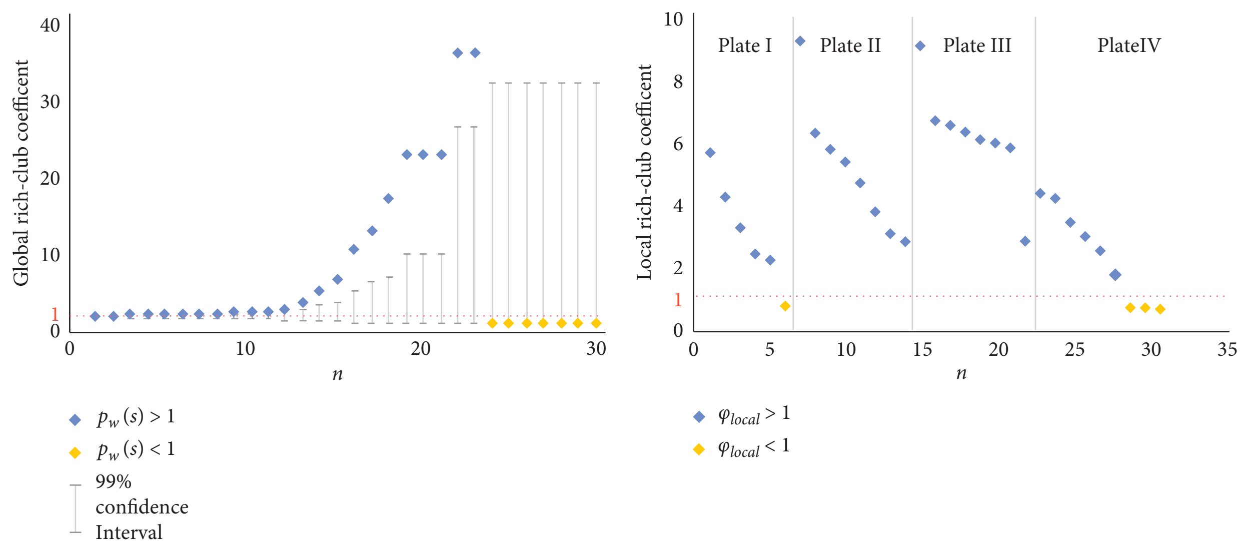
Plate	Density matrix				Image matrix			
	1	2	3	4	1	2	3	4
I	0.2	0.521	0.104	0.000	1	1	0	0
II	0.396	0.054	0.125	0.000	1	0	0	0
III	0.104	0.000	0.321	0.028	0	0	1	0
IV	0.167	0.014	0.125	0.361	1	0	0	1

maintains a distinct two-stage format. In the first stage, the $p_w(s)$ is greater than 1, while the observed coefficient is outside the 99% confidence interval, showing that the results are statistically significant and, in turn, indicating a clear rich-club phenomenon in the CO_2 emission network of the Yangtze River middle reaches megalopolis. On the other hand, with strength equaling 2.5×10^7 and being a significant demarcation point, the curve continues to rise and remains greater than 1 when strength is lower than 2.5×10^7, and when higher than 2.5×10^7, the curve begins to be unstable and declines to less than 1. Therefore, we consider strength to be equal to 2.5×10^7 as the selection condition for identifying the rich-club phenomenon of the CO_2 emission network. Based on these analyses, the "rich-clubs" of the CO_2 emission network in the Yangtze River middle reaches megalopolis were selected, including Wuhan, Changsha, Xiaogan, and Zhuzhou. However, Nanchang, one of the capital cities in the Yangtze River middle reaches megalopolis, is not listed in these "rich-club." Armed with the rising society and economy, it follows that Nanchang does not excel especially in regional influence, in contrast to Wuhan and Changsha. Moreover, the closer distance to the central city may be the reason why Xiaogan and Zhuzhou appear in the "rich-club" list.

On the basis of the above four rich nodes, we further calculated the local rich-club coefficient of each city in the CO_2 emission network, as shown in Figure 6(b). The cities were divided into two categories, whereby type 1 (that $\varphi_{\text{local}} > 1$) tends to connect with rich nodes and type 2 (that $\varphi_{\text{local}} < 1$) intends to connect with nonrich nodes. Only four cities, three of which are located in the fourth plate, tend to link with nonrich nodes. Furthermore, 87.1% of cities accounted for in total are inclined to connect with rich nodes, proving that rich nodes control the major connections in the network. In Figure 7, the type 2 cities of the Yangtze River middle reaches megalopolis are distributed on the edge and are not concentrated in the CO_2 emission network. Type 2 is comprised of Nanchang, Xinyu, Yichang, and Yingtan, mostly located in Jiangxi Province, which proves that Nanchang still plays a certain core role without contacting and echoing the network's core. Moreover, compared with Wuhan and Changsha, Nanchang's infection is obviously limited to the geographical neighboring cities, which belong to the weak core in the middle reaches of the Yangtze River middle reaches megalopolis. At the same time, Yichang also tends to connect with nonrich nodes, which means that at the same level, it maintains a certain influence on surrounding cities, with the possibility of becoming one

Table 2: Role of the CO_2 emissions in the spatial correlation network.

