land

Article

Influence of Intercity Network on Land Comprehensive Carrying Capacity: A Perspective of Population Flow

Xiang Shi [1], Xiao Yu [1,*], Shijun Wang [2] and Feilong Hao [2]

1 Northeast Asian Studies College, Jilin University, Changchun 130012, China; shixiang@jlu.edu.cn
2 School of Geographical Science, Northeast Normal University, Changchun 130024, China; wangsj@nenu.edu.cn (S.W.); haofl587@nenu.edu.cn (F.H.)
* Correspondence: yuxiao@jlu.edu.cn

Abstract: The world is experiencing the largest wave of urban growth in history. Maintaining the rapid growth of cities without causing land and resource shortages is a severe problem that must be solved urgently. With the rapid development of globalization and information technology, the meaning of land comprehensive carrying capacity presents new changes. It is no longer entirely dependent on local resources and is likely to benefit from intercity connections beyond urban boundaries. However, can an inter-city network be a non-local solution to sustain urban growth without increasing land pressure? To address this question, this study adopted 287 cities in China as the research object to describe the spatial carrying characteristics of land at the national level by constructing an evaluation index system for land comprehensive carrying capacity. Furthermore, we constructed a population flow network model through social network analysis to explore the influence of intercity network on land comprehensive carrying capacity. Our findings are as follows: (1) The regional differentiation characteristics of land comprehensive carrying capacity at the national scale are evident, and reveal a spatial pattern significantly related to the urban economic development level. (2) The weighted in-degree, weighted degree centrality, and betweenness centrality in the intercity network positively impact the land comprehensive carrying capacity, and land use efficiency has a partial mediating effect. (3) Land comprehensive carrying capacity can be determined by non-local factors rather than local factors. As an effective non-local channel, strengthening intercity population flow and network integration can flexibly manage urban land scarcity.

Keywords: intercity network; population flow; land comprehensive carrying capacity; influencing factor; China

check for updates

Citation: Shi, X.; Yu, X.; Wang, S.; Hao, F. Influence of Intercity Network on Land Comprehensive Carrying Capacity: A Perspective of Population Flow. *Land* **2023**, *12*, 1515. https://doi.org/10.3390/land12081515

Academic Editor: Maria Rosa Trovato

Received: 8 June 2023
Revised: 24 July 2023
Accepted: 25 July 2023
Published: 30 July 2023

1. Introduction

The rapid growth of cities, due to population inflow and urban land expansion has placed great pressure on the land-carrying system. Many scholars believe that city size should have a threshold limit to maintain a balance between nature and society [1]. They hold that excessive socioeconomic activity will have an irreversible negative impact on resources and the environment, thereby weakening urban development [2]. Therefore, urban development should be limited by carrying capacity [3–5]. However, there is no scientific consensus on how to determine the upper limit of urban growth. The opposing view is that openness and agglomeration are the essence of the city. This view holds that cities cannot maintain normal operations through self-sufficiency and their development depends more on resource exchange with other cities [6]. Therefore, the sustainable development of a city requires more than simply controlling its scale [7]. Instead, macro planning on a larger geographical scale is required to realize the free flow and optimal distribution of factors among cities [8].

With the ever-changing transportation and information technology, the cyberspace logic of "flow determines place" has gradually become the core of intercity relations research. Breaking the scope limitation of the center-hinterland, urban networks have become an important organizational model of modern urban systems. Some cities have extremely high network power and link capabilities through better embedding in the network, and benefit from the "networking" effect of intercity relations [9]. For example, resource migration encourages some cities to specialize and strengthens their comparative advantages [10,11]. The differences between cities create further complementary effects [12]. However, some cities experience the downward cycle accumulation caused by network connections [13–16]. For example, small- and medium-sized cities experience a "siphon effect" or "agglomeration shadow" because their resources are plundered resources by neighboring large cities [17,18]. Therefore, the externalities generated by intercity networks may be either synergistic/complementary effects or competitive/siphon effects [19,20]. In other words, the intercity network formed by the flow of various factors may have opposite effects on different cities, regions, and their stages of development.

Population flow is an important part of the intercity network. According to the seventh national census data, China's floating population reached 376 million in 2020 [21]. Large-scale and normalized cross-regional population flow promotes the transformation of low-mobility "local China" to high-mobility "migrating China". In the future, population flow will continue to become an important driving force for regional coordination and economic development and promote more frequent intercity connections [22,23]. However, it is not known whether large-scale cross-regional population flow will promote the human-land relationship in a region to reach a higher level of dynamic balance or result in imbalance instead. Therefore, it is of great significance to explore the impact of inter-city networks on land comprehensive carrying capacity from the perspective of population flow. The literature on land-carrying carrying capacity has a long history and has formed a mature theoretical framework over time. However, with the wide application of geospatial big data, people's understanding and research methods of land-carrying capacity have changed [24–27]. In particular, on the basis of the existing research, the research data and horizon need to be supplemented and improved. In the context of population flow, there is still a research gap in the exploration of changes in land comprehensive carrying capacity and the role of intercity networks.

First, in the study of the carrying relationship between population and land, the existing literature is primarily based on traditional data such as census data and urban statistical yearbooks. Since 2015, large internet companies led by Baidu and Tencent have collected and measured the daily population flow between cities at all levels using the spatial positioning of millions of users. Compared with traditional data, big data on population flow provide accurate spatial and temporal information. Spatial-and-temporal-behavior big datasets make it possible to study the interaction between human activities and geospatial space in a larger study area with finer spatial units and more continuous time observations [28–30]. It has become an important trend to study the interactive process and mechanism of the human–land relationship using geographic big data.

Second, the current research on land comprehensive carrying capacity is mainly based on relatively closed local thinking [24] and does not consider the interaction of geographical elements such as population flow, ecological footprint, virtual water trade, and embodied carbon emissions between cities [31]. The influence and function of network externalities generated by intercity connections on land comprehensive carrying capacity, variables considered under open systems thinking, are ignored. The current research mostly follows the basic paradigm that human activities cannot exceed the carrying capacity of local resources and the environment and focuses on the coupling and co-ordination of land, society, economy, and population under the local thinking model [32–34]. However, the city is not an independent island; big, economically developed cities are closely linked to other cities, and the flow of population, capital, technology, and other factors is regular. Therefore, we need to put the city into the larger scale of the intercity network, based on a more macro-regional perspective, to think about local issues. Does the formation of an intercity network increase the carrying burden of the city or reduce its carrying burden of the city? In the face of the growing shortage of urban land, should we adopt urban containment or promote intercity connections?

To address these questions, this paper explores the characteristics of the intercity population flow network at the national level using Tencent location big data from 2018. This paper measures the comprehensive land-carrying capacity of 287 prefecture-level cities in China and focuses on the impact of intercity networks on the comprehensive carrying capacity of urban land from the perspective of population flow. This approach enables us to address some gaps in the existing literature such as insufficient spatial scale and discontinuous time scale. Further, compared with the previous research on land-carrying capacity, which emphasizes local thinking, we expand the research scope to a regional level, and the research perspective from local thinking to network thinking, to provide a new perspective based on intercity connections.

2. Materials and Methods

2.1. Study Areas

We selected the city area of 287 prefecture-level cities in China as the research areas and visualized their intercity population flow network and comprehensive land-carrying characteristics. To gain a more intuitive understanding of the status quo of China's land resource carrying capacity, we drew a map of China's land-use distribution based on the Resource and Environmental Science Data Registration and Publishing System (http://www.resdc.cn/DOI, accessed on 12 March 2023) (Figure 1) [35]. Cultivated land is mainly distributed in the Northeast Plain, Huang-Huai-Hai Plain, Sichuan Basin, and the middle and lower reaches of the Yangtze River. Forest land is mainly distributed in the Northeast, Southeast, and Southwest regions. Grassland is mainly distributed in the Mongolian Plateau and Qinghai–Tibet Plateau. The scale of urban and rural construction land in Shandong, Henan, Jiangsu, Guangdong, Hebei, Beijing, and Shanghai is significantly higher than that in other regions. The large-scale construction land reflects large populations, and economically developed areas exert greater pressure on land resources. There is a large area of unused land in Xinjiang, western Inner Mongolia, northwestern Qinghai, and northwestern Tibet. In terms of natural location, Northeast China, Central South China, and East China have flat terrain, mainly cultivated land and forest land, rich land resources, and great advantages in land-carrying capacity. On the contrary, the Northwest and Southwest regions have limited available land resources, poor soil quality, and weak land-carrying potential.

2.2. Data Resources

The research data were mainly of two kinds: population flow data and land resource data. Between them, the population flow data came from Tencent location big data (https://heat.qq.com/wap_qqmap_big_data/index.html, accessed on 5 January 2020). Tencent recorded the daily population inflows, outflows, and total flows of 287 cities in 2018. According to the 2022 China Mobile Internet Annual Report released by QuestMobile, the number of mobile internet users in 2022 reached 1.203 billion, among whom the number of Tencent app users reached 1.176 billion, and the penetration rate of mobile Internet reached 74.15%. This shows that the dataset is representative and can reflect the real situation of population flow in China accurately. Land resources data mainly came from the China Land and Resources Statistical Yearbook, China Environment Statistical Yearbook, China City Statistical Yearbook, China Urban Construction Statistical Yearbook, and the public information and annual reports of the relevant departments in various cities.

2.3. Research Methods

2.3.1. Evaluation of Land Comprehensive Carrying Capacity

The Concept of Land Comprehensive Carrying Capacity

Academic research on land-carrying capacity has experienced an evolution from the single-factor carrying of land grain to population to the comprehensive carrying of land resources on all aspects of human social development [36–38]. This concept has been extended from a single land factor to a more comprehensive and scientific resource field. The land comprehensive carrying capacity derived from the new conception is a complex system with a complex feedback relationship [39]. Due to the duality of nature and society, the land comprehensive carrying capacity usually covers multiple carrying subsystems such as resources, environment, economy, and society [40,41]. Its size is determined by the carrying state and the interaction of each subsystem.

