Evolution of the Spatial Network Structure of Indirect Carbon Emissions from Chinese Household Consumption: A Postprint Based on Social Network Analysis

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Abstract

Understanding the spatial clustering and structural characteristics of household consumption indirect carbon emissions is of great significance for China to achieve the "dual carbon" goals under the new development pattern. Based on the calculation of China's household consumption indirect carbon emissions, this study employs social network analysis to explore the structural characteristics of the spatial correlation network of China's household consumption indirect carbon emissions from 2013 to 2022. The results indicate that: (1) The overall household consumption indirect carbon emissions show an upward trend, increasing by 1.2-fold over the 10-year period; among them, "food", "housing", "transportation and communication", and "education, culture and entertainment" constitute the main components, accounting for 75% of the total. (2) Overall network characteristics: With Jiangsu, Beijing, Zhejiang, Shanghai and other provinces and municipalities as the center, it exhibits a "core-periphery" distribution trend. Among them, network density and the number of connections have decreased, while hierarchical gradient and correlation density have increased. (3) Block model characteristics: Based on node spillover and receiving effects, it is divided into four major blocks, namely "net spillover", "net beneficiary", "broker", and "bidirectional spillover", with each block playing different roles in the field of spatial correlation. (4) Individual network characteristics: Shanghai, Jiangsu, Zhejiang and other provinces and municipalities have the highest centrality, are located in the core area of the correlation network, exhibit significant spatial correlation influence and characteristics of outward radiation, while Qinghai, Heilongjiang and other provinces are in the peripheral area of the correlation network with relatively weak correlation effects.

Full Text

Evolution of Spatial Correlation Structure of Indirect Carbon Emissions from Household Consumption in China: Based on Social Network Analysis

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Abstract: Grasping the spatial clustering and structural characteristics of indirect carbon emissions from household consumption is of great significance for China to achieve its "dual carbon" goals under the new development pattern. Based on the calculation of indirect carbon emissions from household consumption in China, this study employs social network analysis to explore the spatial correlation network structure of these emissions from 2013 to 2022. The results show that: (1) Indirect carbon emissions from household consumption exhibit an overall upward trend, increasing by 1.2 times over the decade. "Food," "housing," "transportation and communication," and "education, culture, and entertainment" constitute the main components, accounting for 75% of the total. (2) Overall network characteristics: Centered on provinces and municipalities such as Jiangsu, Beijing, Zhejiang, and Shanghai, the network demonstrates a "core-periphery" distribution trend. Network density and the number of connections have declined, while hierarchical gradient and connection density have increased. (3) Block model characteristics: Based on node spillover and reception effects, the network is divided into four major blocks—"net spillover," "net beneficiary," "broker," and "bidirectional spillover"—with each block playing distinct roles in the spatial correlation domain. (4) Individual network characteristics: Shanghai, Jiangsu, Zhejiang, and other provinces and municipalities exhibit the highest centrality, occupying core positions in the correlation network with significant spatial correlation influence and outward radiation characteristics. In contrast, Qinghai, Heilongjiang, and other provinces are situated in peripheral network areas with weaker correlation effects.

Keywords: indirect carbon emissions from household consumption; spatial correlation network; social network analysis; gravity model

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Climate change severely constrains the sustainable development of human society and has become a hot topic of global concern. As the world's largest carbon emitter, China has an obligation to undertake green emission reduction tasks. At the 75th United Nations General Assembly, China announced its commitment to achieving the "dual carbon" goals, which means realizing the largest reduction in global carbon emission intensity within the shortest time frame. Faced with such an arduous emission reduction task, it is necessary to identify breakthrough points for precise carbon reduction. Previous research on carbon emissions has mostly focused on direct energy emissions from industrial production, while neglecting that household consumption represents the final consumption of production materials and should bear corresponding emission reduction responsibilities. This is particularly important as China's industrialization process becomes increasingly mature and domestic demand expansion policies drive consumption-side carbon emissions to exceed production-side emissions, making the consumption sector a key focus for energy conservation and carbon reduction. Households serve as the basic unit of residents' economic and social activities, and achieving precise emission reduction requires starting from household consumption to promote a low-carbon transformation of consumption patterns and implement emission reduction tasks effectively.

