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Assessing and Optimizing the Connectivity of the Outdoor Green Recreation Network in Zhengzhou from the Perspective of Green Travel

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Abstract: With the increasing demand for outdoor recreation and fitness, this study aims to assess the connectivity of the outdoor green recreation (OGR) network from the perspective of green travel and propose optimization framework. The Point of Interest (POI) and Area of Interest (AOI) datasets of OGR spots in Zhengzhou were utilized as the primary research materials. A combination of GIS spatial analysis and Graph index calculation is employed to quantify and diagnose the connectivity of the OGR network based on multi-source data (land cover, topography, and road network). The index system for cost surface establishment was improved and proposed, shifting its focus from previous biological migration and ecological network to human green travel and improving the connectivity of the OGR network. The technical optimization process of the OGR network is explored and presented. The results show that: (1) The scale, number, and distribution of OGR spots and the connectivity of the OGR network are significantly different in urban and rural areas. Numerous small-scale OGR spots and short-distance recreational paths are distributed in urban areas, while a limited number of large-scale OGR spots and long-distance recreational paths are situated in rural areas with better natural resources. (2) Compared with driving travel, the connectivity of the OGR network is poor when walking and cycling. Graph indexes of Dg, BC, and dPC can be used to reflect the connection capability, bridging role, and contribution of each spot to overall network connectivity. (3) The current OGR network is optimized through 30 new spots based on the perspective of green travel and land suitability analysis. The network connectivity will improve by 4%, and the number of recreational paths suitable for green travel increased by 41. (4) The methodologies for quantifying and optimizing OGR network connectivity from the perspective of green travel will offer valuable references for future research in this field.

Keywords: outdoor green recreation; network connectivity; optimization technical process; green travel; human recreation

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1. Introduction

With the ongoing global urbanization, there has been notable improvement in people's living standards and quality of life [1,2], which has fostered an increasing demand for outdoor recreation and physical fitness activities [3]. For example, walking, running, and cycling in places with good scenery and green trails [4,5]. This demand has been further underscored by the global experience of the COVID-19 pandemic, as individuals seek respite from prolonged periods of confinement [6]. Since June 2024, there has been a cycling craze between Zhengzhou and Kaifeng in China [7]. The wave reached its peak in the evening of 8 November 2024, when some hundreds of thousands of young people rode

50 km from Zhengzhou to Kaifeng. Although this incident has produced many social problems, it fully reflects the strong demand of people to carry out outdoor green recreation activities. At the same time, it also reflects the lack of green paths and facilities for outdoor green recreation.

Previous studies have concentrated on assessing human needs for outdoor recreation [8], enhancing accessibility [9] and equity in recreation opportunities [10], understanding experiential dimensions [11], and analyzing the behavioral motivations of recreationists [12,13]. These studies have validated the significant correlation between the layout of outdoor recreation facilities and visitor behavior through extensive analysis of big data and emotional responses of tourists [14]. Urban green parks and natural landscapes in rural areas emerge as the favored destinations for recreational activities [15]. Hence, there is a conjecture that systematically planning the layout and connecting urban and rural green spaces could potentially expand recreation opportunities, improve the continuity of recreation activities, and enrich the overall recreational experience. Current studies on the outdoor recreation network predominantly employ social network analysis methods to examine patterns of crowd flow [16], preferences in recreational behavior [17], formation of network structures [18], identification of node characteristics [19], and capacity of network services based on tourist behavior [20]. However, there remains a gap in research focusing on optimizing connectivity and constructing networks within outdoor recreation spaces to promote sustainable green travel practices.

With the rapid expansion of the urban scale during the process of urbanization, there has been a significant increase in motor vehicles, which have become the primary mode of transportation. Consequently, vehicle emissions have emerged as a critical factor affecting the quality of the ecological environment. In contrast, walking and cycling are considered environmentally friendly and healthy modes of travel, increasingly popular for outdoor recreation and fitness activities [21]. Responding to these trends, countries worldwide have promoted green travel initiatives. For instance, Denmark's Ministries of Environment and Transportation launched "Green Travel Week" to encourage bicycle use [22]. Singapore has promoted bicycles and electric vehicles, installing numerous green bike lanes nationwide [23]. The United States has implemented an intelligent traffic management system (ITS) to promote green travel options [24]. Similarly, France enacted a future orientations of transport act to encourage eco-friendly travel and address environmental challenges [25]. In China, the government advocates a simple, moderate, green, and low-carbon lifestyle, promoting green travel modes such as walking, cycling, and public transport, enhancing urban green travel overall [26]. With sustainable urban development as a policy priority and increasing urban density, it is crucial to encourage and facilitate green transportation modes like walking and cycling by improving the convenience and attractiveness of green travel paths [27].

The term recreation network usually refers to the integration of various recreation resources, facilities, and services within a defined area through deliberate planning and design [28]. This integration forms a network system intended to facilitate tourism, leisure, and entertainment activities for the public. Connectivity stands out as a fundamental characteristic of such networks [29]. Specifically, the outdoor green recreation (OGR) network is a system that focuses on the outdoor green environment and natural landscape, emphasizes utilizing and conserving natural environments, offering opportunities for leisure, sports, adventure, and immersion in nature. Similar to general recreation networks in features and function, the OGR network comprises various recreational spots interconnected by pathways. A key element of the OGR network is the greenway, a path known for its ecological sustainability, connectivity, and scenic landscapes [30]. Internationally and domestically, the development of greenways has contributed to increased participation in activities such as hiking and cycling among urban residents. These OGR spots have emerged as primary destinations for urban dwellers seeking outdoor recreation and fitness activities. Therefore, optimizing the layout of OGR spots and constructing a well-connected OGR network are crucial steps toward promoting sustainable urban development. This approach not only

encourages the adoption of eco-friendly green travel methods but also enhances regional tourism appeal and supports the sustainable growth of communities.

As for the research on network structure, methodologies for studying ecological networks of green spaces from the perspective of biological migration are well-established [31–33]. Approaches such as circuit theoretical models [34], morphological spatial pattern analysis (MSPA) [35], the minimum cumulative resistance model (MCR) [36], graph theory models [37], and similar methods are commonly utilized for spatial connectivity analysis and the construction of green space networks. Scholars have extensively explored the development and optimization of ecological networks from various perspectives. This includes quantitative analyses of urban fringe green space networks [38], assessing the potential contribution of commercial green spaces in urban agglomeration ecological networks [39], establishing multi-functional and efficient small-scale urban green space networks [40], and identifying potential corridors to address current ecological network challenges [41]. These endeavors provide valuable insights for policymakers and urban planners in guiding spatial planning initiatives within urban areas. However, existing research has focused more on the construction of green ecological networks, and less on the construction of OGR networks with the main purpose of serving human green recreation.

The Graphab software and graph index algorithm [37], developed by Jean-Christophe Foltete and Gilles Vuidel, have been widely utilized in research on the connectivity of ecological networks and the identification of critical nodes. They are frequently employed across various disciplines [42], including agronomy [43], physical geography [44], traffic engineering [45], computer science [46], neuroscience [47], and molecular biology [48]. Uroy et al. analyzed weed connectivity in agricultural landscapes to optimize ecological and agronomic weed management strategies [49]. Jahanishakib et al. assessed the connectivity of hydrological runoff processes to mitigate the negative impacts of land use [50]. Golovinskii explored the construction and route optimization of transportation networks [51]. Mu et al. evaluated dynamic changes in surface water and green space connectivity using graph metrics [52,53]. Although Graphab software and its algorithms have been widely adopted, there is still a lack of applied research on the connectivity of OGR networks from the perspective of human recreation behavior.

