

Research Article

Two for the Road: Measuring Regional Disparity and Agglomeration in Human Development Level and Transportation Infrastructure

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As the core element of social-economic development in the Qinghai-Tibet Plateau, transportation dramatically shapes the scale, type, and intensity of human activities. First, this study utilizes night light data and kilometer-grid population data to construct night light development index (NLDI) and to evaluate the human development level at the county scale. Then, based on the complex transportation infrastructure data, the weight assignment method is adopted to create transportation infrastructure influence degree (TIID), which is used to evaluate the location conditions of the counties. Finally, bivariate spatial autocorrelation is utilized to analyze the effect of regional conditions on the county-level human development variation. The results show that (1) NLDI is verified to assess differences in the level of human development among counties in Qinghai-Tibet Plateau and to overcome the difficulties of systematically and integrally obtaining socio-economic statistical data. The pattern of human development level in Qinghai-Tibet Plateau presents a “core-periphery” spatial structure with the transportation network as the axis. (2) On the whole, with the improvement of location conditions influenced by transportation infrastructure, the spatial aggregation of human development level is constantly improving, and the spatial disparity continues to decrease. (3) Locally, four spatial interaction patterns of high/low clustering are recognized and analyzed. It reflects the complexity and spatial heterogeneity between transport infrastructure construction and human development level in the Qinghai-Tibet Plateau.

1. Introduction

The 2030 Agenda for Sustainable Development, adopted by all Member States of the United Nations in 2015, particularly highlights the importance of the Sustainable Development Goals for people and the planet [1]. Sustainable development in the Qinghai-Tibet Plateau has been continuously concerned mainly in terms of climate change, disaster risk management, food security, cultural diversity, biodiversity, migration, and livelihood loss. On 11–15 October 2021, the United Nations Biodiversity Conference-Ecological

Civilization Forum was held in Kunming, China. In the sub-forum of “Ecological Civilization and Ecological Security in the Qinghai-Tibet Plateau,” many experts conducted in-depth discussions on topics such as the “ecological pattern and ecosystem evolution” and “human adaption and alpine civilization” [2]. Qinghai-Tibet Plateau is located in the middle of the Asian continent, with a total area of about 1/4 of China’s land area and an average elevation of more than 4,000 meters. The unique geographical environment on the Qinghai-Tibet Plateau has made the ecosystem fragile and unstable, and caused severe environmental problems, such

as glacier shrinkage, soil erosion, land degradation, and biodiversity loss, as well as seriously restricting high-quality and sustainable development on the plateau [3–5].

In order to dynamically audit the sustainable development level of Qinghai-Tibet Plateau, this study applies the night light remote sensing data to monitor the human development level by establishing night light development index with scale adaptation. Then, based on the data on transportation infrastructure (including highways, railways, and airports), the influence degree of transportation infrastructure is applied to evaluate the location changes and spatial structure reshaping of the Qinghai-Tibet Plateau transportation. Further, this paper explores the variation of human development levels in the Qinghai-Tibet Plateau from the transportation perspective. Finally, it discusses the impact of transportation infrastructure and the spatial differentiation of human development level, thus providing relevant policy references for the protection of the Qinghai-Tibet Plateau, which has global ecological and cultural significance. Figure 1 shows the framework of this study.

2. Literature Review

Due to global warming and excessive disturbance of human activities, the ecological evolution and regional development trend of the Qinghai-Tibet Plateau have attracted extensive attention worldwide. Qinghai-Tibet Plateau is a region with rapid population growth and an extremely fragile ecological environment [6]. Population growth, climate change, and environmental degradation have increased the vulnerability of sustainable development capacity in the plateau region. Dynamic monitoring and evaluation of regional development sustainability have become an essential basis for policy-making [7–9].