Indirect carbon emissions from household consumption refer to the indirect energy consumption generated during the process of using goods and services to meet daily life needs. Bin and Dowlatabadi defined carbon emissions from goods and services used in household consumption as indirect carbon emissions from household consumption. Based on a review of existing literature, this paper divides household consumption into eight categories, with the sum of carbon emissions from corresponding modules referred to as indirect carbon emissions from household consumption. As an emerging branch of international carbon emission reduction research, household consumption carbon emissions have attracted widespread scholarly attention, with research focusing on measurement methods, spatiotemporal characteristics, and other aspects. Regarding measurement methods, scholars employ the consumer lifestyle approach, life cycle assessment, and input-output analysis. The consumer lifestyle approach can analyze energy consumption through the matrix relationship between household consumption expenditure and carbon emissions, but involves extensive micro-survey data, making it difficult to operate and verify data accuracy. The life cycle method requires detailed estimation of data throughout the entire product service cycle, yielding the most accurate but time-consuming results. The input-output method organically links production sectors with consumption carbon emissions through input-output tables, accurately reflecting their relationship, and has been widely applied globally, currently being used more frequently in measuring indirect carbon emissions from household consumption. Regarding spatiotemporal characteristics, as research perspectives have become more micro-oriented, spatial factors have been applied to study the evolution of carbon emission patterns, with most scholars using spatial econometric models to examine how environmental, economic, and urbanization factors influence carbon emissions from a geographical proximity perspective. However, from a global perspective, the revealed spatial characteristics are somewhat limited, making it difficult to further reveal the more complex spatial linkage effects presented by household consumption carbon emissions under regional integration. The development of interdisciplinary studies has introduced social network analysis, widely applied in finance, trade, and population migration, into the carbon emission field, which not only overcomes the limitations of spatial econometrics but also characterizes spatial correlation features of relational data from a global perspective.

In summary, current research on household carbon emissions is abundant, but studies exploring the global spatial correlation characteristics from the perspective of indirect carbon emissions from household consumption are limited. Therefore, this paper organically combines the gravity model and social network analysis to investigate the spatial correlation network characteristics of indirect carbon emissions from household consumption, aiming to leverage inter-regional correlation effects to promote factor mobility and provide references for formulating household carbon reduction policies and achieving cross-regional coordinated governance.

1.1 Data Sources

The indirect carbon emission coefficients involved in calculating indirect carbon emissions from household consumption are derived from the 2012, 2015, 2017, 2018, and 2020 China Energy Statistical Yearbooks and the sectoral energy consumption tables in the China Input-Output Tables. Since input-output tables are compiled every five years, data for other years are adjusted using the method from reference [15]. Data on population, GDP, and other indicators involved in the gravity model are obtained from the 2013-2022 China Statistical Yearbooks. Inter-provincial distances are calculated using geographic coordinate systems in ArcGIS 10.7 software.

The adjustment formula for indirect carbon emission coefficients is:

$$F_z = \begin{cases} 2012 & z = 2013 \\ 2012+1 & z = 2014 \\ 2015 & z = 2015 \\ 2012+2 & z = 2016 \\ 2017 & z = 2017 \\ 2018 & z = 2018 \\ 2012+4 & z = 2019 \\ 2020 & z = 2020 \\ 2018+1 & z \in \{2021, 2022\} \end{cases}$$

where F_z represents the indirect carbon emission coefficient in year z (kg CO · yuan [1]).

The calculation formula for indirect carbon emissions from household consumption is:

$$C = \sum_x E_x \times C_x$$

where C represents per capita indirect carbon emissions from household consumption (kg CO ·yuan ^{1}), E_x represents per capita indirect carbon emissions from consumption type x (kg CO ·yuan ^{1}), and C_x represents per capita consumption expenditure on consumption type x (yuan).