The OGR network is different from previous green ecological networks. Their target spaces and service subjects are both different. The former mainly studies the service of outdoor recreation space to human recreation activities, while the latter mainly studies the service of natural protected areas to biological migration. In addition, the technical indicators and parameter settings in the process of network construction should be different, considering that the paths of human recreation and animal migration differ. Therefore, this study improves the methodologies and technical indicators established in the preceding research on green ecological networks. The main purpose of this study is to propose a new method and framework to study the construction of an OGR network from the perspective of facilitating green travel for recreationists. This study's perspective and methodology aim to offer a scientific reference for the planning of future recreational spots and trails, thereby enhancing the continuity and immersive experience of outdoor green recreational activities.

2. Materials and Methods

2.1. Study Area

Zhengzhou, a metropolis with a population of ten million, is selected as the case study due to its representative and typical characteristics. This area is located at the eastern foot of the Songshan Mountains and along the southern bank of the Yellow River (112°42′–114°14′ E, 34°16′–34°58′ N) in the central and northern region of Henan Province, China (Figure 1a). The terrain of Zhengzhou slopes higher towards the southwest and lower towards the northeast. Encompassing a total area of 7567 km^2, the region includes seven districts (Zhongyuan, Erqi, Guancheng, Jinshui, Shangjie, Huiji, and Zhengdong New District), one county (Zhongmu), three zones (Zhengzhou Airport Economic Com-

prehensive Experimental Zone, Zhengzhou Economic and Technological Development Zone, Zhengzhou High-tech Industrial Development Zone), and five cities (Gongyi City, Xingyang City, Xinmi City, Xinzheng City, and Dengfeng City) (Figure 1b). As the provincial capital, Zhengzhou is renowned as a significant cradle of Chinese civilization, a prominent historical and cultural city in China, a distinguished tourist destination, a national forest city, a model city for greening initiatives, and a national ecological garden city. In the 1990s, the establishment and development of the High-tech Industrial Development Zone and the Economic and Technological Development Zone spurred rapid urbanization in Zhengzhou. Leveraging its strategic location and robust national support policies, Zhengzhou has become a pivotal city in central China, a new first-tier mega-city, and the core city of the Central Plains Urban Agglomeration. By the end of 2022, Zhengzhou's permanent population reached 12.828 million with an urbanization rate of 79.4%. As urbanization progresses into a stable phase, meeting the needs of urban residents for an enhanced quality of life and shaping a distinctive urban landscape have become focal points for Zhengzhou's urban development and societal progress. Living in such a densely populated metropolis with over 10 million residents, urban dwellers in Zhengzhou express a strong demand for OGR spaces. Moreover, in the process of the greening campaign over the past 20 years, many OGR spaces have been built and developed in this area. However, the overall structure of the OGR network currently lacks systematic organization and connectivity. Especially under the condition of green travel, there are fewer suitable paths for citizens to carry out recreation activities, and further planning and improvement are needed in the future.

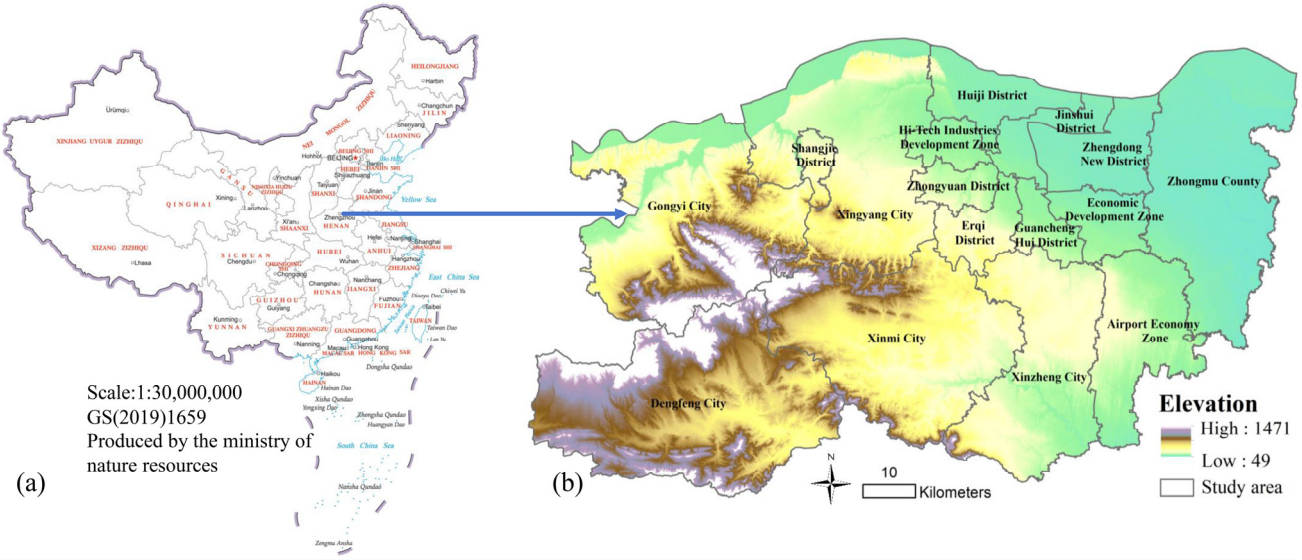


Figure 1. Location (**a**) and administrative districts (**b**) of study area.

2.2. Basic Data Obtaining and Processing

2.2.1. POI and AOI of OGR Spots

Datasets of POI (Points of interest) and AOI (Areas of interest) for OGR spots were obtained from Baidu Map. The categorization of spots in the basic datasets is inconsistent. Therefore, we have selected and classified these recreational areas based on the classification standards for urban green spaces in China and the requirements for outdoor recreation of a green traveler. The criteria for selecting OGR spots are as follows: urban parks (comprehensive park, community park, special park, and small park), scenic recreation green spaces (scenic spot, forest park, wetland park, heritage park, country park), and other recreation spots with sufficient green space, accessibility, and popularity, suitable for outdoor fitness and recreation. Indoor visiting spots, such as museums, churches, aquariums, and temples, are not included. After cleaning the basic datasets, 309 OGR spots

were ultimately selected and divided into 9 categories for analysis based on high-resolution remote sensing image discrimination and field investigation.

2.2.2. Other Basic Data Processing

The land cover dataset (10 m resolution, 2021) was obtained from the European Space Agency (https://esa-worldcover.org/en (accessed on 21 September 2023)), encompassing eight land cover types: tree cover, shrubland, grassland, cropland, build-up, bare, permanent water bodies, and herbaceous wetland. Tree cover, shrubland, and grassland were reclassified as green space, while permanent water bodies and herbaceous wetland were combined into blue space (Figure 2). These blue-green spaces were utilized to help the selection of OGR spots. Digital elevation model data (ALOS, 12.5 m) were purchased from the store of Local Space View platform (www.tuxingis.com/store.html, accessed on 21 April 2020). Road network data were downloaded from the Open Street Map platform. The new administrative boundary of Zhengzhou (vector) was derived from the third land change survey data. All data were standardized within the administrative boundary and coordinate projection as WGS_1984_UTM_Zone_49N using ArcGIS 10.8 software. The land cover data, elevation data, and road data primarily assisted in determining the recreation costs between OGR spots.

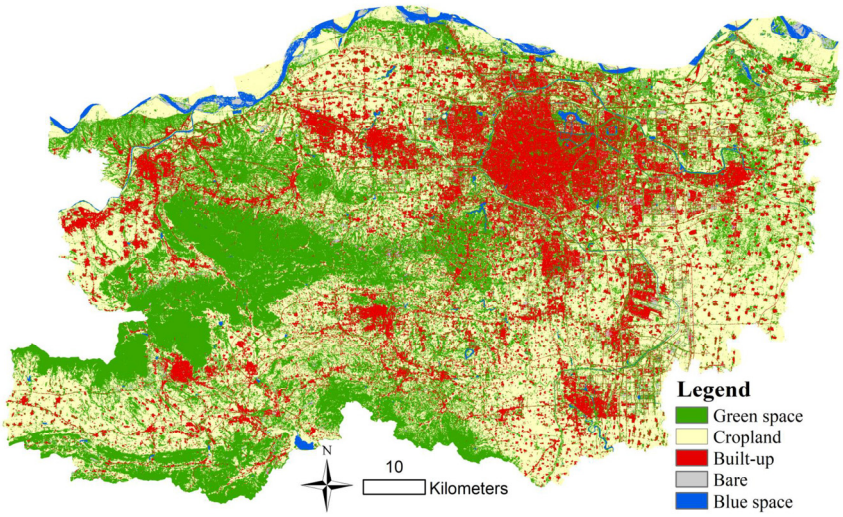


Figure 2. Land cover reclassification of Zhengzhou in 2022.