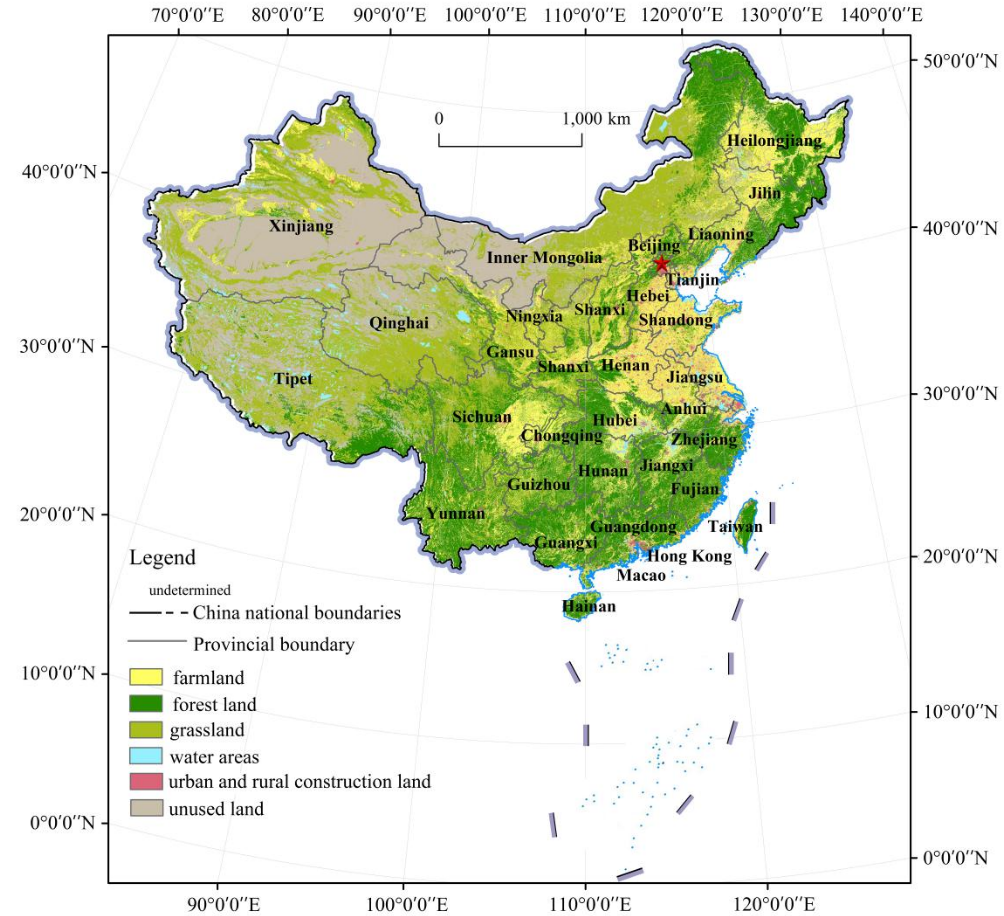

Figure 1. Distribution of land-use types in China (data are sourced Resource and Environmental Science Data Registration and Publishing System (http://www.resdc.cn/DOI, accessed on 12 March 2023)).

This study is based on the original concept of carrying capacity. Land comprehensive carrying capacity was divided into two pairs of interaction forces: pressure and supporting force, and destructive force and restoring force. The pressure and destructive force represent the negative load of the land, the supporting force and restoring force represent the positive load of the land, and the resultant force under the two pairs of forces is the land comprehensive carrying capacity (Figure 2) [42]. Among them, the pressure and destructive force represent the negative load of the land, and the supporting force and restoring force represent the positive load of the land. The ideal state of land comprehensive carrying capacity is a stable state that does not reach the threshold [43]. The four forces restrict each other and penetrate each other. Based on the above concepts, we constructed the land comprehensive carrying PS-DR (pressure–support and destructiveness–resilience) quadrilateral interaction force model to measure the land comprehensive carrying capacity of 287 cities in China [34,44].

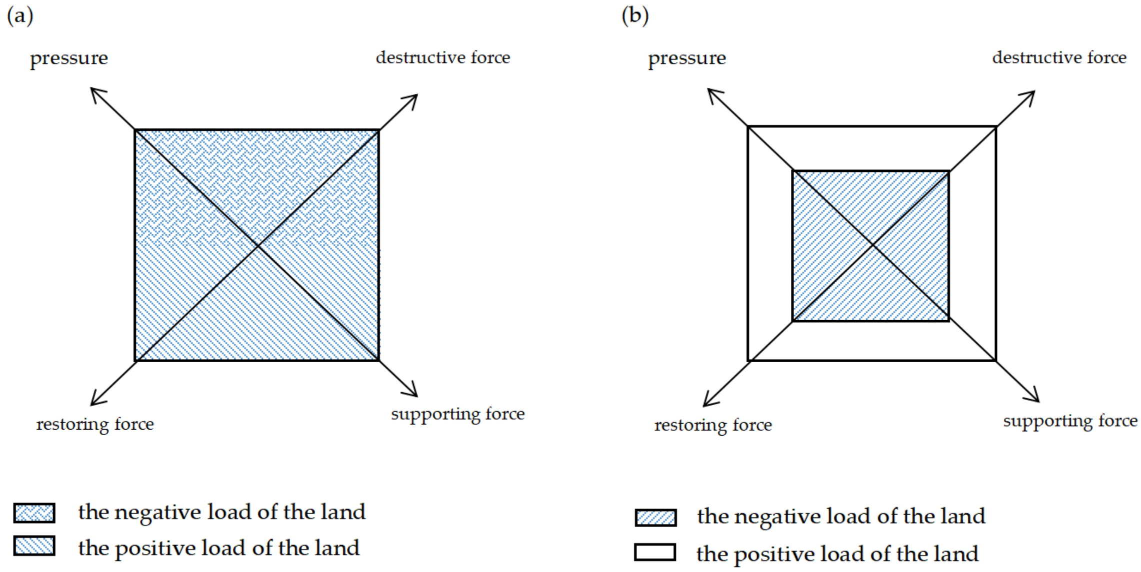

Figure 2. Conceptual models of land comprehensive carrying capacity: (**a**) early warning model of complete carrying state of land; (**b**) ideal carrying state model of land.

Evaluation Index System of Land Comprehensive Carrying Capacity

Previous studies have introduced various indicator systems for assessing urban land-carrying capacity. These studies provide valuable references for the research team to select proper indicators for measuring land comprehensive carrying capacity under the framework of the PS-DR model [34]. According to the principle of sustainable development [45], these indicators can be further classified into the categories of water, land, population, economic, and social (Table 1). It appears that some indicators are expressed in different ways but carry similar meaning; in these cases, the most representative expression was used.

Table 1. Evaluation index system of land comprehensive carrying capacity.

Goal Layer	Impact Factors	Indicators	Serial Number	The Nature of Indicators
Pressure	Water resources	Water consumption per capita	$P^1{}_1$	-
		Total urban water supply	$P^1{}_2$	-
	Land resources	Occupied land of industrial and mining	$P^1{}_3$	-
		Annual cultivated land reduction area	$P^1{}_4$	-
	Population	Population density	$P^1{}_5$	-
		Permanent resident population	$P^1{}_6$	-
		Natural population growth rate	$P^1{}_7$	-
		Urban unemployment rate	$P^1{}_8$	-
Supporting force	Resource support	Per capita water resources	$S^2{}_1$	+
		Land area	$S^2{}_2$	+
		Cultivated land area	$S^2{}_3$	+
		Per capita grain output	$S^2{}_4$	+
	Economic and social support	Whole-society productivity	$S^2{}_5$	+
		Investment intensity of fixed assets	$S^2{}_6$	+
		Per capita disposable income of urban residents	$S^2{}_7$	+
		Per capita disposable income of rural residents	$S^2{}_8$	+
Destructive force	Water environment	Discharge amount of industrial wastewater	$D^3{}_1$	-
		Total wastewater discharge	$D^3{}_2$	-
	Edatope	Output of industrial hazardous solid waste	$D^3{}_3$	-
		Output of general industrial solid waste	$D^3{}_4$	-
Restoring force	Pollution treatment capacity	Treatment rate of domestic sewage	$R^4{}_1$	+
		Industrial hazardous solid waste disposal volume	$R^4{}_2$	+
		Industrial general solid waste disposal volume	$R^4{}_3$	+

Based on the concept of carrying capacity, we took the water and soil resources owned by the city itself and the economic wealth created as the supporting force of the land carrying system. The consumption of water and soil resources and population factors are regarded as the pressures of the land carrying system. The destruction of the water and soil environment is regarded as the destructive force of the land carrying system, and the governance of the water and soil environment is regarded as the restoring force of the land carrying system [46]. This understanding of the carriers and loads of urban land carrying capacity is also echoed in the studies of Shen et al. (2020) and Liao et al. (2020) in investigating urban resource and environmental carrying capacity and regional water resource carrying capacity [47,48].

Based on the above division principles, we further refined the indicators. We selected water consumption per capita and total urban water supply as indicators to measure the supporting force of water and land resources [49]. At the same time, considering that the essence of land carrying capacity is the relationship between human and grain, we also included per capita grain output and cultivated land area into the evaluation index of supporting force [50]. Based on the three aspects of urban–land–resident, whole-society productivity, investment intensity of fixed assets and per capita disposable income represent a city's production capacity, assets, and income level, which can be used to measure the economic and social support capacity of a city [51]. Water consumption per capita represents the consumption of domestic water for residents, and total urban water supply is the total amount of water supplied by water supply enterprises, that is, the sum of various water consumption levels in urban and rural areas. Therefore, water consumption per capita and total urban water supply were selected as the evaluation indices to measure the consumption of water resources [47]. Occupation of land by industry and mining is considered to be a type of land use that consumes more serious land resources [52]; therefore, this land and annual cultivated land reduction area were selected as the evaluation index for land resource consumption. It was considered that the permanent residential population can better reflect the real habitant status of a city, given the fact that large rural-to-urban migrant populations are not registered with urban "hukou" in the urbanizing China [42]. Natural population growth rate indicates the growth of population size, and urban unemployment rate indicates idle labor capacity. They are the main pressures on a city's economy and society [53]. Therefore, we selected permanent resident population, population density, natural population growth rate, and urban unemployment rate as indicators to measure population pressure. Drawing on the research of Shen et al. (2020) and Wang et al. (2019) [34,47], we selected the discharge amount of industrial wastewater and total wastewater discharge as indicators to measure destructive force to the water environment, and we selected output of industrial hazardous solid waste and output of general industrial solid waste to measure destructive force to edatope [53]. Corresponding to the destructive force, we selected treatment rate of domestic sewage, industrial hazardous solid waste disposal volume, and industrial general solid waste disposal volume to measure restoring force to water and land environment [32]. Based on the existing literature research index system, combined with the availability of index data, an evaluation index system of land comprehensive carrying capacity was constructed (Table 1).