2.1. Night Light Development Index and Human Development Level. At present, many scholars have carried out plenty of research on the construction of index systems and evaluation methods of sustainable development and achieved fruitful results [10, 11]. However, existing studies primarily rely on traditional statistical data, with relatively single data sources, types, and poor availability. Research areas are mainly limited to large-scale levels such as national, provincial, or municipal regions, and there is a lack of refined research on county or small-scale areas. In recent years, Earth observation solutions have been playing an increasingly important role in monitoring regional social and economic conditions in a more precise, rapid, continuous, and large-scale manner [12, 13].

Night light remote sensing is an optical remote sensing technology that can detect low light at night. Since most of the stable light comes from artificial light sources, night light remote sensing images have been proved to intuitively reflect the differences in human activities at night, with advantages of broad coverage, fast updating, and easy acquisition [14–16]. Elvidge et al. [17] built the night light development index (*NLDI*) from night light data and population density data on the principle of *Gini* coefficient to evaluate the

regional socio-economic development. *Gini* coefficient is a statistical index to measure the fairness of income distribution of residents in a country or region, which is a well-established method of measuring income distribution [18]. The basic principle of *NLDI* is that people who live in well-lit areas are more likely to have access to goods and public services, and the level of human development is relatively higher [7]. This index is demonstrated to be significantly correlated with the Human Development Index (*HDI*), closely linked with poverty rate, population distribution, ecological footprint, etc., reflecting human development to a certain extent [19, 20].

NLDI has been used to evaluate the level of human development on global, national, and subnational scales in the world. Elvidge et al. [17] first developed and evaluated the list of *NLDI* scores for countries of the world. Li et al. [21] found that the nighttime light data, which replaces GDP, is highly consistent with the trade development and forecast trends of more than 60 countries along the Belt and Road. The results show that the *NLDI* can be used as an effective economic indicator for trade analysis. Andreano et al. [20] showed that there are indeed considerable advantages to the use of night light data to map the poverty situation in Latin American and Caribbean countries. Xu and Gao [22] utilized *NLDI* to evaluate China's urbanization process (31 provinces, 1992–2012), and correlated these results with public health datasets (birthrate, elderly population, cancer rate, etc.) to identify the important factors. Similar few attempts have also been used in the Qinghai-Tibet Plateau and shown good application results. Wang et al. [23] quantified the urbanization level on the Qinghai-Tibet Plateau with LuoJia1-01 nightlight data. Huang et al. [7] evaluated the human development level in Qinghai-Tibet Plateau by combining the *NLDI*, cultural diversity, and the city rank-size rule.

The nighttime light imagery has broadened the research fields in the empirical evaluation of human development, public service evaluation, small-scale regional development spatial imbalance investigation, and other research fields with the characteristics of spatial scale adaptability, and data sources accessibility and stability [24]. Qinghai-Tibet Plateau is facing significant challenges brought by population migration patterns and climate change. This condition also reduces the ability of Qinghai-Tibet Plateau to provide essential ecological goods and services. Therefore, Earth observation can provide a timely and effective appraisal of human development and provide a scientific footing for policy-making.

2.2. Transportation and Human Development Level. Transportation infrastructure mainly plays a vital role in guiding, supporting, and guaranteeing regional development from the aspects of improving regional accessibility, accelerating the urbanization process, and promoting the formation of an industrial economic belt along the road, thus improving the regional human development level and realizing regional sustainable development [25–27]. Toivonen et al. [28] found that the geographical distance from the