2.3. Distribution Analysis of OGR Spots

Kernel density estimation is a primary method for analyzing the density distribution of point elements. It is used to estimate the density distribution of research objects based on non-parametric tests, thereby directly reflecting their spatial distribution and aggregation characteristics. Higher kernel density indicates greater distribution density [54]. Therefore, the kernel density tool in ArcGIS 10.8 was employed to analyze the spatial distribution and aggregation characteristics of OGR spots. The types, number, and size of OGR spots were statistically analyzed and compared to find their differences in urban and rural areas.

2.4. Analysis of Graph Metrices for the OGR Network Using Graphab Software

The graph index can be used to quantify the connectivity of the OGR network formed by these OGR spots. It can be calculated using Graphab 2.8 software at four levels: global, component, local, and delta. The process generally involves four steps: selecting target patches (309 OGR spots), constructing cost surfaces (Table 1), creating recreation paths and graphs, and then calculating the selected graph indexes (Table 2).

Table 1. Setting of cost values and weights for each impact factor.

Cost Value	Distance to Road/m	Land Cover	Distance to Residential Site/m	Slope /(°)	Elevation /m
10	0–50	Built-up land	0–50	0–10	0–200
20	50–100	Green land	50–100	10–20	200–500
40	100–150	Water bodies	100–150	20–30	500–800
80	150–200	Cropland	150–200	30–40	800–1000
160	>200	Unused land	>200	>40	>1000
Weight	0.5128	0.2615	0.1290	0.0634	0.0333

Table 2. The connotation and calculation formula of the selected graph metrices.

Graph Metrices	Meaning	Level	Formula
Equivalent Connectivity (EC)	The square root of the probability score for connection between any two points in the region.	Component	$EC = \sqrt{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i a_j e^{-\alpha d_{ij}}}$
Probability of Connectivity (PC)	This refers to the probability of a link between any two points in the study area, with values ranging from 0 to 1.	Global	$PC = \frac{1}{A^2}\sum_{i=1}^{n}\sum_{j=1}^{n} a_i^{\beta} a_j^{\beta} e^{-\alpha d_{ij}}$
Integral index of Connectivity (IIC)	To assess the importance of landscape elements to the overall connectivity of the study area, with values ranging from 0 to 1.	Global Component	$IIC = \frac{1}{A^2}\sum_{i=1}^{n}\sum_{j=1}^{n} \frac{a_i a_j}{1 + nl_{ij}}$
Size of the Largest Component (SLC)	The larger the value, the greater the number of interconnected patches is, and the stronger the global connectivity is.	Global	$SLC = max\{ac_k\}$
Number of Components (NC)	The smaller the number, the stronger the global connectivity is	Global	$NC = nc$
Node degree (Dg)	Indicates the capacity of a patch to connect with other patches	Local	$Dg_i = \lvert N_i \rvert$
Betweenness Centrality Index (BC)	Refers to the sum of the shortest paths through a node, reflecting the bridging role and carrying capacity of nodes in the space network.	Local	$BC_i = \sum_j \sum_k a_j^{\beta} a_k^{\beta} e^{-\alpha d_{jk}}$ $j,k \in \{1 \ldots n\}, k < j, i \in P_j$
Fractional delta probability of connectivity (dPC)	Refers to using changes in Patch Connectivity (PC) after a patch is removed to measure the patch's importance in maintaining landscape connectivity.	Delta	$dPC = \frac{PC - PC_{remove}}{PC} \times 100\%$

Note: In the above formulae, n refers to the number of patches, a_i refers to the carrying capacity of patch i (generally refers to the surface area), d_{ij} refers to the distance between patch i and patch j (generally refers to the minimum distance between them), $e^{-\alpha d_{ij}}$ refers to the possibility of flow between patch i and patch j, α refers to the obstruction coefficient of moving distance, β refers to the index measuring carrying capacity, A refers to the total area of the study area, ac_k refers to the carrying capacity of connecting unit k (the sum of the carrying capacity of all patches comprising the connecting unit k), nc refers to the number of connecting units, N_i refers to all patches close to patch i.

2.4.1. Construction of Recreation Cost Surface

Cost surface analysis was used to generate the least-cost paths connecting various spots. The index system for cost surface establishment in previous studies was mostly set for the continuous migration of organisms [55–58], while in this study it was determined for green travel and human recreation (Table 1). Five impact factors (land cover type, elevation, slope, distance to road, and distance to residential site) related to outdoor recreation behavior were selected for establishing the recreation cost surface (Figure 3). The cost values of each factor were determined based on the degree of resistance encountered by individuals accessing an OGR spot. The weights of these factors were determined by the Analytic Hierarchy Process (AHP) considering the importance of each indicator in influencing the choice of outdoor green recreation behavior.

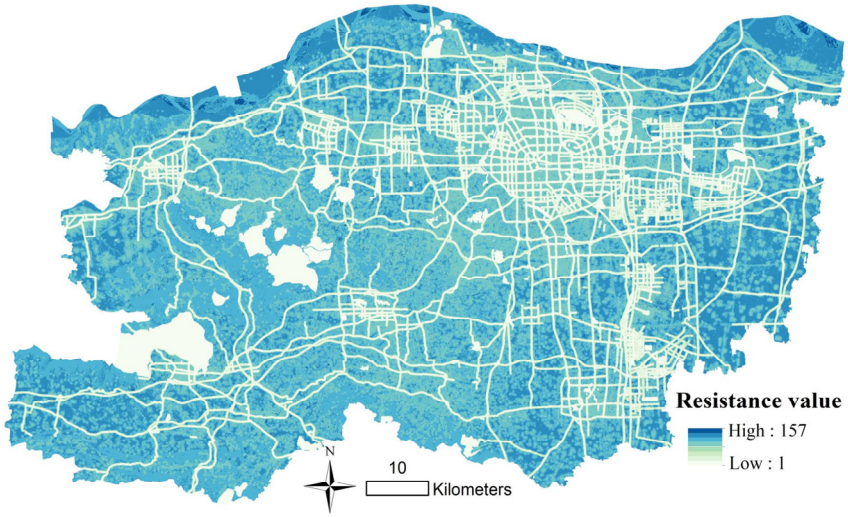


Figure 3. The recreation cost surface of the study area.

2.4.2. Calculation of Graph Metrics

In Graphab software, the minimum cumulative resistance model was applied to create recreation paths and a graph network using the selected target patches and constructed cost surface. The setting of distance threshold considers the tolerance of different recreational behaviors to time and distance [59]. The maximum acceptable distance for people walking is 3 km, while for cycling, it is 10 km. Distances of 30 km and 60 km require driving for half an hour and one hour, respectively. Different distance thresholds can be divided into three types and four levels: 3 km being suitable for walking, 10 km suitable for cycling, and 30 km and 60 km requiring driving. These were the primary parameters for analyzing graph metrices and network connectivity within the Graphab software. Considering the energy consumption and pollution associated with travel, walking and cycling are categorized as "green travel" due to their minimal environmental impact.

With reference to previous studies [60,61], eight graph metrices were selected to quantitatively and visually analyze the spatial connectivity and important role of OGR spots at four levels: global, component, local, and delta (Table 2).