Land Comprehensive Carrying Capacity Contribution Value

Based on the improved evaluation method of the full-array polygon graphic index of resource and environmental carrying capacity by Liang et al. [34], we constructed an evaluation model of land comprehensive carrying capacity. This method sets a total of standardized indicators, with origin O as the center and standardized upper limit value 1 as the radius, to form a central polygon. Each index value is taken between the origin and vertex of the central polygon, and the index value is connected to form an irregular polygon. According to the principles of classification and multiplication, each index can form a different irregular polygon. We defined the ratio of the mean value of each irregular polygon area to the central polygon area as the contribution value of each subitem carrying capacity, indicating the influence of each sub-item on the land comprehensive carrying capacity.

$$C = \frac{\sum_{i<j}^{i,j}\left(k_i^m + 1\right)\left(k_j^m + 1\right)}{N(N-1)} \tag{1}$$

$$S = \frac{\sum_{i=1}^{i} C_i^p}{\sum_{j=1}^{j} C_j^n} \tag{2}$$

where C represents the contribution value of the partial carrying capacity; N represents the number of subindicators; k_i^m and k_j^m are the i and j index values in the mth index system; and S denotes the carrying status. C_i^p represents the ith positive contribution value, and C_j^n represents the jth negative contribution.

We defined the ratio of the sum of the positive and negative contribution values as the carrying state. A ratio is greater than 1 indicates that the regional carrying status is good; the larger the ratio, the better is the regional carrying status. In contrast, a ratio less than 1 indicates that the regional carrying status is overloaded and should be taken as warning [34].

2.3.2. Intercity Flow Network Construction

The population flow between cities has flow rate and direction; hence, the weighted asymmetric matrix of intercity population flow at the national level was constructed based on Tencent location big data.

$$R = \begin{bmatrix} 0 & R_{12} & \dots & R_{1(n-1)} & R_{1n} \\ R_{21} & 0 & \dots & R_{2(n-1)} & R_{2n} \\ \dots & \dots & 0 & \dots & \dots \\ R_{(n-1)1} & R_{(n-1)2} & \dots & 0 & R_{(n-1)n} \\ R_{n1} & R_{n2} & \dots & R_{n(n-1)} & 0 \end{bmatrix} \tag{3}$$

We introduced the multicenter evaluation model of social network analysis to describe the characteristics of intercity networks from five aspects: the core position of network nodes, agglomeration and diffusion ability, intermediary role, and closeness [54].

Weighted degree centrality (C_{WD}) characterizes the importance or influence of nodes in the network. In the intercity network, if a city node has a direct population connection with many other nodes, the city is at the center. That is, the wider the relationship between city nodes, the more important the city. For a directed weighted network, the weighted degree centrality is more representative of a node's rights and status in the network than the degree centrality. This is a comprehensive reflection of the number of other nodes connected to the city node (with population flow) and the size of the edge (population flow intensity).

$$C_{WD}(i) = \sum_{j=1}^{N} R_{ij} \tag{4}$$

where $C_{WD}(i)$ denotes the weighted degree centrality of city i, and R_{ij} is the intensity of population flow between city i and city j.

The weighted in-degree (C_{WI}) represents the sum of the edge weights of all arcs ending at node i. The in-degree value of urban node i can be expressed as:

$$C_{WI}(i) = \sum_{j=1}^{N} R_{i\leftarrow j} \tag{5}$$

where $R_{i\leftarrow j}$ denotes the population size flowing from city j to city i.

The weighted out-degree (C_{WO}) represents the sum of edge weights of all arcs starting from node i. The out-degree value of urban node i can be expressed as:

$$C_{WO}(i) = \sum_{j=1}^{N} R_{i \to j} \tag{6}$$

where $R_{i \to j}$ denotes the population size of city i flowing out to city j.

Closeness centrality (C_C) represents the ratio of the number of cities with population flow to the sum of the shortest paths from those cities to other cities. In the intercity network, if the distance between a city node and other cities with population flow is very short, the city has a high closeness centrality in the whole intercity network. Closeness centrality was used to measure the closeness of the related cities in the population flow network.

$$C_c(i) = \frac{N-1}{\sum_{j=1;j \neq i}^{N} d_{ij}} \tag{7}$$

where d_{ij} denotes the number of shortest paths between city i and city j. N denotes the number of city nodes.

Betweenness centrality (C_B) is a statistical index that measures the intermediary role of city nodes in the intercity flow network. Betweenness centrality represents the transfer capability or gateway function of the city in the intercity network. If a city is in the shortest path of multiple population flows in the intercity flow network, the city has an important media role. The higher the betweenness centrality of a city, the greater its control over the intercity flow network.

$$C_B(i) = \sum_{j=1;k=1;j \neq k \neq i}^{N} \frac{N_{jk}(i)}{N_k} \tag{8}$$

where N_{jk} denotes the shortest path number of population flow between city j and city k; and $N_{jk}(i)$ denotes the number of shortest paths through city i.

2.3.3. Spatial Econometric Model

Considering the significant spatial correlation between land comprehensive carrying capacity and population flow [32], we introduced a spatial econometric model based on ordinary least squares (OLS) regression. The spatial lag model (SLM) with the spatial lag factor of the dependent variable and the spatial error model (SEM) considering the spatial error of the independent variable were selected for factor detection.

The SLM expression is as follows [55]:

$$Y = \rho W_Y + X\beta + \varepsilon \tag{9}$$

where Y is the dependent variable; X is the independent variable; W is the spatial weight matrix; ρ is the coefficient of the spatial lag term W_Y, which represents the degree of spatial interaction of dependent variables; β is the regression coefficient of X, which reflects the influence of the independent variable on the dependent variable; and ε is the error term.

The space error model expression is as follows [55]:

$$Y = X\beta + \varepsilon \tag{10}$$

$$\varepsilon = \lambda W_\varepsilon + \mu \tag{11}$$

where λ is the coefficient of the spatial error term, and μ is the random error vector of the normal distribution.

3. Results

3.1. Spatial Characteristics of Land Comprehensive Carrying Capacity

In 2018, the comprehensive land carrying capacity of cities nationwide was mainly at medium and low levels, and the spatial distribution was relatively balanced (Figure 3) and mostly concentrated in small- and medium-sized cities. Cities with high and relatively high carrying levels form evident spatial agglomerations in the Yangtze River Delta urban agglomeration, Beijing–Tianjin–Hebei urban agglomeration, Guangdong–Hong Kong–Macao Greater Bay Area, Yangtze River Basin, the middle and lower reaches of the Yellow River Basin, and Songhua River Basin. Cities with high carrying levels are mostly distributed around cities with high carrying or higher carrying levels. At the same time, cities with low carrying levels have formed large-scale concentrated contiguous areas in Northeast and Northwest China. The agglomeration characteristics of low-carrying and lower-carrying cities with the same or similar grades are evident. Overall, there is a strong correlation between the land comprehensive carrying capacity and the level of urban economic development.

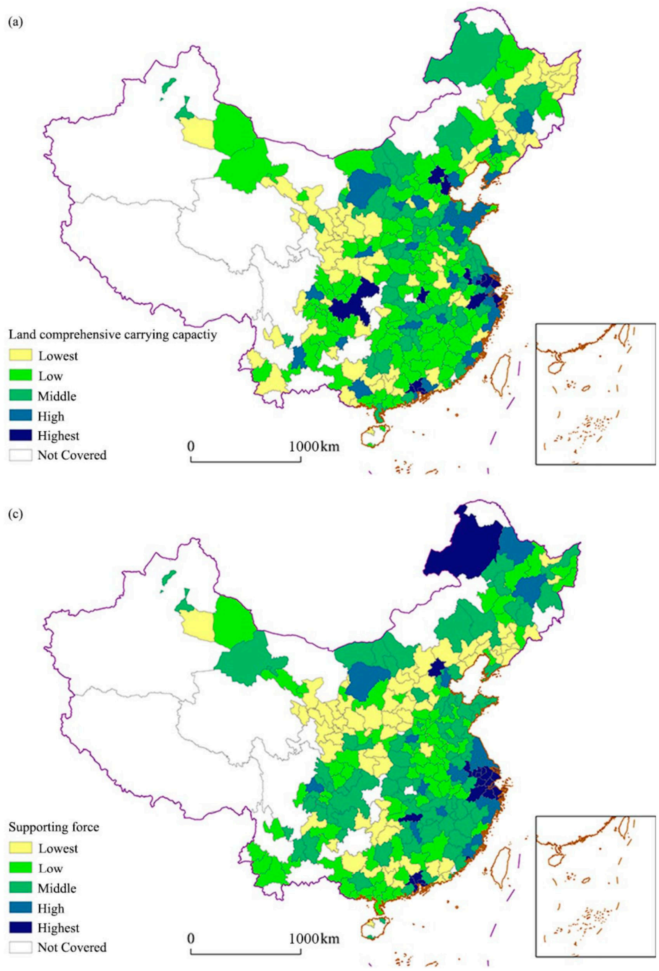

Figure 3. *Cont*.