1.2 Research Methods

Based on the calculation of indirect carbon emissions from household consumption across provinces and municipalities, this study employs the gravity model to generate a correlation matrix for analyzing spatial network structure characteristics, where "nodes" represent provinces and "lines" represent correlations.

1.2.1 Calculation of Indirect Carbon Emissions from Household Consumption Following Sun Min [16], household consumption types in China's input-output tables and sectoral energy consumption tables are divided into eight categories: food; clothing; housing; household goods and services; transportation and communication; education, culture, and entertainment; healthcare; and other goods and services (Table 1). The indirect carbon emission coefficients for each category are derived from input-output analysis.

1.2.2 Spatial Correlation Network Analysis Method Spatial correlation network analysis integrates spatial interaction theory and social network theory, forming the foundation for constructing correlation network analysis [17]. Spatial interaction theory posits that no city can survive in isolation and must engage in factor flows with other regions to maintain normal operation. Mayer and Ullman [18] define "complementarity, accessibility, and intermediacy" as conditions for spatial interaction occurrence. Indirect carbon emissions from household consumption are influenced by multiple factors such as economy and technology, exhibiting complementarity among provinces and municipalities. Well-developed transportation and information networks between provinces create conditions for accessibility. Policies promoting regional coordinated development, such as the Western Development Strategy, Northeast Revitalization, and Central Region Accelerated Rise, play an intermediary role in building "bridges" for inter-provincial exchanges [19]. In summary, indirect carbon emissions from household consumption in China exhibit spatial interaction forces, where changes in relevant factors in any single province or municipality will trigger changes in the spatial correlation network. Skillfully utilizing these interaction forces can promote rational resource allocation and achieve regional coordinated emission reduction. Social network theory constitutes a system of interrelationships among nodes, where the density, position, and number of connections of nodes in the network all affect factor flow status. Therefore, constructing a spatial correlation network of indirect carbon emissions from household consumption and grasping the spatial structural characteristics of factor flows under spatial interaction forces are of great significance for achieving regional coordinated emission reduction.

Construction of Spatial Correlation Network. Models describing spatial correlation relationships mainly consist of vector autoregression models and modified gravity models. After comprehensive comparison, the former shows strong data sensitivity, easily causing result deviations due to variable lag, while the latter can overcome this characteristic and comprehensively consider inter-regional economic and geographical distance factors. Therefore, this study selects the gravity model to construct the spatial correlation matrix. Since indirect carbon emissions from household consumption involve factors such as consumption and income, the gravity model formula is modified by adding indicators such as indirect carbon emissions, gross national product, and population size. The specific formula is:

$$x_{ij} = \alpha_{ij} \frac{\sqrt[3]{P_i C_i G_i}\sqrt[3]{P_j C_j G_j}}{D_{ij}^2}, \quad D_{ij} = \frac{d_{ij}}{g_i - g_j}$$

where x_{ij} represents the degree of correlation in indirect carbon emissions from household consumption between provinces i and j; α_{ij} represents the correlation contribution of province i in the indirect carbon emissions between i and j; D_{ij} represents the economic distance between provinces i and j; d_{ij} represents the actual geographical distance between provinces i and j (km); P_i and P_j represent the year-end population of provinces i and j (10 persons); C_i and C_j represent indirect carbon emissions from household consumption in provinces i and j (kg CO · yuan ^{1}); G_i and G_j represent the gross national product of provinces i and j (10 yuan); and g_i and g_j represent per capita gross national product of provinces i and j (yuan).

From this, an asymmetric spatial correlation network matrix representing indirect carbon emissions from household consumption in China is constructed. The element values in the matrix represent the degree of spatial correlation of indirect carbon emissions. The row means of the gravity matrix are used as thresholds for comparison, with results divided into two categories: values greater than the threshold are recorded as 1, indicating spatial correlation between the corresponding regions; values less than the threshold are recorded as 0, indicating no spatial correlation.