2.5. Construction and Optimization of the OGR Network

The OGR network consists of these OGR spots and paths between them. To improve the integrity and connectivity of this network, this paper proposed an optimization framework (Figure 4). This technical process consists of three steps: (1) Analyze problems such as node degree, contribution degree, and bridging role of current OGR spots, along with the cost of outdoor recreation paths based on four types of threshold distance. (2) Find problems including missing areas of the OGR network, OGR spots with significant bridging roles and optimization potential, and recreation paths with high-cost values. (3) Solve these problems with two strategies. One is to expand the scale of those spots with a high bridging role according to the graph index analysis results. The other is to add spots in the missing areas and highly suitable land according to the results of network problem and land suitability analysis [62,63].

Table 3 shows the evaluation index system of the land suitability analysis for newly added OGR spots. Figure 5 shows the result of the land suitability analysis. Urban master planning, land use planning, tourism planning, and other related planning are also referred to for the selection of new OGR spots. Then, the method of least-cost analysis was again used in Graphab 2.8 software to generate new recreational paths, and optimize the network connectivity based on these old and new OGR spots. Finally, the optimization effect is verified and the feasibility of the optimization framework is proved by comparing the connectivity index and the number of green recreation paths before and after optimization.

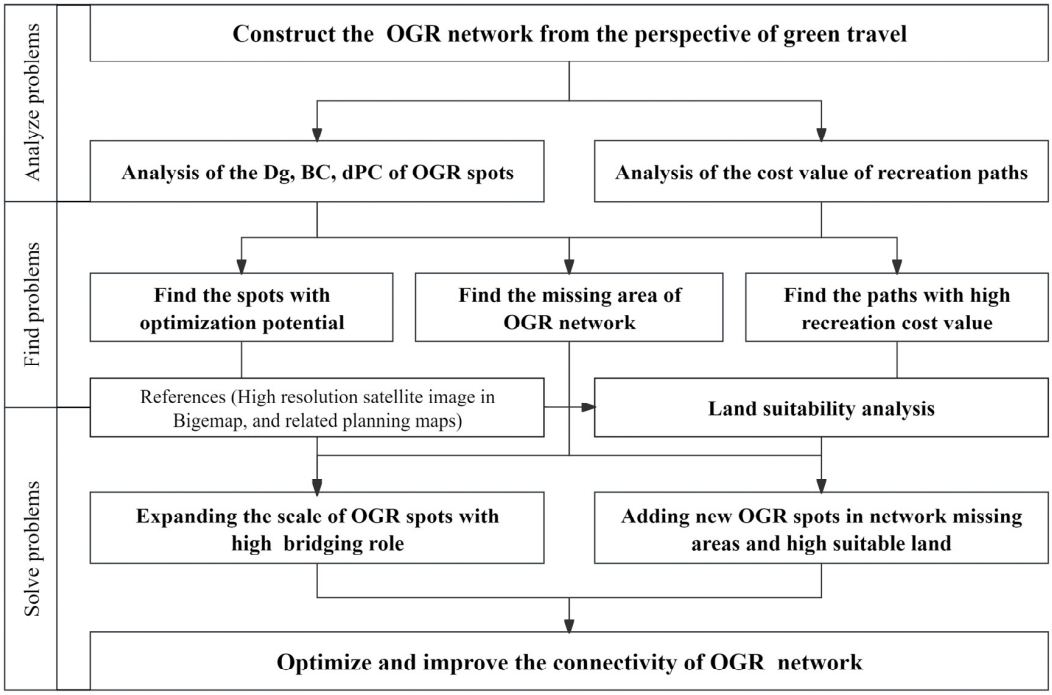


Figure 4. Framework and technical process for OGR network optimization.

Table 3. The evaluation index system for the land suitability analysis.

Suitability	Score	Land Cover	Distance to Road/m	Distance to OGR Spot/m	Distance to Residential Sites/m	Distance to Water Bodies/m	Slope /(°)	Elevation /m
Not Suitable	1	Built-up	>3000	>9000	>3000	>3000	>40	>1000
Marginally Suitable	2	Cropland	1000–3000	6000–9000	1000–3000	1000–3000	30–40	800–1000
Moderately Suitable	3	Bare	500–1000	3000–6000	500–1000	500–1000	20–30	500–800
Suitable	4	Blue space	300–500	1000–3000	300–500	300–500	10–20	200–500
Highly Suitable	5	Green space	0–300	0–1000	0–300	0–300	0–10	0–200
Weight	1	0.4051	0.2251	0.1467	0.0990	0.0664	0.0366	0.0211

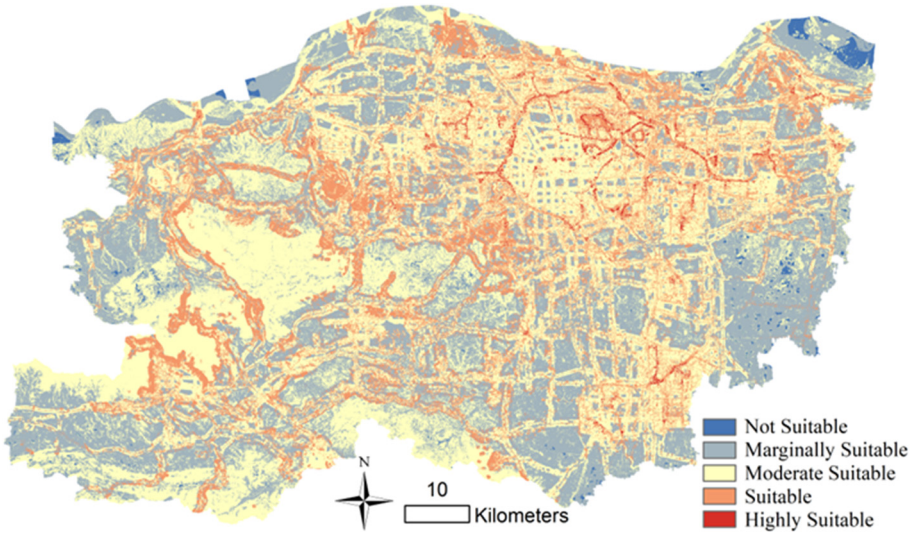


Figure 5. The result of land suitability analysis.

3. Results

3.1. Spatial Distribution Characteristics of OGR Spots

3.1.1. Distribution and Density Analysis of OGR Spots

As shown in Figure 6a, there are a total of 309 OGR spots in Zhengzhou region, predominantly located in the central urban area. The number of OGR spots in Zhengdong New District, Gongyi City, Xinyang City, Erqi District, and Xinzheng city ranked in the top five (Table 4). Kernel density analysis results (Figure 6b) reveal a high-density region, four sub-high-density regions, seven medium-density regions, and several low-density regions. The high-density area is located in the main urban area of Zhengzhou City with a total of 58 OGR spots. Zhengdong New District has the largest number of OGR spots in this central urban area. The sub-high-density areas extend from the high-density areas to surrounding satellite cities such as the northwest of Gongyi City, the middle section of Xingyang City, and southern Xinzheng City. The low-density areas are widely distributed in Xinmi City, Dengfeng City, Zhengzhou Airport Economic Comprehensive Experimental Zone, and Zhongmu County. This may be because these four regions have fewer green resources and a small scale of urban area. Zhengzhou Airport Economic Comprehensive Experimental Zone is a newly developed urban area with the least number of OGR spots.