Plate	Number of contacts received		Number of contacts sent		Expected proportion of internal relationship (%)	Actual proportion of internal relationship (%)	Role of plates
	Inside	Outside	Inside	Outside			
I	6	33	6	30	16.7	16.7	Agent
II	3	26	3	27	23.3	10.0	Agent
III	18	22	18	7	23.3	72.0	Main in-flow
IV	26	2	26	19	26.7	57.8	Bidirectional spillover



(a) (b)

Figure 6: CO_2 emission network rich-club global coefficient (a) and local coefficient change trend (b). Note: N represents the number of random networks in Figure 6(a), and the judgment basis for defining rich nodes is the total strength of the nodes' external connections.

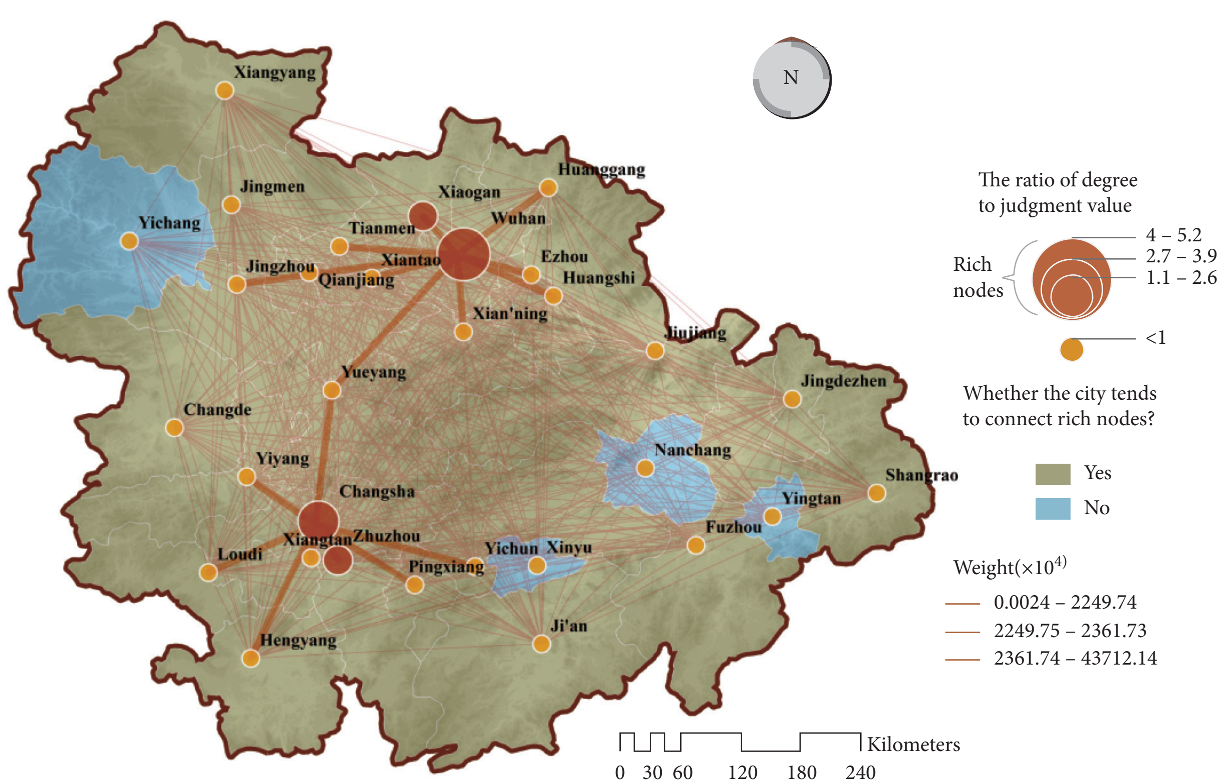


Figure 7: "Rich-club" cities in the CO_2 emission network and local rich-club coefficient.

of the centers in the network of the middle reaches of the Yangtze River middle reaches megalopolis.