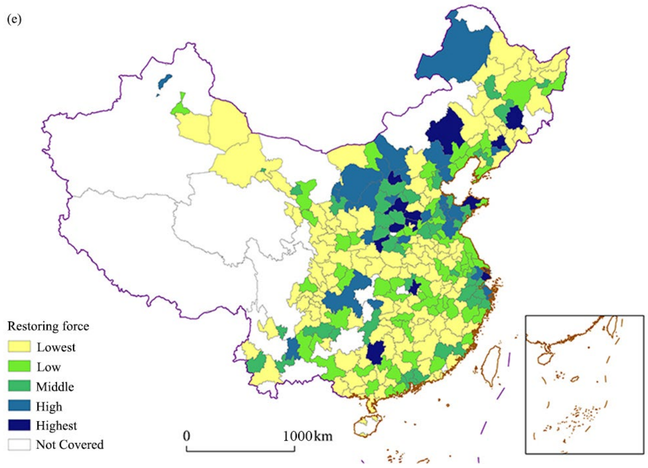

Figure 3. Spatial characteristics of land comprehensive carrying capacity and four carrying components: (**a**) land comprehensive carrying capacity; (**b**) pressure; (**c**) supporting force; (**d**) destructive force; (**e**) restoring force.

The four load-carrying component forces showed significant regional differentiation characteristics in space. Among them, the land supporting force in Northeast China and Southeast coastal areas is mainly medium and high, and generally higher than the pressure level. The land supporting force in North China is mainly in medium and low levels, and the supporting force level is generally lower than the pressure level. In Central China, Southwest China, and Northwest China, the supporting force and pressure are mainly low and medium level, and the two are balanced. However, the carrying pressure of large cities with more developed economies is generally higher than the supporting force. Cities with high destructive force were mainly distributed in the Beijing–Tianjin–Hebei urban agglomeration, Yangtze River Delta, Chengdu–Chongqing urban agglomerations, and Guangdong–Hong Kong–Macao Greater Bay Area. In contrast, the spatial distribution of the restoring force generally shows regional differentiation characteristics, low in the south and high in the north, on the national level. Economically developed and densely populated first-tier and new first-tier cities, such as Beijing, Chengdu, Shanghai, Nanjing, Suzhou, and Hangzhou, often have high destructive force and restoring force simultaneously.

3.2. Intercity Population Flow Network Characteristics

On the national level, the intercity population flow has formed a diamond network structure with Beijing as the core, connecting the four major regions of Northeast, Southwest, East, and South China (Figure 4). The vertices of the diamond network are composed of five city nodes: Shanghai, Guangzhou, Shenzhen, Chengdu, and Beijing. At the provincial level, population flow has formed a radial network structure with the provincial capital city as the core connecting other cities in the province. On the interprovincial scale, only the population flow scale between the five major node cities (Shanghai, Guangzhou, Shenzhen, Chengdu, and Beijing) is more than 10 million. In addition, every two cities with a population flow of more than 10 million are in the same province. The obstructive effect of provincial administrative boundaries on population flow between small- and medium-sized cities is obvious. The important nodes and main channels of the population flow network are concentrated on the eastern side of the Hu Huanyong Line. The flow direction gradually changed from one-way inflow from the inland areas of the central and western regions to the southeast coastal areas to a more balanced flow in both directions between the coastal and inland areas.

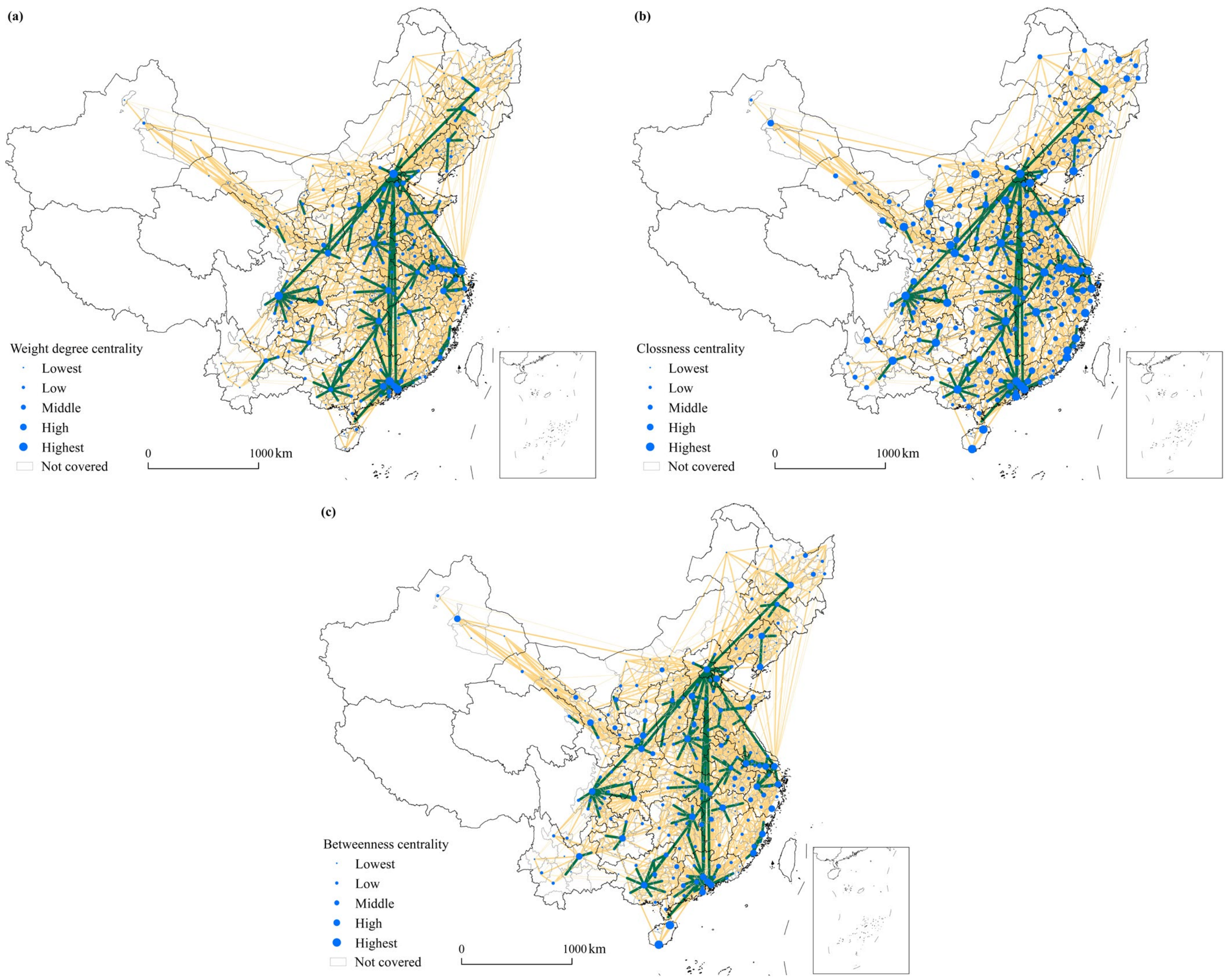

Figure 4. Network characteristics of intercity population flow: (**a**) weight degree centrality; (**b**) closeness centrality; (**c**) betweenness centrality.

The high-value areas of weighted degree centrality are distributed in megacities such as Beijing, Shanghai, Guangzhou, Shenzhen, and Chengdu, and have a central position in the national level population flow network. The low-value areas of weighted degree centrality are mostly distributed in small- and medium-sized cities, among which the Northeast and Northwest regions form a large-scale concentrated area. The distribution of high and low values of closeness centrality no longer has significant regional differences between the north and south. Small- and medium-sized cities close to large cities showed a lower level of closeness centrality, while small- and medium-sized cities located at a distance from large cities showed a middle and high level of closeness centrality. The spatial patterns of betweenness centrality and closeness centrality are similar. As the gateway node of the intercity network, large cities have the ability to control and restrict population flow to small- and medium-sized cities, resulting in a low level of betweenness centrality in small- and medium-sized cities. Marginal small- and medium-sized cities located at a distance from large cities have node independence in the population flow network, so their betweenness centrality is at a medium or high level.

3.3. Influence of Intercity Network on Land Comprehensive Carrying Capacity

3.3.1. Model Construction and Selection

The above-mentioned land comprehensive carrying capacity and population flow show significant spatial agglomeration characteristics and regional differentiation rules. Therefore, we introduced a spatial econometric model to measure the impact of the intercity network on land comprehensive carrying capacity. The OLS regression results show that the Moran's I index is 0.329, and the probability value is 0.00316. That is, the null hypothesis is rejected at a significance level of 1%, and there is a spatial positive correlation between the residuals. Further, the Lagrange multiplier test (Table 2) shows that the robust LM-error is significant at the 1% level. Therefore, we chose the SEM and performed maximum likelihood estimation. Table 3 presents the regression results.

Table 2. Lagrange multiplier test results.

Land Comprehensive Carrying Capacity	Coeff.	Std. Err.	t-Statistic	P > z
C_{WD}	0.331944	0.150606	2.20405	0.02815
C_B	1.43435	0.294987	4.86241	0.00000
C_C	−0.0130182	0.0293354	−0.443772	0.65747
C_{WI}	0.0593548	0.0885587	0.670231	0.00314
C_{WO}	−0.0778451	0.0916931	−0.848974	0.39645
_cons	−0.000051978	0.024079	0.00215864	0.005
R^2	0.725452			
Log likelihood	−236.824			
AIC	491.648			
SC	526.894			
LM-lag	64.2471			0.00000
Robust LM-lag	6.8005			0.05911
LM-error	94.1731			0.00000
Robust LM-error	36.7266			0.00000

Table 3. Estimation results of SLM and SEM.