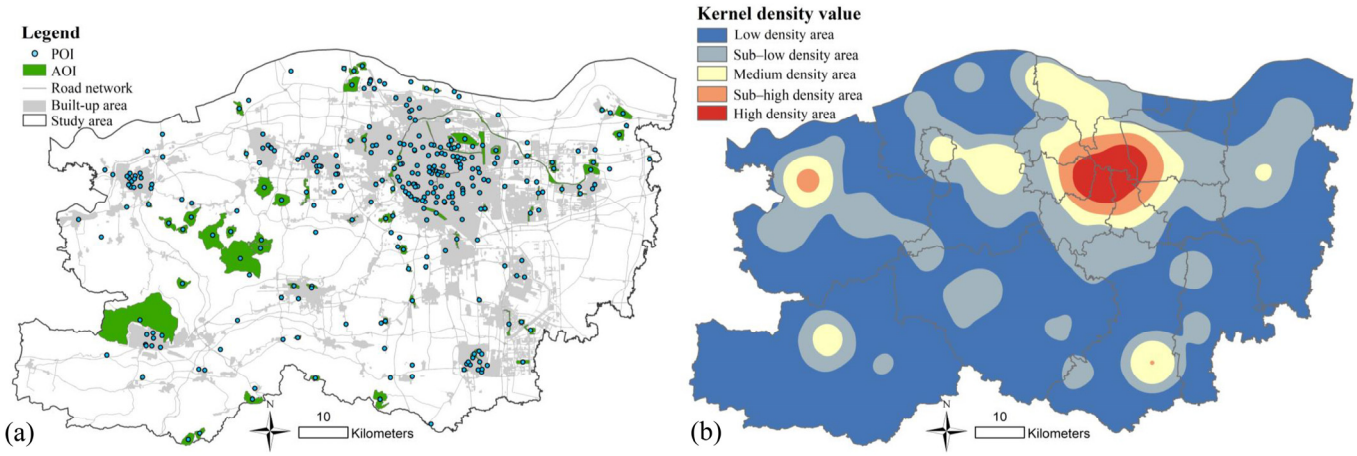


Figure 6. Distribution of selected OGR spots (**a**) and kernel density analysis of these spots (**b**).

Table 4. Number of OGR spots in different cities and districts.

City/District	Number	Area/km^2	City/District	Number	Area/km^2
Dengfeng City	20	107.91	Jinshui District	17	3.28
Gongyi City	31	38.63	Shangjie District	9	11.84
Xinmi City	16	55.91	Zhengdong New District	32	20.51
Xinzheng City	25	13.18	Zhongyuan District	20	4.49
Xingyang City	27	31.98	Zhengzhou Airport Economy Zone	7	6.60
Erqi District	26	10.44	Zhengzhou Economic Development Zone	12	4.40
Guancheng District	16	2.13	Zhengzhou Hi-Tech Industries Development Zone	10	3.64
Huiji District	23	5.90	Zhongmu County	18	24.32

3.1.2. Differences in Types and Scale of OGR Spots Between Urban and Rural Areas

As shown in Table 5, there are great differences in the types and scale of OGR spots between urban and rural areas. The number of OGR spots in urban areas is about 2.7 times more than that in rural areas. Among the various types of urban parks, comprehensive

parks have the largest scale, covering 36.88% of the total area. Community parks have the highest number, comprising 40.44% of the total. Small parks have the smallest number and scale. Among all types of scenic recreational green spaces, scenic spots have the most number and largest scale, with the mean area of 6.51 km^2. The number of wetland parks is the least, while the scale of heritage parks is the least.

Table 5. Differences in type, number, and scale of OGR spots between urban and rural areas.

Urban Area_Urban Parks				Rural Area_Scenic Recreation Green Spaces			
Type	**Number**	**Area/km²**	**Mean Area /km²**	**Type**	**Number**	**Area/km²**	**Mean Area /km²**
Comprehensive park	33	28.64	0.87	Scenic spot	35	227.92	6.51
Community park	91	2.62	0.03	Country park	24	17.07	0.71
Special park	78	46.07	0.59	Forest park	8	12.97	1.62
Small park	23	0.33	0.01	Wetland park	5	8.45	1.69
				Heritage park	12	1.06	0.09
Total	225	77.66	0.34	Total	84	267.47	3.18

3.2. Spatial Connectivity Analysis of the OGR Network

3.2.1. Global and Component Level

According to the analysis of IIC, SLC, and NC at the global level (Figure 7), significant differences in the spatial connectivity of the OGR network are apparent among various travel modes. IIC and SLC gradually increased with the increase in the threshold distance for different travel modes, while NC gradually decreased. When driving for 60 km travel, the IIC and SLC values are the highest, while the NC values are the lowest, indicating the highest accessibility and largest spatial connectivity of the OGR network. In contrast, choosing walking for green travel exhibits the opposite trend for all three indicators, indicating that the lowest accessibility and spatial connectivity between these OGR spots are found under this condition.

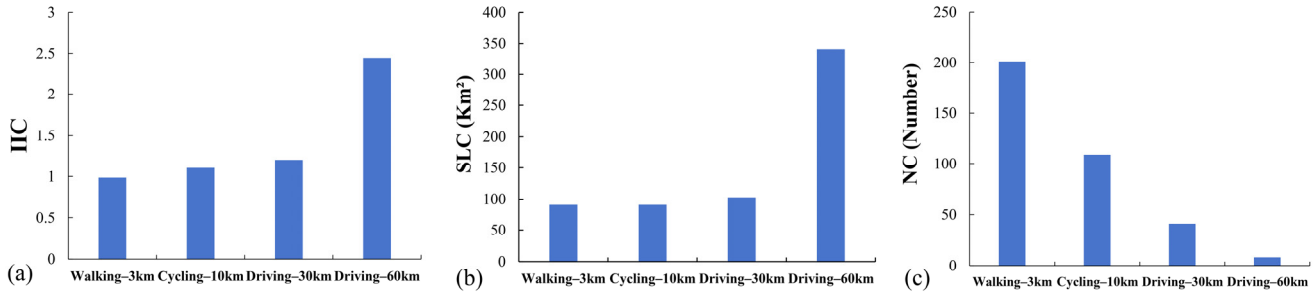


Figure 7. Graph metrices analysis at global level under walking, cycling, and driving ((**a**): IIC, (**b**) SLC, (**c**): NC).

At the component level, the EC and IIC values show similar differences and trends as the metrices at the global level (Figure 8). EC and IIC are at their lowest levels for walking travel and reach their highest levels for driving for 60 km. The spatial connectivity among these OGR spots shows less impact when driving, but is significantly affected when walking and cycling. Many discontinuous components were produced. Therefore, it is imperative to optimize the OGR network from the perspective of green travel to enhance accessibility and spatial connectivity among these OGR spots, thereby catering to the increasing demand for hiking and physical exercise.

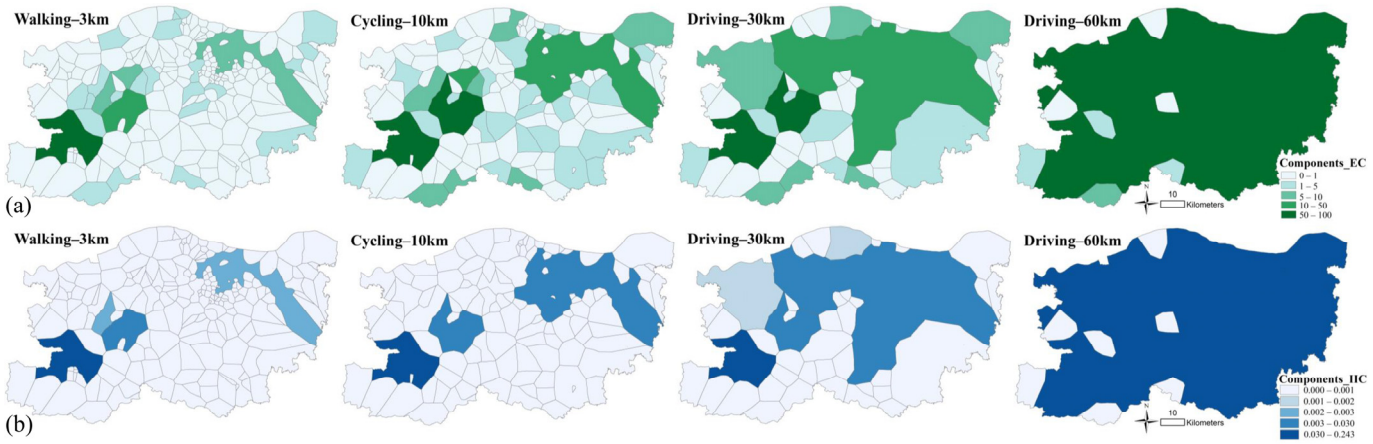


Figure 8. Graph metrices analysis of the OGR network at component level for walking, cycling, and driving ((**a**): EC, (**b**): IIC).