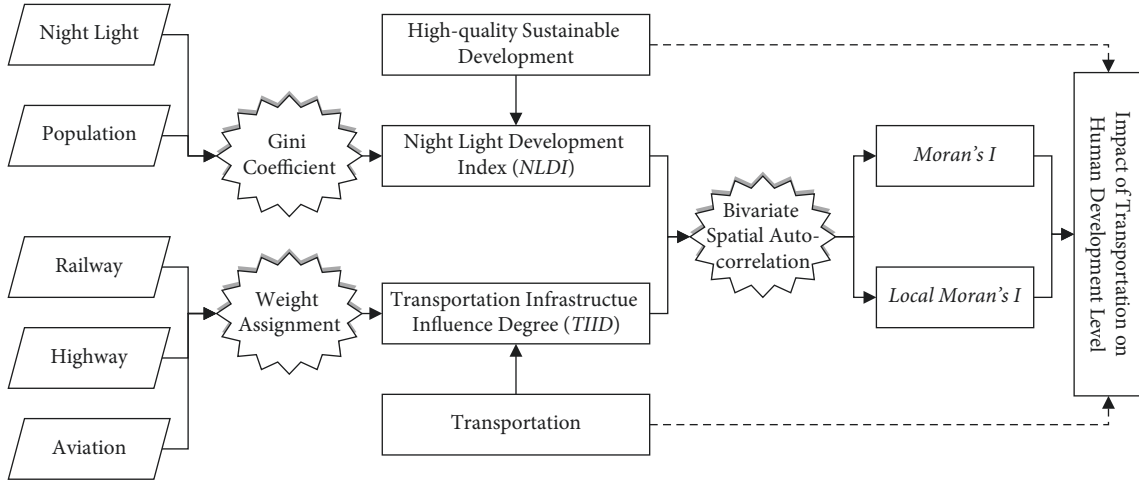


FIGURE 1: Research framework.

nearest village, road, or market center can be used as a spatial structural variable of forest reduction in the Andes region, to predict forest degradation. Freitas et al. [29] selected Sao Paulo (Brazil) as the study area and analyzed the influence on the social and economic environment with the distance to the center of city, that is, by improving the accessibility of transportation and advantage of location, highways change the land value and attract the agglomeration of population, capital, technology and industry, and thus promoting the change of land use in different locations. Lieskovský et al. [30] analyzed the historical accessibility and its role in the landscape of Southern Slovenia by using the Cost-Distance method and found that the straight-line distance between settlements and towns was an important factor affecting the preservation and abandonment of traditional agricultural landscape.

In terms of the influence of regional social and economic development level, many scholars believe that transportation infrastructure is an important factor that causes unbalanced economic development among regions. Bajar and Rajeev [31] theoretically demonstrated the significant impact of transportation infrastructure on narrowing regional disparities. Based on the analysis of regional economic differences in Hunan Province (China), Tang et al. [32] pointed out that transportation development and construction layout are the leading factors affecting regional economic disparities. Jiang [33] studied the driving mechanism of China's regional economic differences and believed that the quality of regional economic location and perfection of social security are determined by the regional transportation infrastructure, which is a key factor in the formation and evolution of regional economic patterns. In the context of sustainable development, it is worth paying special attention to the phenomenon of spatial unbalanced development and complex patterns of population migration caused by the construction of transportation in the plateau region, which results in intensified siphon effect and unbalanced spatial development.

3. Study Area

The Qinghai-Tibet Plateau is located in southwestern China, with a total area of about 2.6 million square kilometers, most of which are above 4,000 meters above sea level. From the perspective of administrative divisions, it includes the entire scope of Qinghai Province and Tibet Autonomous Region, as well as parts of Yunnan, Sichuan, Xinjiang, and Gansu Provinces. In terms of ecological environment, the Qinghai-Tibet Plateau is one of the regions with the richest biodiversity in the world, the source area of many major rivers in Asia, and a significant ecological security barrier for China and even for Asia [34]. The overview of the Qinghai-Tibet Plateau is shown in Figure 2.

Global satellite night light data has become one of the most widely used geospatial data products. Defense Meteorological Satellite Program (DMSP) provides global low light data from 1992 to 2013 and ceased updating in February 2014. Visible Infrared Imaging Radiometer Suite (VIIRS) then continued to capture global nighttime low light data and provided raw data from 2012 [35]. Besides artificial illumination, the low light data on the Earth collected by VIIRS inevitably contain other low light phenomena, such as stray light, lightning, biomass burning, gas flares, etc. According to relevant research results [14, 35], the threshold method is utilized in this paper to process the raw data to eliminate the influence of low-quality light sources and irrelevant features, in order to produce high-quality night light data reflecting human activities [36], as shown in Figure 3.