Indicators of Spatial Correlation Network Characteristics. Social network analysis is a collection of multiple nodes and relationships, expressed as $Y = (V, E)$, where Y represents the overall network graph and V and E represent nodes and relationships. This method has been widely applied across multiple fields and has become a common approach for characterizing spatial correlation network features [20]. This paper introduces it to study the dynamic evolution of China's indirect carbon emissions from household consumption spatial network, analyzing from three perspectives: overall network characteristics, block model characteristics, and individual network characteristics (Figure 1).

[Figure 1: see original paper]

Regarding overall network characteristics, indicators including network density, hierarchy, efficiency, and connectivity are selected, with calculation formulas (Table 2) referencing Ji Xueqiang et al. [21]. Network density refers to the closeness of spatial correlations of indirect carbon emissions from household consumption—the more connections between nodes, the greater the density and the closer the ties. Network hierarchy indicates differences among provinces, with larger values showing more pronounced hierarchical gradients. Network efficiency reflects the stability of the spatial correlation network; higher efficiency indicates a more stable overall network. Network connectivity reflects spatial robustness, with a value of 1 indicating strong connectivity.

Regarding block model characteristics, spatial clustering methods are used to analyze connections within and between blocks. Following Wasserman and Faust [22] and combining block model principles, the network is divided into four major blocks: "bidirectional spillover," "net beneficiary," "net spillover," and "broker," each playing distinct roles in the network [23] (Table 3).

Regarding individual network characteristics, these include degree centrality, betweenness centrality, and closeness centrality. Degree centrality assesses the linking capability between nodes, with larger numbers indicating greater influence. Betweenness centrality measures communication capacity between nodes, with larger numbers indicating more important positions. Closeness centrality is not controlled by other nodes, with larger numbers indicating stronger collection and transmission capabilities.

2.1 Analysis of Indirect Carbon Emissions from Household Consumption in China

From an overall perspective, indirect carbon emissions from household consumption show a fluctuating upward trend from 2013 to 2022, with a relatively slow growth rate. Per capita indirect carbon emissions increased from 3.28 t to 4.57 t, representing a growth of approximately 1.2 times over ten years. The reasons are twofold: on one hand, economic growth and domestic demand expansion strategies indirectly stimulate demand for high-quality and personalized consumption, driving increases in indirect carbon emissions; on the other hand, after the proposal of ecological civilization construction in 2012, the issue attracted widespread social attention, and a series of emission reduction measures implemented across industries transformed residents' consumption patterns to some extent, offsetting part of the indirect carbon emissions triggered by income increases, thus resulting in a relatively gentle growth trend. The 2020 COVID-19 pandemic caused industry shutdowns and household spending contraction, leading to a noticeable reduction in indirect carbon emissions.

From the perspective of individual consumption categories, "food," "housing," "transportation and communication," and "education, culture, and entertainment" constitute the main components, accounting for over 75% of the total. Among these, "housing" consumption continues to grow, "food" consumption shows relatively stable changes, while "education, culture, and entertainment" and "transportation and communication" show upward trends except for a brief decline in 2020. Specifically, "food" and "housing" involve people's livelihoods and are major concerns. With improving living standards, demand in the food consumption sector has diversified, transitioning from meeting basic needs to balanced diets, leading to decreased staple food consumption and increased consumption of eggs, dairy, and meat products. Under the sustainable development background, food production also tends toward green and low-carbon practices. Therefore, "food" consumption changes are relatively stable. "Housing" consumption continues to grow under multiple factors including rising urbanization rates and rural housing renovation. "Education, culture, and entertainment" and "transportation and communication" consumption have increased significantly due to people's growing needs for a better life, with more frequent enjoyment-oriented consumption and travel activities, showing clear growth momentum except for the 2020 pandemic impact.

2.2 Analysis of Spatial Correlation Structure of Indirect Carbon Emissions from Household Consumption in China

This study conducts visual analysis of the spatial correlation of indirect carbon emissions from household consumption in China from 2013 to 2022 using UCINET 6.0 and NETDRAW software, examining overall network characteristics, block model characteristics, and individual network characteristics. Due to space limitations, the overall network diagram uses 2022 data for analysis, while block model and individual network characteristics analyze data from 2013-2022.