3.2.2. Local and Delta Level

At the local and delta levels, the metrices Dg, BC, and dPC reflect the connection capacity, bridging role, and contribution degree of each OGR spot, respectively.

The Dg value indicates the capacity of one spot to connect with other spots. The higher the node degree index of a spot, the more significant its radiative connection effect on neighboring spots. As shown in Figure 9a, under walking travel conditions, most OGR spots show low Dg values, with only three OGR spots having a Dg value greater than 5 (Dongfengqu Riverside Park, West Canal Park, and Jialu Riverside Park). The highest Dg value is 9, indicating poor connectivity among these OGR spots. Cycling travel enhances the Dg values of OGR spots; the highest Dg value is 13. The number of OGR spots with a Dg value greater than 5 increased to 41. The top five OGR spots with high Dg values include Dongfengqu Riverside Park, Jialu Riverside Park, Shangdu Archaeological Park, Zhengxing Garden, and Xuyuan Park. When driving for outdoor recreation, the value of Dg increased significantly. For example, when driving for 30 km, the number of OGR spots with a Dg value over 5 reached 115. The top five OGR spots with high Dg values are Jingxiu Park, Bishagang Park, South-to-north Water Diversion Ecological Culture Park, Xionger Riverside Park, and Changping Garden. When driving for 60 km for outdoor recreation, 170 OGR spots have a Dg value exceeding 5, which is 57 times higher than walking, and the highest Dg value is 19, which is 11 times greater than walking. The top five OGR spots with high Dg values are Bishagang Park, Jingxiu Park, South-to-north Water Diversion Ecological Culture Park, Yufeng Ecological Park, and Xionger Riverside Park. OGR spots with high Dg values play a crucial role in connecting surrounding recreational areas throughout the region and should be prioritized for protection in future development efforts.

The BC value reflects the "footstone" function of OGR spots in the connected component. The spots with high BC value play an important role in maintaining the overall connectivity of the OGR network. A higher BC value indicates a stronger bridging effect. As shown in Figure 9b, under walking travel conditions, the highest BC value is observed in the West Canal Football Park, followed by the Dongfengqu Riverside Park, Longhu East Canal Park, Xianghu Ecological Wetland Park, Jialu River Park, and other OGR spots. Under cycling and driving travel conditions, Fuxi Mountain Scenic Area also has a high BC value. This spot is far from the urban area, so its BC value is low under walking conditions. The value of BC maybe affected by the travel mode. Under green travel conditions, walking and cycling, each OGR spot has a lower BC value and weaker bridging effect. Conversely, a higher BC value is observed under the condition of driving. It shows that fast vehicles can increase the accessible distance, expand the connected area, and enhance the BC values of OGR spots, as well as their bridging impact.

The dPC value is used to evaluate the contribution of OGR spots to overall connectivity. The removal analysis (Figure 9c) indicates that those five OGR spots, including

Songshan National Scenic Area, Fuxi Mountain Tourist Area, Fuxi Mountain Snow Cave Scenic Area, Wuyunshan Mountain Ecological Park, and Zhengzhou Longhu Park, contribute significantly to the connectivity of the OGR network. Removing these spots would notably reduce regional OGR network connectivity. Songshan National Scenic Area has a considerable contribution among all spots. The contribution ranking of OGR spots remains unaffected by the distance threshold, but the dPC value of each OGR spot correlates with the distance threshold.

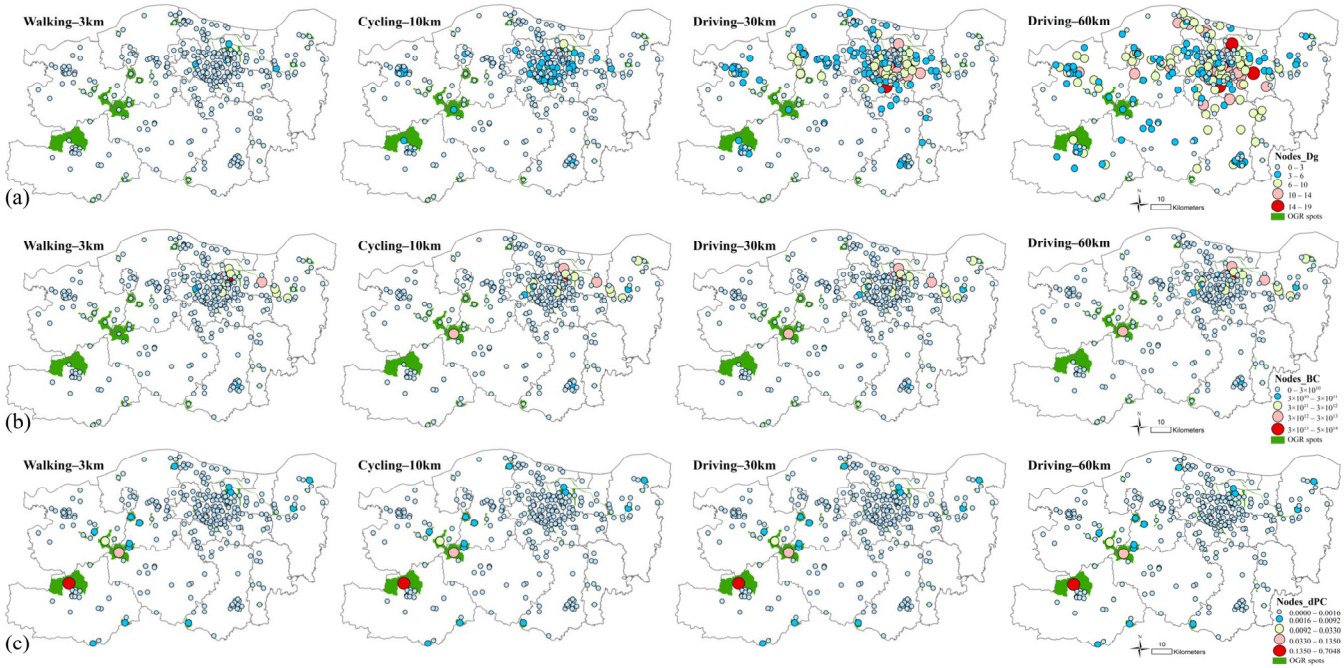


Figure 9. Graph index analysis of every OGR spot at local and delta level under walking, cycling, and driving ((**a**): Dg at local level, (**b**): BC at local level, (**c**): dPC at delta level).

3.3. Optimization of the OGR Network from the Perspective of Green Traveling

Through spatial connectivity analysis of the current OGR network, it was observed that connectivity among OGR spots is lowest when walking or cycling. Therefore, optimizing and improving the OGR network's connectivity holds significant importance from a green travel perspective.

As shown in Figure 10a, before optimization, there are a total of 882 recreation paths, including 116 paths suitable for walking and 207 paths suitable for cycling. Additionally, 332 paths require a half-hour drive, while 227 paths necessitate an hour-long drive. The cost values of these recreation paths range from a minimum of 101 to a maximum of 198,650. Areas with the lowest recreation costs and great network connectivity were mainly distributed in the central urban area, including Zhengdong New District, Zhongyuan District, Erqi District, Zhengzhou High-tech Industrial Development Zone, Guancheng Hui District, and Jinshui District. Conversely, Xinmi City, Dengfeng City, and Gongyi City exhibit the highest recreation costs and worse connectivity, likely affected by complex terrain and less road network. The northeast and southeast regions of Zhengzhou display the worst network connectivity, possibly due to fewer OGR spots being distributed in these areas. Consequently, optimizing the connectivity of the OGR network should prioritize the northeast, southeast, and southwest areas of Zhengzhou.