Land Comprehensive Carrying Capacity	Spatial Lag Model			SEM		
	Coef.	Std. Err.	P > z	Coef.	Std. Err.	P > z
C_{WD}	0.25109	0.135898	0.00000 ***	0.718362	0.1386	0.00000 ***
C_B	0.0925256	0.030035	0.00207 ***	1.61875	0.259608	0.00000 ***
C_C	−0.00535188	0.0264466	0.83963	−0.0098843	0.0239549	0.67988
C_{WI}	0.0385628	0.079804	0.01275 **	0.0147454	0.0776941	0.046 *
C_{WO}	−0.0993748	0.0827668	0.22988	−0.046713	0.0767127	0.54257
R^2	0.771509			0.794416		
Log likelihood	−207.089			−196.953756		
AIC	434.177			411.908		
SC	473.339			447.153		

Note: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

3.3.2. Regression Results

The regression results show that weighted degree centrality, betweenness centrality, and weighted in-degree are significantly correlated with land comprehensive carrying capacity. Among them, the weighted in-degree is positively correlated with the comprehensive carrying capacity of land; that is, the high inflow of the intercity network can improve land comprehensive carrying capacity. Cities with a higher weighted in-degree usually have a higher socioeconomic level. The expansion of population size caused by high inflow promotes economic development, social progress, and technological innovation [56,57], which is conducive to improving the carrying potential of the urban economy and society. On the other hand, the positive impact of high population inflow on the economy and society is sufficient to offset its negative impact on the consumption of resources and on the environment. The overall level of land comprehensive carrying capacity is on the rise. At the same time, there is no significant correlation between weighted out-degree and land comprehensive carrying capacity. The high outflow of urban nodes in the intercity network does not have a significant impact on the comprehensive carrying capacity of land, which indirectly confirms that the outflow of population cannot effectively reduce the pressure on land carrying capacity, and limiting of the urban scale may not be an effective way to enhance the carrying capacity of cities.

The weighted degree centrality in the population flow network was positively correlated with the comprehensive carrying capacity of the land. When a city has large-scale population flow with more cities, its land comprehensive carrying capacity will increase. The stronger the degree centrality of a city in the flow network, the closer its network relationship with other cities in terms of economic ties, trade ties, and social ties. It often has a core position in the regional contact network (examples include Beijing, Shanghai, Guangzhou, and Shenzhen), which can attract the agglomeration of surrounding urban resources and promote the improvement of land comprehensive carrying capacity.

Betweenness centrality is positively correlated with the comprehensive carrying capacity of land, indicating that the more times a city acts as an intermediary bridge in the intercity network, the stronger its comprehensive carrying capacity of land is. When a city's betweenness centrality is high, it is more likely to become a transportation hub in the regional connection network (examples include Chengdu, Wuhan, and Changsha). Correspondingly, the higher the level of transportation infrastructure construction, cross-regional personnel exchange, and material transfer organization, the higher the land comprehensive carrying capacity is.

3.3.3. Further Examination Results

The regression results of the spatial econometric model showed that the weighted in-degree, weighted degree centrality, and betweenness centrality of the intercity network have a positive impact on land comprehensive carrying capacity, which seems difficult to understand intuitively. Therefore, in order to further explain the influence mechanism of intercity network on land comprehensive carrying capacity, we selected two indicators of land use efficiency and environmental pollution governance as intermediary effect analysis. Many studies have confirmed that land use efficiency and environmental pollution governance have significant impacts on land carrying capacity [53,58–60]. The improvement of land use efficiency will relieve the pressure of land carrying capacity under the condition that the supporting force is difficult to change as the land foundation [61]. At the same time, the improvement of the level of environmental pollution governance will help to alleviate the resilience of the land carrying system and slow down the damage caused by environmental pollution [62].

However, the impacts of intercity networks on land use efficiency and environmental pollution are still controversial [63–65]. The intercity network can produce synergy and integration effects through communication and co-operation, functional complementarity and technology spillover, which can better integrate intercity resources, and promote economic activities to be more specialized and scaled in a larger geographical space. This network effect will help regional division of labor, industrial restructuring and innovative technology applications, thereby enhancing land use efficiency [66]. The research of Mao et al. (2020) also shows that urban land use efficiency can benefit from the synergistic effect of cities [63]. On the other hand, the externality effect of intercity network will produce environmental positive externalities such as pollution governance scale effect and technology spillover, which is conducive to pollution reduction. Another view is that production expansion, energy consumption, and congestion effects generated by urban networks may also exacerbate regional pollution emissions [64,67–69].

Whether the impact of intercity network on land use efficiency and environmental pollution governance is positive or negative is still controversial, but it is undoubtedly significant. At the same time, land use efficiency and environmental governance level are important factors affecting land comprehensive carrying capacity. Therefore, we took the two indicators as the mediating variables of the impact of intercity network on land comprehensive carrying capacity to analyze whether there is a mediating effect [63,64,70–72]. We selected GDP per land and CO_2 emission reduction per land as two indicators to measure land use efficiency and environmental governance level, and constructed a mediating effect model. The test results are shown in Tables 4 and 5:

Table 4. Results of the mediating effect test of land use efficiency.

Variable Name	Model I		Model II		Model III	
	Land Comprehensive Carrying Capacity		Land Use Efficiency		Land Comprehensive Carrying Capacity	
	β	t	β	t	β	t
Weighted degree centrality	0.800	22.629 ***	0.657	14.797 ***	0.673	14.770 ***
Weighted indegree	0.800	22.611 ***	0.658	14.825 ***	0.673	14.746 ***
Betweenness centrality	0.481	9.303 ***	0.331	5.955 ***	0.304	6.768 ***
Land use efficiency					0.193	4.228 ***
Sample size	287		287		287	
R^2	0.64		0.432		0.661	
Adjusted R^2	0.639		0.43		0.659	
F value	F (1,288) = 512.069, p = 0.000		F (1,288) = 218.965, p = 0.000		F (2,287) = 279.972, p = 0.000	

Note: *** $p < 0.01$.

Table 5. Results of the mediating effect test of environmental governance level.

Variable Name	Model IV		Model V		Model VI	
	Land Comprehensive Carrying Capacity		Environmental Governance Level		Land Comprehensive Carrying Capacity	
	β	t	β	t	β	t
Weighted degree centrality	0.800	22.629 ***	0.013	0.229	0.800	22.586 ***
Weighted in-degree	0.800	22.611 ***	0.012	0.198	0.800	22.570 ***
Betweenness centrality	0.481	9.303 ***	−0.120	−2.044 *	0.490	9.426 ***
Environmental governance level					0.075	1.444
Sample size	287		287		287	
R^2	0.231		0.014		0.237	
Adjusted R^2	0.228		0.011		0.231	
F value	F (1,288) = 86.545, p = 0.000		F (1,288) = 4.180, p = 0.042		F (2,287) = 44.478, p = 0.000	

Note: * $p < 0.1$; *** $p < 0.01$.

The results showed that land use efficiency has a partial mediating effect on the influence of weighted degree centrality, betweenness centrality, and weighted in-degree of the intercity network on land comprehensive carrying capacity. The mediating effect of the environmental governance level on the influence of weighted degree centrality and weighted in-degree on land comprehensive carrying capacity is not significant, but it has a masking effect on the influence of betweenness centrality on land comprehensive carrying capacity.

The above results indicated that the influence of the intercity network on land comprehensive carrying capacity is mainly attributed to economic performance, whilst its effect on environment governance is insignificant. This finding echoes with the urban network theory [73]. The theory holds that strengthening the collaborative network between cities can bring more economic benefits than the sum of the development of a single city [18]. In addition, the research of Capello (2016) on European city network strategy also provides similar results. This research found that member cities in the network can benefit from intercity co-operation and gain additional economic advantages [73].

Therefore, we can further explain the influence mechanism of the intercity network on land comprehensive carrying capacity through mediating effect. On the one hand, the city obtains the positive externality effect of the network through better integration into the network. Cities with weighted in-degree, weighted degree centrality, and betweenness centrality have the characteristics of gathering resources, strong mobility, and convenient transportation, which are conducive to the formation of resource borrowing and scale effect, thus improving land comprehensive carrying capacity [72]. On the other hand, the weight degree centrality, betweenness centrality, and weighted in-degree are conducive to improving land use efficiency. The intercity network affects land comprehensive carrying capacity through the intermediary of land use efficiency. However, the impacts of weight degree centrality and weighted in-degree on environmental governance are not significant.

4. Discussion

4.1. Regional Differentiation Law of Land Comprehensive Carrying Capacity: Economic Relevance

The comprehensive carrying capacity of land at the national scale presents a spatial pattern that is related significantly to the level of urban economic development. Cities with the highest or higher land carrying levels are concentrated in mature and developed large urban agglomerations. These include the Beijing–Tianjin–Hebei urban agglomeration, Yangtze River Delta urban agglomeration, Guangdong–Hong Kong–Macao Greater Bay Area, and the urban agglomeration in the middle reaches of the Yangtze River. Most cities with the lowest or lower land carrying level are small- and medium-sized cities with relatively backward economic development. The spatial distribution characteristics of the pressure level were similar to the comprehensive carrying level. Megacities, such as municipalities and provincial capitals, have higher carrying pressure. Although the rapid development of the economy exerts a certain pressure on the land carrying system, the impact on the overall carrying level is still mainly positive. In order to further verify the results, we analyzed the correlation between land comprehensive carrying capacity and GDP in 287 cities, and the two showed a strong positive correlation (Pearson coefficient = 0.859, p = 0.000). However, they showed obvious nonlinear characteristics. Further, we performed logarithmic transformation on the two indicators and found that this nonlinear relationship was transformed into a linear relationship (Figure 5). This is consistent with the existing literature. Urban scale and economic performance are important determinants of land comprehensive carrying capacity [74]. The level of destructive force also shows that the distribution characteristics are significantly related to the level of economic development [75]. However, in contrast to the carrying pressure, the spatial pattern of the destructive force level is polarized. It is worth noting that a few developed cities have a high destructive force, while their restoring force remains low. For example, in Tianjin, Nanjing, Hangzhou, Guangzhou, and other cities, there is a risk of imbalance in the land carrying system.