The population of the Qinghai-Tibet Plateau is obtained from *Worldpop* (<https://www.worldpop.org/>), as shown in Figure 4. The unit is the number of people per pixel with county totals adjusted to match the corresponding official United Nations population estimates that have been prepared by the Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat. The mapping approach is Random Forest-based dissymmetric redistribution [37].

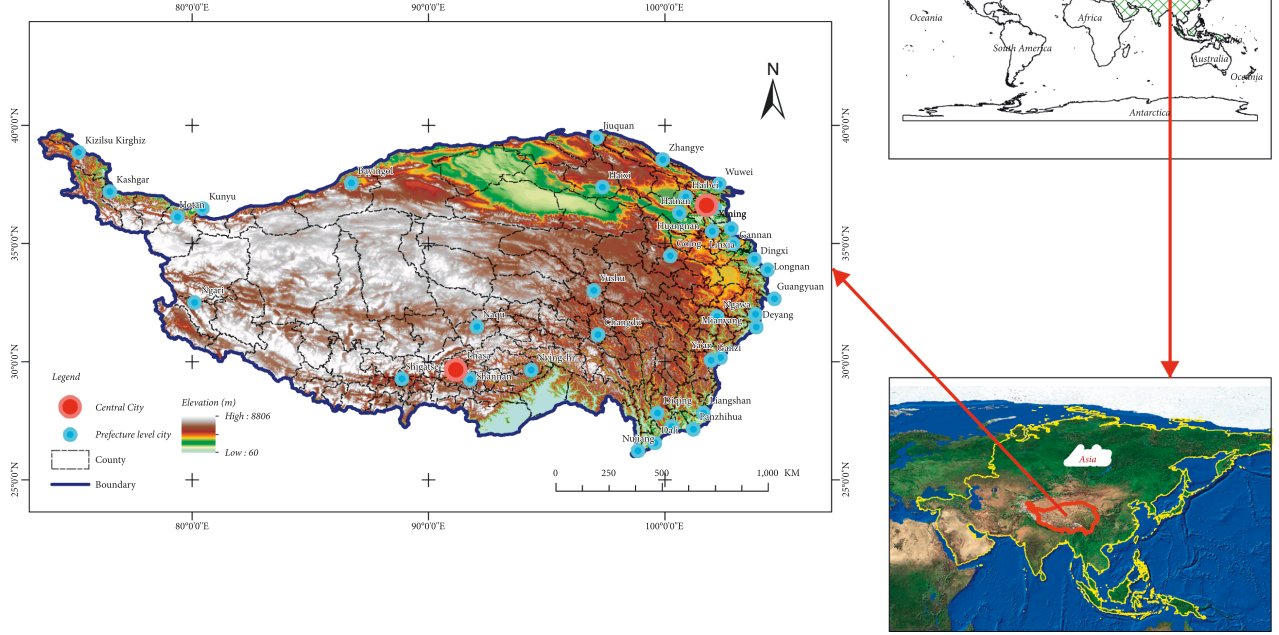


FIGURE 2: Overview of the Qinghai-Tibet plateau.

Abundant transportation spatial datasets provide the possibility to evaluate the construction and development of transportation infrastructure on a large scale [38]. In this study, the transportation infrastructure data resources (highways, railways, and airports) are obtained mainly from Open Street Map (<https://www.openstreetmap.org/>), National Catalogue Service for Geographic Information (<https://www.webmap.cn/main.do?method=index>), and Gaode Map (<https://www.amap.com/>). After the processing of data cleaning, topology checking, and projection correction, the datasets of transportation infrastructure are shown in Figure 5.

For the validity and rationality of the study, it is necessary to collect all kinds of data in the same year for pre-processing. Considering the data accuracy, quality, and integrity of each period, we ultimately choose to unify various data sources in 2015.