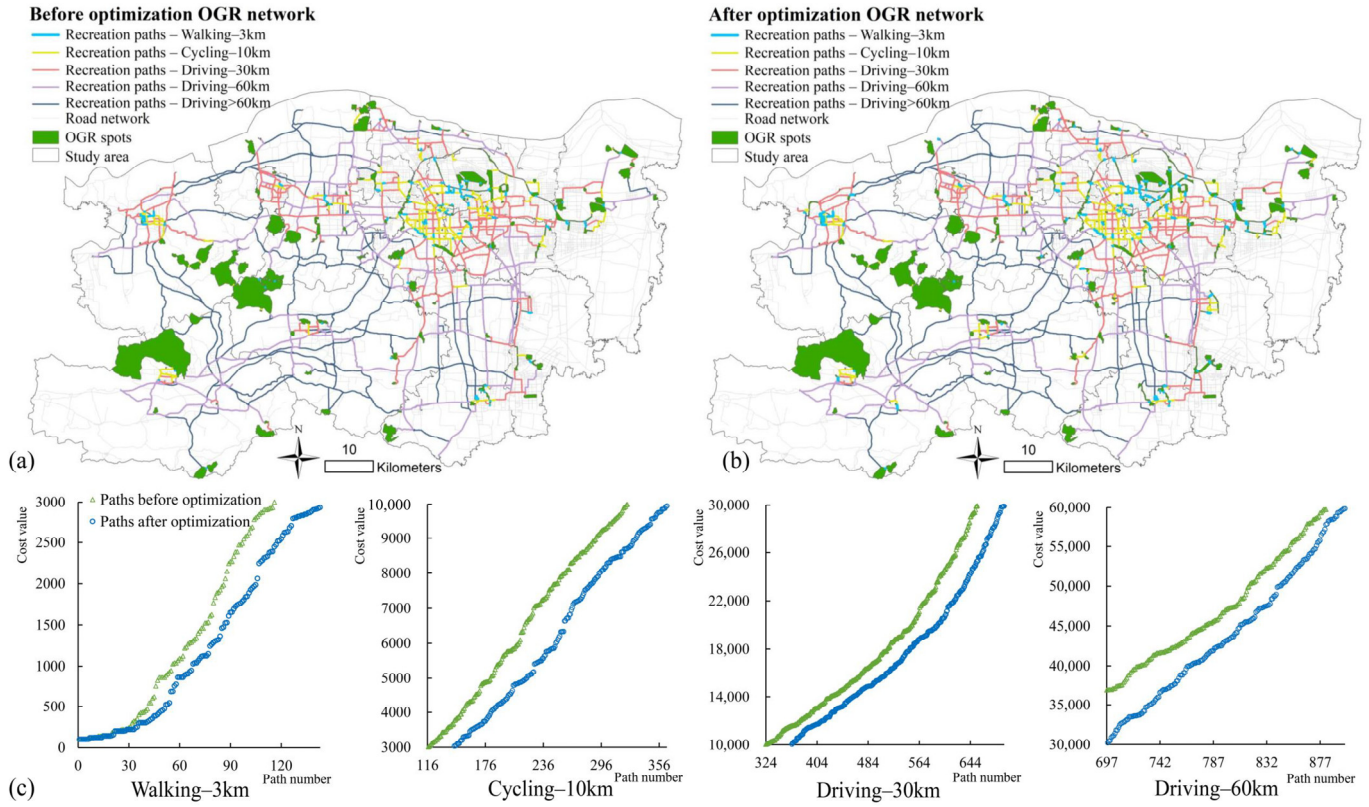


Figure 10. OGR network maps ((**a**): before optimization, (**b**): after optimization), and the changes in number and cost values of various path types (**c**).

According to the above results and the technical optimization process of the OGR network, 30 new OGR spots were identified through land suitability analysis from the perspective of green traveling (Figure 11a). These new spots are located within a 10 km cycling distance from existing spots to ensure that they can improve network connectivity when traveling by walking and cycling. Comparing the values of IIC and PC at global level, they both increased by 4% after network optimization (Figure 11b,c). The contribution ranking of newly added OGR spots to the overall network connectivity is presented in Figure 11a.

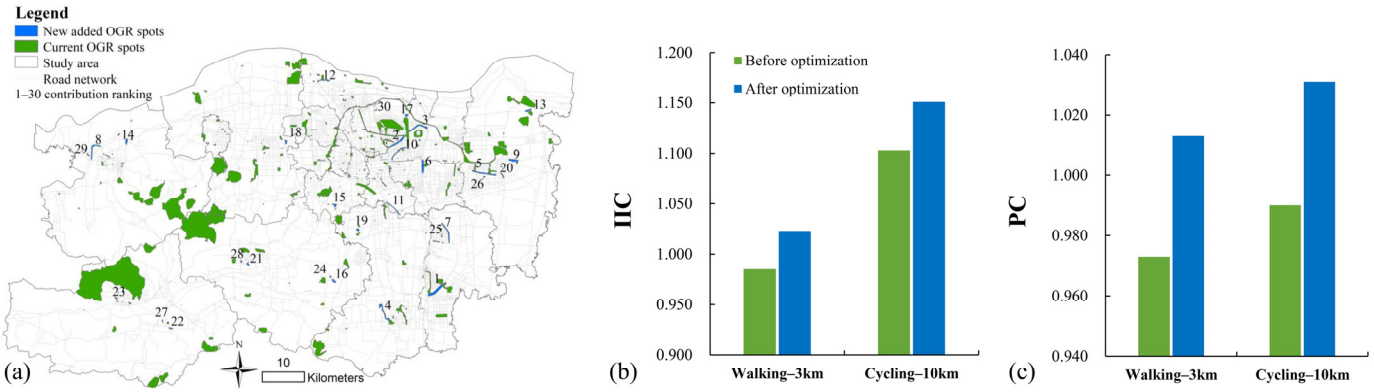


Figure 11. Location of current and newly added OGR spots ((**a**): the numbers represent the contribution ranking of new OGR spots to the overall network connectivity), and changes of IIC and PC at global level ((**b**): IIC, (**c**): PC).

Figure 10b shows the results of the optimized OGR network. There are a total of 898 recreation paths, including 143 paths suitable for walking, 221 paths suitable for

cycling, 333 paths that require a half-hour drive, and 201 paths that necessitate an hour-long drive. Comparing the path number and their cost values before and after optimization (Figure 10c), we observe a significant increase in the number of recreation paths under green recreation behavior conditions. Paths that are suitable for walking recreation increased by 27 from 116 previously to 143 after optimization, as well as paths that are suitable for cycling recreation which increased by 14 from 207 previously to 221 after optimization. The number of paths which need driving 30 km to achieve continuity has increased by only one path, while the number of paths which require driving 60 km to achieve continuity has decreased by 26, from 227 previously to 201 after optimization. The observed changes in cost values indicate that low-cost paths increased and high-cost paths decreased after network optimization based on the tolerance distance threshold for green travel. This also reflects that the overall connectivity of the OGR network is enhanced. However, we also find that if the parameters of the distance threshold are determined according to the acceptable driving distance, the connectivity does not improve for walking or cycling. Therefore, a comprehensive recreational network with green travel giving priority should be planned and constructed in future urban green recreation planning.