2.2.1 Overall Network Characteristics

From the perspective of overall correlation structure (Figure 3), significant spatial interaction forces exist in indirect carbon emissions from household consumption across provinces and municipalities, with inter-regional correlations breaking through traditional geographical proximity limitations and presenting more complex global correlations. Jiangsu, Beijing, Zhejiang, Shanghai, and other provinces and municipalities occupy core network positions with higher connection numbers than other regions, demonstrating a "core-periphery" distribution pattern.

[Figure 3: see original paper]

From the perspective of network density and connection numbers (Figure 4), network connection numbers show a fluctuating downward trend, maintaining between 180-230, indicating that although the correlation degree among provinces in indirect carbon emissions has a loose trend, connections remain very close. Even though the maximum connection number (230) differs from the maximum possible value (31 × 30), this reflects considerable development potential in spatial correlations of indirect carbon emissions from household consumption.

Network connectivity is 1, indicating that all nodes in the network have certain connections with no unreachable points, and the overall network maintains robust connections. Network density remains at a low level, decreasing from 0.21 to 0.18, with small evolution amplitude, indicating weak inter-regional interaction forces that need strengthening. The reasons are threefold: first, economic disparities—large gaps in regional economic development and low-carbon technology levels lead to different household consumption concepts, becoming a factor hindering inter-regional factor flows; second, policy impacts—under the influence of ecological civilization construction policies in 2012, consumption concepts changed and high-carbon industries began transformation, indirectly affecting household consumption choices and reducing indirect carbon emissions, leading to decreased network density; third, pandemic interference—in 2020, the COVID-19 pandemic caused industry shutdowns and household spending contraction, resulting in cliff-like declines in both household consumption expenditure and spatial correlation density.

[Figure 4: see original paper]

From the perspective of network hierarchy and efficiency (Figure 5), both show fluctuating upward trends. Network hierarchy increased from 0.32 to 0.51, indicating pronounced hierarchical gradients in indirect carbon emissions from household consumption in China, with central nodes enhancing their "control" over the overall network. The overall correlation structure (Figure 3) also shows that the central positions of Shandong, Guangdong, and Fujian gradually disintegrated, while the central effects of Shanghai, Jiangsu, Zhejiang, and Beijing strengthened. This is because eastern coastal provinces possess economic, geographical, and technological advantages with strong influence and radiation on other nodes. Particularly under the digital economy background, higher requirements for infrastructure and informatization levels increase hierarchical gradients among provinces. In 2016 and 2020, regional coordinated development policies and pandemic impacts respectively narrowed household consumption gaps, leading to decreased hierarchy. Network efficiency increased from 0.68 to 0.79, indicating that consumption policies, while boosting domestic consumption levels, indirectly widened consumption gaps among residents. Different consumption concepts and patterns hinder factor flows, resulting in reduced internal connection lines.

[Figure 5: see original paper]

From the perspective of local correlation structure, Shandong, Jiangsu, Beijing, Zhejiang, Guangdong, Shanghai, and other provinces and municipalities are located in the "Bohai Rim," "Yangtze River Delta," and "Pearl River Delta" economic circles, with top-ranked transportation location and economic development levels. Household consumption levels and quality of life are generally high, with greater demand for high-carbon foods such as eggs, dairy, and meat, as well as cultural and entertainment activities like tourism. Internally, these regions attract population inflows and trade exchanges through advanced low-carbon technologies, infrastructure, and capital advantages, indirectly increasing population density and daily consumption of housing, transportation, and food. Externally, they export low-carbon technologies and high-energy-consuming industries, promoting economic development in surrounding regions and improving household living standards. Therefore, these provinces and municipalities occupy core positions in the spatial correlation network, maintaining close ties with other regions. Guangxi, Qinghai, Inner Mongolia, Ningxia, and other central and western regions have lower economic development levels, incomplete internal infrastructure, and household consumption at relatively low levels, with weak attraction to external labor and industries, thus being situated in "peripheral" areas of the spatial correlation network. Under the dual drive of western development policies and natural geographical environments, seasonal tourism population increases and regional trade exchanges affect household consumption structures to some extent, so corresponding correlation lines still exist spatially. In summary, China's household consumption carbon reduction needs to target core provinces and municipalities in the spatial correlation network, continuing to develop low-carbon technologies internally, promote green industry development, advocate high-quality household consumption, and fundamentally reduce indirect carbon emissions. Externally, it should radiate capital, energy-saving technologies, and clean energy to other provinces through inter-regional correlation effects, promoting regional economic development while achieving coordinated emission reduction. Peripheral provinces and municipalities need to utilize policies such as western development and northeast revitalization to develop internal economies, improve infrastructure, guide green and low-carbon development while improving household living standards.