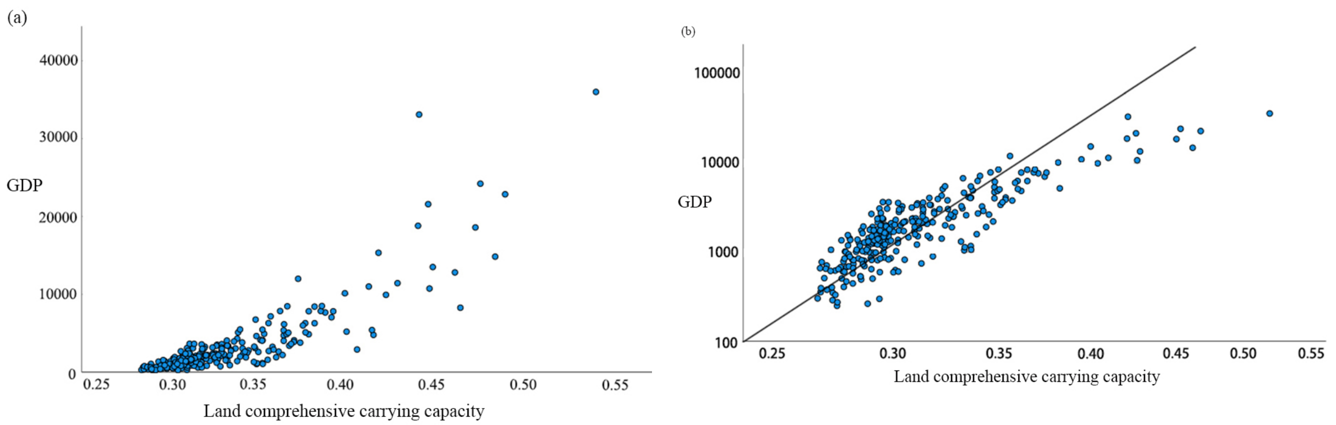

Figure 5. Correlation analysis of land comprehensive carrying capacity and GDP: (**a**) bivariate correlation; (**b**) logarithm conversion.

4.2. External Effects on the Comprehensive Carrying Capacity of Land: Intercity Network Effect

In addition to the local resources, environment, economic and social factors of the city, is land comprehensive carrying capacity also affected by the external intercity network connection? This issue was probed by an empirical study on the impact of population flow network on land comprehensive carrying capacity among 287 cities in China. The weighted degree centrality, weighted in-degree, and betweenness centrality of the intercity network have a significant impact on land comprehensive carrying capacity, and are strengthened by land use efficiency as an intermediary variable. When a city node has a central position in its regional connection network, it is likely to become the distribution center of capital, technology, market, and talent flow in its region and have a strong control function on various resource elements [40]. Such cities have an absolute advantage in the intercity network and are able to benefit from the integration of the intercity network and obtain the positive externalities of the network [13]. Therefore, land comprehensive carrying capacity can benefit from the intercity network. Land comprehensive carrying capacity can be determined by external factors rather than local factors [63], such as government-led projects including the South-to-North Water Diversion Project, Yellow River Water Diversion Project, and Luanhe River Water Diversion Project. On the other hand, there is also cross-city commuting under market traction. For example, the city's carrying capacity of the cross-city commuting floating population can not only benefit from the economic value created by their work but also not have to bear their living needs, thus alleviating the carrying pressure [76].

It should be noted that the level of environmental governance (CO_2 emission reduction) has a masking effect on the impact of betweenness centrality on land comprehensive carrying capacity. Betweenness centrality represents the transportation hub capacity of the city in the intercity network [44,73]. Cities with high betweenness centrality have more convenient intercity transportation and higher density of transportation facilities such as railways, highways, and aviation [18]. Traffic accessibility and density directly affect CO_2 emissions. Therefore, the mediating effect model detected that the impact of betweenness centrality on CO_2 emission reductions is negative. In the regression results, we measured the impact of betweenness centrality on land comprehensive carrying capacity as positive. Therefore, the level of environmental governance weakened the influence of intermediary centrality on land comprehensive carrying capacity, to a certain extent, and has a masking effect. This is different from the views of some scholars [12,77,78]. The research of Veneri and Burgalassi (2012) found that there were no stable correlations between urban agglomeration measures and environment sustainability in Italy [12].

4.3. Population Factor of Land Comprehensive Carrying Capacity: Dynamic Mobility

We enrich and expand the existing research perspective of human–land interaction and demonstrate the difference in the impact of population flow on land comprehensive carrying capacity compared with static population factors. The existing literature focuses more attention on the change in urban population size and the impact on the comprehensive carrying capacity of land caused by population migration. Past studies have confirmed that population outflow can reduce the load on resources and the environment in a region and improve the carrying capacity [79]. In contrast, we find that the dynamic mobility of the population itself and the change in population size capacity caused by migration have different effects on land comprehensive carrying capacity. As an important component of the intercity network, population flow can break the boundaries of cities and promote intercity connections across geographical distances and administrative levels. The population flow between cities makes the intercity relationship closer in same-level, cross-level, neighborhood, and remote areas, which has a profound impact on improving the vitality of urban spaces and promoting economic and social interaction between cities and urban network collaboration [80]. We confirmed that population flow between cities and the resulting population inflow positively affect land comprehensive carrying capacity. Therefore, the improvement of land carrying capacity cannot rely solely on the control of population size but should promote the mobility of various resource factors by reasonably promoting the cross-regional flow of the population, leading to a higher level of supply and demand balance and benign interaction between population and land comprehensive carrying capacity being realized.

4.4. Policy Implications

Cities with high centrality, high betweenness centrality, and high inflow in the intercity network have higher land comprehensive carrying capacity. However, the change in closeness centrality and weighted out-degree cannot significantly change the comprehensive carrying capacity of urban land in the short term. These findings provide different perspectives for understanding the limits and thresholds of land comprehensive carrying capacity. The impact of intercity network connections on the objective existence of land carrying capacity confirms that solutions to alleviate urban land shortages and resource constraints can be nonlocal (intercity). Traditional policy interventions often focus on solutions based on a city's local resource base, including limiting urban land expansion by controlling urban land supply and prioritizing stock land reconstruction before new land acquisitions [81]. The impact of intercity networks has prompted cities to use the external effects of network linkages to enhance the comprehensive carrying capacity of land, and intercity networks have become a potential nonlocal solution to alleviate the shortage of land resources [63]. China's current city planning practice emphasizes the control of city size within its resource and environmental carrying capacity [82,83]. Traditional thinking attempts to determine the limitations of urban growth. However, this capacity-limiting thinking is static, ignoring the key role of transportation and technological development in resource and environmental protection. This thinking is also location-based, ignoring the inherent nature of the city as an open system [63,72,73]. It is clear that assessing the local basis of a city is an important prerequisite; however, the local basis should not be a threshold or limit for assessing the size of a city. The theoretical and empirical results in this study can provide new ideas for sustainable urban growth in response to the scarcity of land resources. Assessing the local basis helps researchers to understand the structural adjustment within the city and the interdependence between cities. Simultaneously, it is important to determine various intercity networks related to urban functions. A city is a typical open system with a large quantity of resources and energy flowing in and out. Therefore, urban economic growth is often an interrelated process rather than a self-sufficient process [84]. Although land is a nontradable resource, linkages between cities can change the allocation of resources, pattern of specialization between cities, and comprehensive carrying capacity of urban land. Although sustained urban growth exposes urban land to the risk of diseconomies of scale, intercity network connections can effectively extend economies of scale beyond administrative boundaries. All cities in the city network can benefit from their interconnections. Therefore, strengthening urban network integration could be a flexible way for urban development to cope with land scarcity.

5. Conclusions

In the past decade, many studies have directly or indirectly confirmed the openness and mobility of urban land comprehensive carrying systems. However, the description and evaluation of land carrying capacity in the existing literature still focused on closed systems. The study of urban carrying limits and thresholds was based on independent systems and local thinking. With the rapid development of information and communication technology and the maturity of intercity transportation facilities, the connections between cities are becoming increasingly closer. The influence of the intercity network formed by factor flows on the comprehensive carrying capacity of land cannot be ignored. In this study, we used Tencent location big data to analyze the impact of intercity network connection on land comprehensive carrying capacity from the perspective of population flow. The main conclusions are as follows:

The land comprehensive carrying capacity of most cities in China is at a medium or low level and is mainly concentrated in small- and medium-sized cities. Low-carrying cities have formed a large-scale contiguous distribution in the Northeast and Northwest regions. Cities with high carrying levels are mostly distributed in developed and mature large urban agglomerations. Overall, the comprehensive carrying capacity of urban land in China is characterized by a spatial pattern related to the level of economic development.

On the national level, the intercity network formed by intercity population flow is a spatial streamline organization with a diamond structure as the core skeleton and Beijing, Shanghai, Guangzhou, Shenzhen, and Chengdu as the central nodes. At the provincial level, the population flow forms a radial network structure with the provincial capital city as the core, connecting other cities in the province. The distribution of high and low values of betweenness centrality and closeness centrality no longer presents as a spatial pattern strongly related to the urban scale. On a national level, the geographical distribution of the two is more balanced, and the difference between the north and south is not obvious.

The regression results show that the weighted degree centrality, betweenness centrality, and weighted in-degree in the intercity network are significantly positively correlated with the land comprehensive carrying capacity. Urban nodes with a core position, intermediary function, and agglomeration ability in the intercity network have a higher land comprehensive carrying capacity. As a nonlocal connection, the intercity network can enable a city to transcend its local foundation and improve its carrying capacity by means of the externality effect of the network connection. There is no significant correlation between the weighted out-degree and the comprehensive carrying capacity of land, which indirectly confirms that population outflow cannot effectively reduce the pressure of land carrying, and limiting the urban scale may not be an effective way to improve the carrying capacity of cities. On the other hand, the intercity network can affect land comprehensive carrying capacity through the intermediary of land use efficiency.

The following shortcomings of this study deserve attention: in the real world, various connections exist between cities. The large-scale flow of factors complicates the interaction between human activities and the geographical environment [85]. Future research can apply various types of intercity connections and combine different urban network indices to capture the impact of intercity networks on land carrying capacity. On the other hand, the evaluation of land comprehensive carrying capacity from the perspective of mobility needs to be expanded. With the improvement in the level of land resource utilization technology and the degree of regional economic connection, the cross-regional flow and complementarity of water, food, oil, carbon, and other resources are increasingly common in the real world [35]. Starting from the spatial transfer of factor flow, it is also particularly important to incorporate liquidity resource elements into the carrying capacity evaluation system to realize the dynamic monitoring of land comprehensive carrying capacity.