4. Methods

4.1. Nighttime Light Development Index (NLDI). The Gini coefficient is regarded as the competent indicator to measure whether a country or region's income is balanced or not. According to the *Lorenz Curve*, it judges the equal distribution of a country or region. Elvidge et al. [35], and Salvati et al. [19] constructed the Nighttime Light Development Index (NLDI) in 2012, and the Equation is as follows:

$$NLDI = 1 - \frac{2 \sum_{i=1}^{n-1} Q_i}{n-1}, \quad 0 \leq NLDI \leq 1. \quad (1)$$

In equation (1), n is the number of grids; $Q_i = \sum_{j=1}^i x_j / \sum_{j=1}^n x_j$, is the proportion of lights

corresponding to the grid with proportion P_i of inhabitants in which x_j is the value of radiance class. $P_i = \sum_{j=1}^i x_j / n$, The closer the NLDI is to 0, the higher the level of human development in the region. Otherwise, the level of human development in the region will be lower. Considering the data structure characteristics of night light data and population data used in the study, the detailed calculation process of NLDI is further adjusted and optimized based on equation (1), as shown in Figure 6.

4.2. Transportation Infrastructure Influence Degree (TIID).

In this study, we build the Transportation Infrastructure Influence Degree (TIID) to reflect the support and guarantee capacity of transportation infrastructure for regional development, and the ability of regional external connection. The greater the influence of transportation infrastructure, the stronger their supporting capacity for regional development [39–43].

$$C_i = \sum_{j=1}^m T_{ij}, \quad i \in (1, 2, 3, \dots, n). \quad (2)$$

As is shown in equation (2), n is the number of counties. m represents the total number of types of transportation infrastructure in county i . C_i refers to the influence degree of transportation infrastructure in county i , and j refers to the different types of transportation. T_{ij} refers to the influence of the transportation infrastructure of type j in county i . Based on the characteristics of the Qinghai-Tibet Plateau and existing research results [44, 45], the weights are determined by the situation of highways, railways, and airports owned by the county. The weight assignment is shown in Table 1.

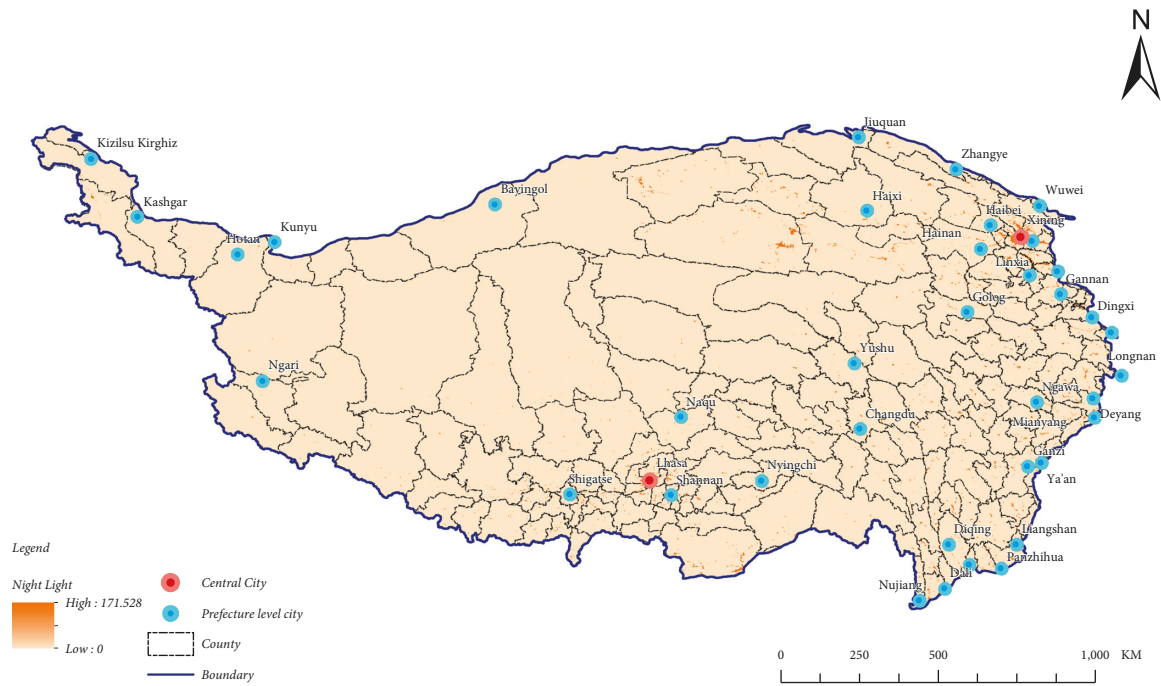


FIGURE 3: Distribution of night light of the Qinghai-Tibet plateau.