4. Concluding Discussion

Challenged by regional emission reductions since the differences in regional economic levels and resource endowments appeared, China's urban agglomerations have sought a coordinated low-carbon and green development path, which has become a crucial issue for regional sustainable development in China. Regarding the agglomeration area of economic and social development covering Hubei, Hunan, and Jiangxi provinces, whether the Yangtze River middle reaches megalopolis can achieve coordinated CO_2 emission reduction is a crucial issue for the Yangtze River Economic Belt, and even for China as a whole. With that purpose in mind, a spatial network analysis framework was constructed to explore the spatial structure and complexity of the CO_2 emission network in the Yangtze River middle reaches megalopolis. Clear regional differences emerged, such as the low density of the CO_2 emission network, the loose intercity links, and the unobvious Nanchang's core role occurs in the CO_2 emissions, which is perhaps due to the closer interaction between Nanchang, which lies closer to the Yangtze River Delta Urban Agglomerations, and cities on the lower Yangtze River. Meantime, the first and the second plate, as the main body in the network, are divided into the "agent" plate by the city roles, whose internal links are one of the crucial factors to consolidate the development of urban agglomerations. Moreover, there is a big disparity between in-degree and out-degree, which indicates that the CO_2 emission network in the Yangtze River middle reaches megalopolis is poorly balanced. At the same time, Wuhan and Changsha show higher resource dependency, which also enlightens us on grasping the interaction between cities under the overall space, considering the spatial network characteristics of urban agglomerations for making policies, achieving synergistic emission reduction. Therefore, formulating regional emission reduction policies should take into account regional differences and refined management. Not only should government further highlight the well-coordinated and interconnected governance theory in regional emission reductions in the Yangtze River middle reaches megalopolis but also ought to establish a green and low-carbon long-term mechanism, encourage cooperation among cities to reduce emissions, lower cooperation barriers, and break the collective action dilemma. The eventual attention will be on the radiation capacity of core cities, simultaneously based on strengthening the complementary functions and dislocation competition within Wuhan, Changsha, and Nanchang, to improve the relatively weaker core position of Nanchang as the provincial capital in the Yangtze River middle reaches megalopolis.

Excelling in denoting multilateral and multidimensional complex relational networks, social network analysis can effectively characterize the interactive relationships among individuals. Hierarchical clustering is beneficial to understand the clustering phenomenon and the member behavioral tendency, thereupon then formulating more effective policies for the subgroup. In addition, integrating GIS with complex network visualization tools provides an effective platform for spatial analysis as well as visualization, through which tools the network structure can be combined with geographic space so as to intuitively reveal the complexity in the network. However, this study has several limitations. Firstly, there remains enormous potential to develop the structural network analysis of the Yangtze River middle reaches megalopolis. Considering that this paper only probes cross-sectional data, limited by time and data availability, a valuable research direction would be focusing on how to apply panel data to explore the change law about the CO_2 emission network of the Yangtze River middle reaches megalopolis on a time and space scale. Secondly, several urban agglomerations besides the Yangtze River middle reaches megalopolis are founded in China following. Assuming that data can be enriched, the spatial structural complexity of CO_2 emissions among different urban agglomerations could be comparatively analyzed based on this framework. Finally, a gravity model rather than traditional O-D data is used to construct the network in this paper, leading to certain limitations in terms of the network structure and spatial relationships in the Yangtze River middle reaches megalopolis.

Incorporating the rich-club coefficient into the indicator system, this paper makes further efforts to enlarge the body of empirical research on CO_2 emissions in complex networks. Following this, a spatial correlation network of CO_2 emissions was found based on urban CO_2 emissions, gross production data, and others based on the gravity model. Moreover, by analyzing the complexity of the CO_2 emission network from three viewpoints in the Yangtze River middle reaches megalopolis, this study reveals the key elements of the network's "rich-club," containing Wuhan, Changsha, Xiaogan, and Zhuzhou, by calculating network features such as density, efficiency, rich-club coefficient, and network structural equivalence; this also demonstrates that cities that tend to connect with rich nodes account for 87.1% in the total. Then, by applying the CONCOR algorithm, the 31 cities in the Yangtze River middle reaches megalopolis were divided into four plates, acting out different roles in the network, in which these cities present key regional traits.

In general, the integrated application of geographic information systems and network visualization assists powerfully with coupling and visualizing the urban CO_2 emission network geography and flow space. Further research may benefit from optimizing the analysis framework, digging the superiorities about the social network in the urban low-carbon development, strengthening the integration with geographic visualization and data availability, and exploring in-depth the regional differences in urban sustainable development and regional collaboration. Secondly, the CO_2 emission network is an interesting topic, such as other networks of urban agglomerations how to affect the structure of CO_2 emission network, and what kind of interaction between cities can accurately describe the complexity of CO_2 emission network. The necessity of urban low-carbon sustainable development, the complexity of the factors leading to regional differences, and the limitations of myriad studies on coordinated development in regional CO_2 emissions may also be our future direction.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

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

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