Author Contributions: Conceptualization, X.S.; methodology, X.S. and X.Y.; software, F.H.; validation, X.S. and S.W.; formal analysis, X.S.; resources, S.W.; data curation, X.S.; writing—original draft preparation, X.S.; writing—review and editing, S.W.; visualization, F.H.; supervision, X.Y.; funding acquisition, X.Y. and S.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Nature Science Foundation of China (Grant No. 42201216; Grant No. 42171198), the China Postdoctoral Science Foundation (Grant No. 2022M721303), and the National Social Science Foundation of China (Grant No. 18BRK024).

Data Availability Statement: The land use, land resource, and population flow data in this study are publicly accessible, and the URLs are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Shi, Y.; Wang, H.; Yin, C. Evaluation method of urban land population carrying capacity based on GIS–A case of Shanghai, China. *Comput. Environ. Urban Syst.* **2013**, *39*, 27–38. [CrossRef]
2. Chen, H.; Jia, B.; Lau, S.S.Y. Sustainable urban form for Chinese compact cities: Challenges of a rapid urbanized economy. *Habitat Int.* **2007**, *32*, 28–40. [CrossRef]
3. Song, X.; Kong, F.; Zhan, C. Assessment of water resources carrying capacity in Tianjin City of China. *Water Resour. Manag.* **2011**, *25*, 857–873. [CrossRef]
4. Zhu, Y.; Drake, S.; Lu, H.; Xia, J. Analysis of temporal and spatial differences in eco-environmental carrying capacity related to water in the Haihe River Basins, China. *Water Resour. Manag.* **2010**, *24*, 1089–1105. [CrossRef]
5. Lu, S.; Guan, X.; He, C.; Zhang, J. Spatio-temporal patterns and policy implications of urban land expansion in metropolitan areas: A case study of Wuhan Urban Agglomeration, Central China. *Sustainability* **2014**, *6*, 4723–4748. [CrossRef]
6. Seto, K.C.; Reenberg, A.; Boone, C.G.; Fragkias, M.; Haase, D.; Langanke, T.; Marcotullio, P.; Munroe, D.K.; Olah, B.; Simon, D. Urban land teleconnections and sustainability. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 7687–7692. [CrossRef]
7. He, F.; Yang, J.; Zhang, Y.; Sun, D.; Wang, L.; Xiao, X.; Xia, J. Offshore Island Connection Line: A new perspective of coastal urban development boundary simulation and multi-scenario prediction. *Giscience Remote Sens.* **2022**, *59*, 801–821. [CrossRef]
8. Au, C.C.; Henderson, J.V. Are Chinese cities too small? *Rev. Econ. Stud.* **2006**, *73*, 549–576. [CrossRef]
9. Glaeser, E.; Ponzetto, G.A.M.; Zou, Y. Urban Networks: Connecting Markets, People, and Ideas. *Pap. Reg. Sci.* **2016**, *95*, 17–59. [CrossRef]
10. Fang, C. The basic law of the formation and expansion in urban agglomerations. *J. Geogr. Sci.* **2019**, *29*, 1699–1712. [CrossRef]
11. McPhearson, T.; Haase, D.; Kabisch, N.; Gren, Å. Advancing understanding of the complex nature of urban systems. *Ecol. Indic.* **2016**, *70*, 566–573. [CrossRef]
12. Su, S.; Liu, Z.; Xu, Y.; Li, J.; Pi, J.; Weng, M. China's megaregion policy: Performance evaluation framework, empirical findings and implications for spatial polycentric governance. *Land Use Policy* **2017**, *63*, 1–19. [CrossRef]
13. Tao, M.; Huang, Y.; Tao, H. Urban network externalities, agglomeration economies and urban economic growth. *Cities* **2020**, *107*, 102882. [CrossRef]
14. Wang, Y.; Sun, B.; Zhang, T. Do polycentric urban regions promote functional spillovers and economic performance? Evidence from China. *Reg. Stud.* **2022**, *56*, 63–74. [CrossRef]
15. Sheng, K.; Wang, L.; Sun, W. Patterns and determinants of functional division of cities across product value chain in China. *Geogr. Res.* **2020**, *39*, 2763–2778. [CrossRef]
16. Camagni, R.P.; Salone, C. Network urban structures in northern Italy: Elements for a theoretical framework. *Urban Stud.* **1993**, *30*, 1053–1064. [CrossRef]
17. Burger, M.J.; Meijers, E.J.; Hoogerbrugge, M.M.; Tresserra, J.M. Borrowed size, agglomeration shadows and cultural amenities in North-West Europe. *Eur. Plan. Stud.* **2015**, *23*, 1090–1109. [CrossRef]
18. Meijers, E. Polycentric urban regions and the quest for synergy: Is a network of cities more than the sum of the parts? *Urban Stud.* **2005**, *42*, 765–781. [CrossRef]
19. Masahisa, F.; Paul, K.; Anthony, J. *Venables. The Spatial Economy: Cities, Regions and International Trade*; Translated by Liang Qi; China Renmin University Press: Beijing, China, 2005.
20. Wang, Y.; Ruan, H.; Tian, C. Access to high-speed rail and land prices in China's peripheral regions. *Cities* **2022**, *130*, 103877. [CrossRef]
21. National Bureau of Statistics of the People's Republic of China. *Main Data of the Seventh Census*; China Statistics Press: Beijing, China, 2021.
22. Duan, C.; Lv, L.; Wang, H.; Xie, D. From Rural China to Migrating China: Rethinking Migration Transition in China. *Popul. Res.* **2020**, *44*, 19–25.
23. Li, S. Population migration regional economic growth and income determination: A comparative study of Dongguan and Meizhou China. *Urban Stud.* **2014**, *34*, 999–1026. [CrossRef]
24. Tan, M.; Li, X. Paradigm transformation in the study of man-land relations: From local thinking to global network thinking modes. *Acta Geogr. Sin.* **2021**, *76*, 2333–2342. [CrossRef]
25. Xue, B.; Li, J.; Xiao, X.; Xie, X.; Lu, C.; Ren, W.; Jiang, L. Overview of Man-Land Relationship Research Based on POI Data: Theory, Method and Application. *Geogr. Geo-Inf. Sci.* **2019**, *35*, 51–60. [CrossRef]
26. Li, X.; Yang, Y.; Liu, Y.; Lu, Y.; Xia, S. The Systematic Structure and Trend Simulation of China's Man-land Relationship Until 2050. *Sci. Geogr. Sin.* **2021**, *41*, 187–197. [CrossRef]
27. Yang, Y.; Li, X.; Dong, W.; Hong, H.; He, Z.; Jin, F.; Liu, Y. Comprehensive evaluation on China's man-land relationship: Theoretical model and empirical study. *J. Geogr. Sci.* **2019**, *29*, 1261–1282. [CrossRef]
28. Sevtsuk, A.; Ratti, C. Does Urban Mobility Have a Daily Routine? Learning from the Aggregate Data of Mobile Networks. *J. Urban Technol.* **2010**, *17*, 41–60. [CrossRef]
29. Anto, A.; Pilleriine, K.; Erki, S.; Jan, Š.; Janika, R. Spatial interpolation of mobile positioning data for population statistics. *J. Locat. Based Serv.* **2021**, *15*, 239–260. [CrossRef]
30. Loibl, W.; Toetzer, T. Modeling growth and densification processes in suburban regions—Simulation of landscape transition with spatial agents. *Environ. Model. Softw.* **2003**, *18*, 553–563. [CrossRef]