2.2.2 Block Model Characteristics

To further understand the roles and correlation relationships within the spatial correlation structure of indirect carbon emissions from household consumption, the CONCOR algorithm is used with convergence index and segmentation degree set to 2 and 0.2, respectively, dividing 31 provinces and municipalities into four major blocks based on spatial correlation network characteristics (Table 4). Among them, the number of internal block connections is 43, while inter-block connections number 187.

From the perspective of block structure characteristics and spillover effects: (1) The net beneficiary block includes Beijing, Jiangsu, Shanghai, and Zhejiang, with spillover and reception relationship numbers of 31 and 68, respectively. The reception effect far exceeds the spillover effect, playing a dominant role, thus belonging to the "net beneficiary" block. Due to the high economic development levels within the block, residents emphasize high-quality lifestyles, generating significantly higher household consumption than other provinces. Simultaneously, with complete infrastructure, convenient transportation and communication, and entrepreneurial employment opportunities, these areas attract substantial industry and labor inflows, resulting in strong block reception effects. (2) The net spillover block includes Gansu, Guangxi, Guizhou, Hainan, Heilongjiang, Hunan, Jilin, Jiangxi, Liaoning, Ningxia, Qinghai, Tibet, Xinjiang, Yunnan, Chongqing, Sichuan, Shaanxi, Anhui, and Henan. Spillover relationships far exceed reception relationships, with most located in northern and central-western regions with relatively slow economic development, focusing on energy industries or agriculture, and weak attraction to labor and industries. Internally, they rely on natural energy advantages to attract capital, industries, and technologies from other provinces; externally, they increase income through population outflows and product exports, with relatively small populations and industries within the provinces, showing obvious spillover relationships. (3) The broker block includes Hebei, Inner Mongolia, Shanxi, Tianjin, and Shandong, with reception and spillover relationship numbers of 41 and 47, respectively. Spillover relationships exceed reception relationships but are intermediate between the first and fourth blocks, belonging to the "broker" block. These provinces and municipalities occupy important regional positions, serving as hubs in economic circles such as the "Yangtze River Delta," "Beijing-Tianjin-Hebei," and "Belt and Road," acting as "bridges" connecting various provinces. They not only receive spillovers from economically developed provinces but also send elements to other provinces. (4) The bidirectional spillover block includes Fujian, Guangdong, and Hubei, meeting the requirement that actual internal relationship proportions exceed expected internal relationship proportions while maintaining both internal and external connections with small gaps, belonging to the "bidirectional spillover" block. Provinces within this block are located in coastal areas with high economic levels, abundant resources, and convenient transportation, resulting in high household happiness indices and unobvious population outflow, with good internal correlation effects. Externally, they maintain close ties with other provinces through good economic and location advantages.

Overall, the spatial correlation blocks of indirect carbon emissions from household consumption exhibit close connections and good regional linkage effects. Leveraging reception and spillover effects among blocks can promote the transmission of low-carbon technologies and green concepts, achieving regional coordinated development, improving household living standards, and reducing household consumption carbon emissions.

2.2.3 Individual Network Characteristics

To further explore the role of each province and municipality in the indirect carbon emissions spatial network, analysis is conducted from degree centrality, betweenness centrality, and closeness centrality (Table 5).