4. Discussion

This paper assessed and optimized the connectivity of the OGR network in Zhengzhou region from the perspective of tourists using various travel modes for continuous recreation. The findings indicate that when adopting a green travel mode (walking and cycling) for outdoor recreation, the recreation network exhibits worse connectivity and does not cover the whole area. Highly connected recreational activities adopting green travel modes can only be realized in the central urban areas. Therefore, with the increasing demand for health, fitness, and outdoor recreation [64,65], this paper proposes a framework and technical process for OGR network optimization based on graph index analysis and land suitability evaluation. The aim is to provide a more convenient, complete, and highly connected outdoor green recreation environment for humans. The results show that the connectivity of the optimized OGR network can be improved by 4%. Compared with previous studies on recreation preference [66] and recreation accessibility [67], this study provides a new research perspective and methodology.

4.1. Construction of the OGR Network and Connectivity Analysis

The primary function of the OGR network focuses is to provide continuous accessible sites and paths for people's outdoor recreation and fitness activities. The promotion of outdoor recreational activities can also better facilitate urban–rural integration and enhance local economic development levels [68]. Additionally, the extensive green spaces and green corridors within the OGR network can provide services for species migration and biodiversity conservation [69]. The network structure composed of scenic spots and green paths is similar to that of ecological networks composed of ecological nodes and ecological corridors. However, due to the distinct service objectives of OGR networks and ecological networks, parameters such as distance thresholds and cost values are determined considering human travel behavior during OGR network construction and connectivity analysis. Graph-based modelling is widely recognized as a robust method for representing and analyzing landscape networks. Graphab software is an open source tool dedicated to the modelling of landscape networks [37]. Our previous research using this software demonstrated its effectiveness in analyzing network structures comprising green spaces, water bodies, and other natural areas [52,53]. It facilitates the identification of key nodes and pathways, thereby aiding in the optimization of landscape patterns and network structures. It is considered that most of the previous studies prefer to study the connectivity of ecological networks serving the migration of organisms [70,71]. However, there has been little research on the role of the OGR network in supporting human recreational behavior. Therefore, this paper considers three travel modes (walking, cycling, and driving) to set four distance thresholds and construct cost surfaces for the construction and connectivity

analysis of the OGR network according to the influence of different factors on human recreation behavior. Graph metrices at global level indicate that the connectivity of the OGR network for walking and cycling is significantly lower compared to driving (Figure 7). The number of connected components is the largest, the equivalent connected area is the smallest (Figure 8), and the connected capacity of each OGR spot is the lowest when walking (Figure 9a). The ranking of each OGR spot in terms of bridging role and contribution degree is primarily influenced by its scale and location (Figure 9b,c). Walking and cycling have high demands on people's age and physical strength. Driving can enhance the connectivity of the OGR network, but in recent years, with the increase in self-driving travel activities, there are serious parking problems in all scenic spots. Therefore, it is of great practical significance to open and develop recreational buses to enhance the connectivity of the OGR network.

4.2. Optimization of the OGR Network and Connectivity Improvement

Analysis of the current OGR network connectivity reveals that urban areas have high connectivity due to dense OGR spots and convenient transportation, while the southwest mountainous region benefits from abundant natural resources and expansive scenic areas. However, due to the complicated terrain and inconvenient transportation, high-cost recreational paths are predominantly found in this area. In the northeast and southeast plain areas, the absence of the OGR network is attributed to the extensive agricultural land, insufficient recreational resources, and few OGR spots and roads. Therefore, after analyzing current network structure issues, assessing land suitability, and identifying potential recreational resources, two optimization strategies are proposed (Figure 4). The first strategy involves expanding the scale of OGR spots with a high bridging role and enhancing their ability to connect with neighborhood spots. For instance, expanding the scale of High-speed Rail Park in the northeast with a high bridging role will increase its ability to connect to the nearby Jialuhe Riverside Park. In the southeast area, expanding Meihe Park will strengthen its connectivity with Garden Expo Park and Yuanling Ancient City Site Park. Another strategy is to select new OGR spots in areas with high suitability on missing areas and high-cost paths; this can reduce recreational costs and enhance recreational network connectivity by increasing the density of OGR spots and the number of recreational paths. For instance, in the missing southern area of the recreation network in Zhongmu County, depending on the natural green resources along the Jialu River and its banks, new OGR spots and low-cost recreational paths can be added in highly accessible areas near the villages. By leveraging surrounding natural resources such as rivers and reservoirs in the southwest mountainous area, new OGR spots have been added along the high-cost recreational paths to reduce their cost value. Depending on the distance threshold for green travel, adding new OGR spots within 10 km of existing spots can significantly increase the overall connectivity of the OGR network. After re-quantitative analysis of the optimized network connectivity (Figure 10b), it was revealed that expanding and adding 30 OGR spots could increase network connectivity by four percentage points in green travel conditions (Figure 11b,c). The ranking of the contribution of these new OGR spots (Figure 11a) to overall network connectivity provides guidance for phased development and construction of recreational resources in the Zhengzhou region. The generated recreation paths can provide a reference for the construction of recreation special line in the future. The optimization techniques and strategies of the OGR network can serve as a reference for future similar research.

4.3. Contribution and Limitations

The contribution of this study is to propose a method to quantify and optimize OGR network connectivity based on the differences in tolerable distances among the three human recreational behaviors (walking, cycling, and driving). It is found that OGR network connectivity is poor under walking and cycling, existing a large optimization potential. An OGR network optimization framework and optimization strategy are proposed, and the

optimization effect under green travel conditions is verified and compared in Zhengzhou region using graph theory and GIS spatial analysis. The research perspective, selected quantitative indicators, network optimization strategy, and technical process serve as a reference for future studies on OGR networks, applicable not only to Zhengzhou but also to other worldwide regions.

The limitation of this study lies in the omission of considering the impact of OGR spot types in typology and hierarchy on tourist behavior, as well as their influence on the parameter setting of distance thresholds and cost values for various factors related to network connectivity. It is worth improving in future continuing research. Additionally, the network optimization strategy overlooked the recreational potential of scenic countryside and agritourism. Future research should focus on gathering additional relevant data and conducting more comprehensive studies on these aspects.

5. Conclusions

This study put forward a new technical process and optimization method of OGR network construction for the purpose of improving the accessibility and connectivity of human outdoor green recreation activities. The index system for cost surface setting and the selection method for new OGR spots based on human travel behavior characteristics and the different distance thresholds for walking, cycling, and driving were proposed. The connectivity differences of the OGR network among various travel modes were quantified and compared. The different roles of OGR spots in the overall network structure were defined using multi-source data and a combination of graph index analysis and GIS spatial analysis. From the perspective of green travel, the optimization of OGR networks still has great potential. A technical optimization process and two strategies for enhancing OGR network connectivity were proposed. It is significant for the improvement and planning of future outdoor green recreation network in Zhengzhou and other similar areas. The connectivity of the OGR network was poor for walking and cycling with most connecting recreation paths located in urban areas. Graph metrices such as Dg, BC, and dPC at local and delta levels can reflect the connectivity capacity, bridging roles, and contribution levels of OGR spots. The cost value of recreation paths was lower in urban areas and higher in southwest mountainous regions, primarily influenced by their distance from roads and residential sites. Expanding the scale of OGR spots with bridging roles, as well as adding new OGR spots in areas missing from the network and highly suitable places, can effectively improve and optimize the connectivity of the OGR network. With the continuous urbanization process and increasing demand for outdoor green recreation and physical fitness, optimizing OGR networks from the perspective of green travel is conducive to human health and well-being as well as the sustainable development of ecosystems. A comprehensive recreational network with green travel given priority should be planned and constructed in future urban green recreation planning. For paths suitable for walking and cycling, the construction of greenway or green trail should be strengthened. For long-distance paths that require driving, the development of public transportation tourism routes should be enhanced to supplement human accessibility. The construction of stations and transfer points should be considered and constructed in the transition areas of different recreation behaviors (walking, cycling, and driving). Methods and perspectives in this study could be applied to regions with different landscape resources, road structure, and topography.

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