31. Niu, F.; Feng, Z.; Liu, H. A review on evaluating methods of regional resources and environment carrying capacity. *Resour. Sci.* **2018**, *40*, 655–663. [CrossRef]
32. Hu, H.; Han, L. Evaluation of Land Carrying Capacity of 31 Provinces in China Based on a Natural–Societal-Supply–Demand Framework. *Sustainability* **2023**, *15*, 1037. [CrossRef]
33. Zhang, D.; Zhu, l.; Ma, X.; Liu, Z.; Cui, H. Uncoordinated Coupling Assessment of New Urbanization and Ecological Carrying Capacity in the Yellow River Basin. *Int. J. Environ. Res. Public Health* **2022**, *19*, 9016. [CrossRef]
34. Wang, L.; Liu, H. The comprehensive evaluation of regional resources and environmental carrying capacity based on PS-DR-DP theoretical model. *Acta Geogr. Sin.* **2019**, *74*, 340–352. [CrossRef]
35. Xu, X.; Liu, J.; Zhang, S.; Li, R.; Yan, C.; Wu, S. *China Multi-Period Land Use and Land-Cover Change Remote Sensing Monitoring Data Set (CNLUCC)*; Data Registration and Publication System of the Data Centre for Resource and Environmental Sciences; Chinese Academy of Sciences: Beijing, China, 2018. [CrossRef]
36. Robert, M.T. *Essay on the Principle of Population: The 1803 Edition*; Yale University Press: London, UK, 2019.
37. Sayre, N.F. The genesis, history, and limits of carrying capacity. *Ann. Assoc. Am. Geogr.* **2008**, *98*, 120–134. [CrossRef]
38. Wang, S.; Mao, H.; Zhao, M. Thinking on the index system design to the land comprehensive carrying capacity—A case study: Coastal region of China. *Hum. Geogr.* **2001**, *16*, 57–61. [CrossRef]
39. Lu, Y. *Study on Evaluation of Regional Land Comprehensive Carrying Capacity and Application Research*; China University of Geosciences: Beijing, China, 2014.
40. Zhang, S.; Ruan, D. Evaluation of resources and environment carrying capacity from the perspective of resource cross-regional mobility: A dynamic evaluation framework and practice. *J. Nat. Resour.* **2020**, *35*, 2358–2370. [CrossRef]
41. Li, C.; Liu, B. Air pollution embodied in China's trade with the BR countries: Transfer pattern and environmental implication. *J. Clean. Prod.* **2019**, *247*, 119126. [CrossRef]
42. Luo, W.; Ren, Y.; Shen, L.; Zhu, M.; Jiang, Y.; Meng, C.; Zhang, P. An evolution perspective on the urban land carrying capacity in the urbanization era of China. *Sci. Total Environ.* **2020**, *744*, 140827. [CrossRef]
43. He, Z.; Wang, H.; Wei, M.; Gui, Y.; Zhao, Z.; Zhang, B.; Liu, Z. Evolution trend and prediction of Keriya river oasis niche in recent 11 years. *J. Arid. Land Resour. Environ.* **2017**, *31*, 75–80. [CrossRef]
44. Shi, X. *The Coupling of Population Movement and Land Comprehensive Carrying Capacity in China*; Jilin University: Changchun, China, 2021. [CrossRef]
45. Nasirzadeh, F.; Ghayoumian, M.; Khanzadi, M.; Rostamnezhad, C.M. Modelling thesocial dimension of sustainable development using fuzzy cognitive maps. *Int. J. Constr. Manag.* **2020**, *20*, 223–236. [CrossRef]
46. Tang, Y.; Yuan, Y.; Zhong, Q. Evaluation of Land Comprehensive Carrying Capacity and Spatio-Temporal Analysis of the Harbin-Changchun Urban Agglomeration. *Int. J. Environ. Res. Public Health* **2021**, *18*, 521. [CrossRef]
47. Shen, L.; Shu, T.; Liao, X.; Yang, N.; Ren, Y.; Zhu, M.; Wang, J. A new method to evaluate urban resources environment carrying capacity from the load-and-carrier perspective. *Resour. Conserv. Recycl.* **2020**, *154*, 104616. [CrossRef]
48. Liao, X.; Ren, Y.; Shen, L.; Shu, T.; He, H.; Wang, J. A "carrier-load" perspective method for investigating regional water resource carrying capacity. *J. Clean. Prod.* **2020**, *269*, 122043. [CrossRef]
49. Zhang, H.; Wang, Z.; Liu, J.; Chai, J.; Wei, C. Selection of targeted poverty alleviation policies from the perspective of land resources-environmental carrying capacity. *J. Rural. Stud.* **2022**, *93*, 318–325. [CrossRef]
50. Zhang, C.; Yang, Y.; Feng, Z.; Lang, T.; Liu, Y. Spatio-temporal patterns of the land carrying capacity in the Belt and Road region based on human-cereals relationship. *J. Nat. Resour.* **2022**, *37*, 616–626. [CrossRef]
51. Liu, Z.; Ren, Y.; Shen, L.; Liao, X.; Wei, X.; Wang, J. Analysis on the effectiveness of indicators for evaluating urban carrying capacity: A popularity-suitability perspective. *J. Clean. Prod.* **2020**, *246*, 119019. [CrossRef]
52. Yuan, Y.; Chuai, X.; Xiang, C.; Gao, R. Carbon emissions from land use in Jiangsu, China, and analysis of the regional interactions. *Environ. Sci. Pollut. Res.* **2022**, *29*, 44523–44539. [CrossRef]
53. Wu, Q.; Cao, Y.; Fang, X.; Wang, J.; Li, G. A systematic coupling analysis framework and multi-stage interaction mechanism between urban land use efficiency and ecological carrying capacity. *Sci. Total Environ.* **2022**, *853*, 158444. [CrossRef] [PubMed]
54. Liu, C.; Yan, S. Spatial evolution and determinants of transnational technology transfer network in China. *Acta Geogr. Sin.* **2022**, *77*, 331–352. [CrossRef]
55. Jiang, L. The Choice of Spatial Econometric Models Reconsidered in Empirical Studies. *J. Stat. Inf.* **2016**, *31*, 10–16.
56. Wei, L.; Chen, Y.; Liu, Q.; Lu, Y. Coupling Research on Re sources and Environment Carrying apacity and Population Mobility in Heilongjiang Province Based on the P-S Curve. *Geogr. Geo-Inf. Sci.* **2020**, *36*, 95–105. [CrossRef]
57. Xiao, Z. Hypothesis on Potential Energy Conversion of Population Migration in Theory: Re-interpretion of the push-pull migration laws. *Popul. Econ.* **2010**, *6*, 77–83.
58. Li, Y. *Spatial-Temporal Coupling Relationship between Urban Land Use Efficiency and Carrying Capacity of Regional Resources and Environment in the Yangtze River Economic Zone*; Wuhan University: Wuhan, China, 2019.
59. Huang, A.; Tian, L.; Yu, J.; Gao, Y.; Li, Y.; Li, Q.; Xiong, B. Comprehensive assessment of resource and environmental carrying capacity of village and town from the perspective of governance. *Trans. Chin. Soc. Agric. Eng.* **2021**, *37*, 232–241. [CrossRef]
60. An, P. *Positive Research on Environmental Protection Investment and Regional Economic Growth Relationship: View from Environmental Capacity Carrying*; Ocean University of China: Qingdao, China, 2010.

61. Tan, C.; Peng, Q.; Ding, T.; Zhou, Z. Regional Assessment of Land and Water Carrying Capacity and Utilization Efficiency in China. *Sustainability* **2021**, *13*, 9183. [CrossRef]
62. Shi, M.; Li, Y.; Zhang, X.; Xiang, N. Will the haze control target of Beijing—Tianjin-Hebei region be realized? an assessment based on environmental carrying capacity. *China Popul. Resour. Environ.* **2017**, *7*, 6675. [CrossRef]
63. Mao, X.; Huang, X.; Song, Y.; Zhu, Y.; Tan, Q. Response to urban land scarcity in growing megacities: Urban containment or inter-city connection? *Cities* **2020**, *96*, 102399. [CrossRef]
64. Zhang, K. The emission reduction effects of economic agglomeration: An explanation based on spatial economics. *Ind. Econ. Res.* **2018**, *94*, 64–76. [CrossRef]
65. Zhou, H.; Gu, G. The evolution of China's city network and its environmental effects from the perspective of externalities. *Geogr. Res.* **2022**, *41*, 268–285. [CrossRef]
66. Wu, C.; Wei, Y.; Huang, X.; Chen, B. Economic transition, spatial development and urban land use efficiency in the Yangtze River Delta, China. *Habitat Int.* **2017**, *63*, 67–78. [CrossRef]
67. Zhao, X.; Shang, Y.; Song, M. What kind of cities are more conducive to haze reduction: Agglomeration or expansion? *Habitat Int.* **2019**, *91*, 102027. [CrossRef]
68. Han, F.; Xie, R.; Lu, Y.; Fang, J.; Liu, Y. The effects of urban agglomeration economies on carbon emissions: Evidence from Chinese cities. *J. Clean. Prod.* **2018**, *172*, 1096–1110. [CrossRef]
69. Zhang, S.; Zhang, L.; Zhang, L.; Gao, S. Coupling relationship between polluting industrial agglomeration and water environment pollution in Southern Jiangsu of Taihu Lake Basin. *Sci. Geogr. Sin.* **2018**, *38*, 954–962. [CrossRef]
70. Hu, Z.; Miao, C.; Yuan, F. Impact of industrial spatial and organizational agglomeration patterns on industrial SO_2 emissions of prefecture-level cities in China. *Acta Geogr. Sin.* **2019**, *74*, 2045–2061. [CrossRef]
71. Gong, P.; Zhang, S. Spatial-temporal effects of industrial agglomeration patterns on urban land use efficiency. *Ind. Organ. Rev.* **2022**, *16*, 54–75.
72. Shen, L.; Cheng, G.; Du, X.; Meng, C.; Ren, Y.; Wang, J. Can urban agglomeration bring "1 + 1 > 2Effect"? A perspective of land resource carrying capacity. *Land Use Policy* **2022**, *117*, 106094. [CrossRef]
73. Capello, R. The City Network Paradigm: Measuring Urban Network Externalities. *Urban Stud.* **2000**, *37*, 1925–1945. [CrossRef]
74. Wei, Y.; Huang, C.; Li, J.; Xie, L. An evaluation model for urban carrying capacity: A case study of China's mega-cities. *Habitat Int.* **2016**, *53*, 87–96. [CrossRef]
75. Zhang, Z.; Jin, G.; Guo, B.; Dong, Y.; Chen, K. Research on the spatial vulnerability and resilience of land in the Yangtze River Economic Belt based on multi-criteria decision. *J. Nat. Resour.* **2020**, *35*, 95–105. [CrossRef]
76. Zheng, S.; Kahn, M. China's bullet trains facilitate market integration and mitigate the cost of megacity growth. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 1248–1253. [CrossRef]
77. Yang, G.; Zhao, Y.; Xing, H.; Fu, Y.; Liu, G.; Kang, X.; Mai, X. Understanding the changes in spatial fairness of urban greenery using time-series remote sensing images: A case study of Guangdong-Hong Kong-Macao Greater Bay. *Sci. Total Environ.* **2020**, *715*, 136763. [CrossRef]
78. Veneri, P.; Burgalassi, D. Questioning polycentric development and its effects. Issues of definition and measurement for the Italian NUTS-2 Regions. *Eur. Plan. Stud.* **2012**, *20*, 1017–1037. [CrossRef]
79. Zhou, K.; Fan, J. Characteristics and influence factors of resources and environment carrying capacity in underdeveloped areas of China. *Geogr. Res.* **2015**, *34*, 39–52. [CrossRef]
80. Xi, G.; Zhen, F.; Qian, Q. Territory spatial security and planning strategies from the perspective of mobility. *J. Nat. Resour.* **2022**, *37*, 1935–1945. [CrossRef]
81. Liu, Y.; Fang, F.; Li, Y. Key issues of land use in China and implications for policy making. *Land Use Policy* **2014**, *40*, 6–12. [CrossRef]
82. Yang, J.; Guo, A.; Li, Y.; Zhang, Y.; Li, X. Simulation of Landscape Spatial Layout Evolution in Rural-urban Fringe Areas: A Case Study of Ganjingzi District. *GIScience Remote Sens.* **2018**, *56*, 388–405. [CrossRef]
83. Wei, Y.; Huang, C.; Lam, P.T.I.; Yuan, Z. Sustainable urban development: A review on urban carrying capacity assessment. *Habitat Int.* **2015**, *46*, 64–71. [CrossRef]
84. Camagni, R.; Capello, R.; Caragliu, A. One or infinite optimal city sizes? In search of an equilibrium size for cities. *Ann. Reg. Sci.* **2013**, *51*, 309–341. [CrossRef]
85. Qin, X.; Zhen, F. Discussion on urban construction land allocation based on element flow. *J. Nat. Resour.* **2022**, *37*, 2774–2788. [CrossRef]