(1) From the perspective of degree centrality, the top five provinces and municipalities are Jiangsu, Shanghai, Zhejiang, Beijing, and Guangdong, showing strong spatial correlations with other provinces. Jiangsu's degree centrality index reaches 90.32, making it the center of the spatial correlation network. Objectively, Jiangsu has close correlation relationships with other provinces, with beneficiary relationships exceeding spillover re-

lationships. Subjectively, top-ranked provinces and municipalities are located in the Bohai Rim, Beijing-Tianjin-Hebei, and Yangtze River Delta economic circles, with absolute advantages in capital, technology, and geographical location, facing fewer barriers in low-carbon correlations with other provinces. They can better play central network roles, spillover low-carbon technologies, capital, and green consumption concepts outward, and attract talent and labor inward, maintaining close connections among provinces. Relatively backward provinces such as Anhui, Inner Mongolia, Liaoning, Jiangxi, and Tianjin have fewer correlations with other provinces and less dense spatial network structures. Anhui has a large population but relatively slow economic development, making external expansion difficult while meeting internal demand; Inner Mongolia and Jiangxi are limited by their own resources and economic development; Liaoning is restricted by geographical location; Tianjin has a large population, but the adjustment of its economic structure has weakened its industrial "leader" advantage, preventing it from occupying a central network position. From the perspectives of indegree and outdegree, representing beneficiary and spillover relationships respectively, top-ranked provinces in degree centrality show dominant beneficiary effects, while lower-ranked provinces show more spillovers, reflecting that eastern developed regions drive development in western and central underdeveloped regions through spatial correlation relationships.

(2) From the perspective of betweenness centrality, top-ranked provinces and municipalities are Beijing, Jiangsu, Shanghai, and Zhejiang, with values far exceeding the average, showing strong "intermediary" effects and serving as "bridges" in the spatial correlation network. Removing these provinces would hinder network connectivity. The economic, geographical, and technological advantages of Beijing, Jiangsu, Shanghai, and Zhejiang provide absolute control over factor reception and radiation, placing them in pivotal positions in the indirect carbon emissions spatial correlation network and enhancing their attraction to surrounding factors. The large differences in centrality values indicate significant spatial heterogeneity in indirect carbon emissions among provinces, requiring the "intermediary" role of provinces with strong betweenness centrality to achieve emission compliance.

(3) From the perspective of closeness centrality, this measures the global centrality of the spatial correlation network and the closeness among provinces. Jiangsu has the highest closeness centrality at 95.83, indicating it is the network center with closer distances to correlated provinces and more information acquisition. The variation amplitude of closeness centrality is smaller than that of betweenness centrality, showing that with regional integration, closeness centrality shows an upward trend and connections are gradually increasing. These increasingly close connections can be leveraged to drive the development of low-carbon industries.

4.1 Conclusions

(1) Regarding indirect carbon emissions from household consumption, the overall trend shows fluctuating growth, increasing by 1.2 times between 2013 and 2022. “Food,” “housing,” “transportation and communication,” and “education, culture, and entertainment” constitute the main components, accounting for over 75% of the total. Among these, “housing” consumption continues to grow, “food” consumption remains relatively stable, while “education, culture, and entertainment” and “transportation and communication” show upward trends except for a brief decline in 2020.

(2) Overall network characteristics: The network has broken through geographical proximity limitations, presenting closer spatial correlations. Network density and connection numbers have declined, indicating that spatial interaction forces have weakened due to economic and policy influences, hindering factor flows. High and rising values of network hierarchy and efficiency demonstrate that the core-periphery pattern dominated by Shanghai, Jiangsu, Beijing, and Zhejiang features significant hierarchical gradients, strong “control” over the overall network, and strong factor attraction. Increased network efficiency reflects that consumption policies, while boosting domestic consumption levels, have indirectly widened consumption gaps among residents. Different consumption concepts and patterns hinder factor flows, leading to reduced internal connection lines.

(3) Block model characteristics: The “net beneficiary” block shows reception effects exceeding spillover effects, with block provinces having high economic development levels but poor resource endowments. While receiving talent, energy, and other inflows, these provinces also provide capital and technical support to other blocks. The “net spillover” block shows obvious spillover effects, with provinces having lower economic levels but resource advantages. The “broker” block indicates that provinces within the block have convenient transportation locations, building “bridges” for factor flows between blocks. The “bidirectional spillover” block shows good geographical locations and resource endowments, capable of simultaneously handling spillover and reception effects.

(4) Individual network characteristics: The network shows a “core-periphery” correlation trend. Jiangsu, Beijing, Shanghai, Zhejiang, and other provinces and municipalities occupy core positions in the spatial correlation network, with degree centrality, closeness centrality, and betweenness centrality all higher than other provinces. They have strong factor attraction and can quickly establish correlations with other provinces as factor agglomeration centers. In contrast, provinces in peripheral network areas generally have low centrality, prominent non-equilibrium development, weak factor attraction, and require spillover effects from core provinces to drive development.

Unlike previous scholars who focused only on correlation effects of direct carbon emissions between regions or influencing factors of household consumption carbon emissions [3,5,6,22], this study examines indirect carbon emissions from the household consumption perspective, focusing on exploring global spatial correlation effects. Based on the density, position, and connection numbers of each province in the network, it grasps spatial characteristics of factor flows under spatial interaction forces to promote regional coordinated emission reduction. Regarding spatial correlation, indirect carbon emissions from household consumption are consistent with Wang Xiaoping et al. [5] and Sun Yanan et al. [6] in that carbon emission factors from each province exhibit complex correlations under spatial interaction forces. However, household consumption carbon emissions are more sensitive and easily influenced by policies, consumption concepts, and technology levels, resulting in greater variation amplitude in network density and hierarchy. Meanwhile, direct carbon emissions can narrow carbon gaps through factor flows such as low-carbon technology and capital, while provincial economic levels and consumption concepts will continue to widen indirect carbon emissions, causing network hierarchy to show opposite trends compared to direct carbon emissions. Regarding household consumption volume, unlike Peng Lulu et al. [3] and Shi Qinqin et al. [4] who focused on exploring influencing effects of economy, population, and technology to formulate micro-level solutions from factor perspectives, this study reveals spatial features that were previously limited to geographically adjacent areas. This study finds that factor correlations have broken through "proximity" regional limitations, making traditional influencing factors insufficient for global emission reduction. Therefore, based on each province's position in the spatial network and the impact of reception and spillover effects on factor flows, global coordinated emission reduction measures should be formulated.

4.2 Recommendations

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

(1) Optimize household consumption structure and promote the transformation of residents' consumption concepts toward low-carbon patterns to reduce household consumption carbon emissions from the source. Break administrative restrictions between regions and adopt a global perspective on indirect carbon emissions from household consumption, building a "national chessboard" regional coordinated governance framework for carbon emissions. Address network relationship numbers, network efficiency, and network hierarchy one by one to enhance regional correlations, drive factor flows, and strengthen inter-regional mutual benefits.

(2) Promote the integration of the digital economy with real industries to advance informatization development. Provinces and municipalities with high digitalization levels such as Shanghai, Jiangsu, and Zhejiang should leverage their location and economic advantages to spill over relevant fac-

tors to surrounding provinces and promote informatization development. Provinces such as Inner Mongolia, Xinjiang, and Yunnan should seize opportunities from receiving spillover factors from economically developed provinces, adjust internal economic structures, and improve infrastructure to lay foundations for rapid internal informatization development.

(3) Play the "leading-following" role of provinces in the spatial correlation network. Central provinces and municipalities should radiate low-carbon industries or technologies to other provinces through technical exchanges and ecological compensation, driving development in peripheral regions. Other provinces can learn from central provinces' development experiences to drive local development and narrow comprehensive level gaps during the "following" process. Internally, each province should also emphasize implementing carbon reduction measures. Provinces in core network positions should minimize dependence on fossil energy from peripheral provinces and increase the proportion of clean energy consumption. Peripheral provinces should focus on improving their own industrial layout "green" thresholds while receiving low-carbon technology spillovers from core provinces.

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Note: Figure translations are in progress. See original paper for figures.