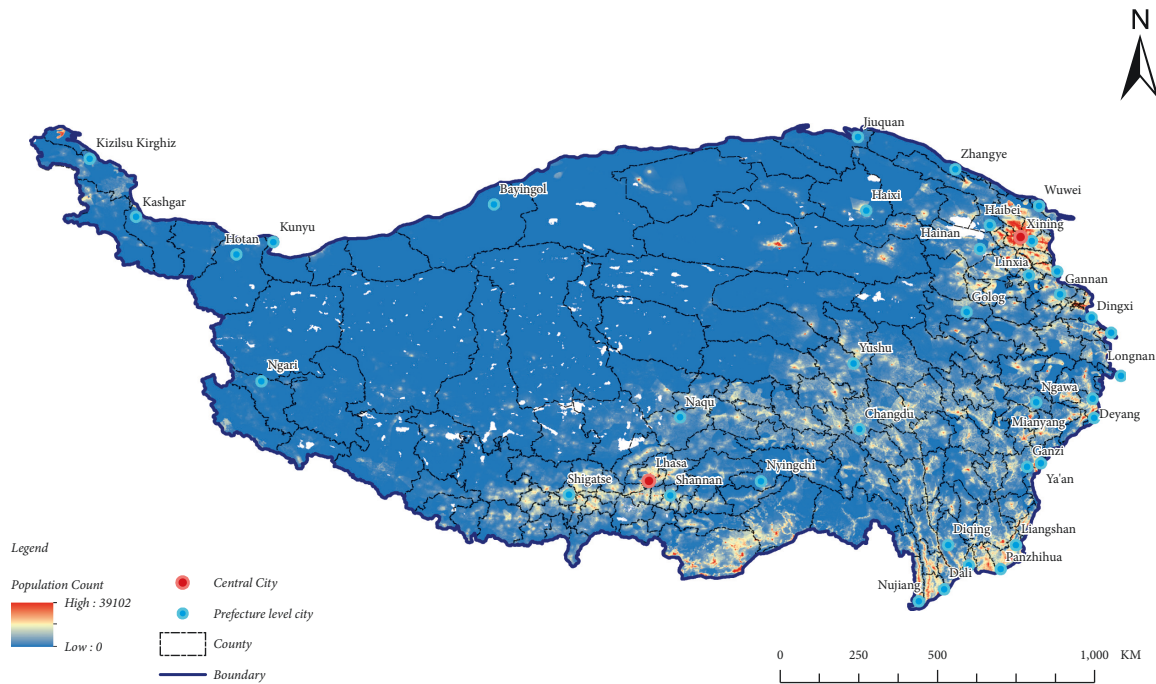


FIGURE 4: Population distribution of the Qinghai-Tibet plateau.

4.3. Spatial Autocorrelation. The spatial autocorrelation theory mainly includes global and local spatial autocorrelation, which reflects the spatial aggregation degree of research objects. Global Moran's I index and local Moran's I index are adopted in this study. Global Moran's I measure the spatial interrelationship based on the feature's location

and value [46]. The value of this index is between $[-1,1]$. When it is equal to 0, indicating that there is no spatial autocorrelation. The closer it is to 1, the higher the degree of aggregation. When the index is less than 0, it is a negative correlation. The equation of global Moran's I calculation equation is as follows:

TABLE 1: The weight of transportation infrastructure with different types.

Type	Criterion	Weight
Highways	Contains freeway exits	2.5
	$L_h \leq 30$ km	2.0
	$30 \text{ km} < L_h \leq 60$ km	1.0
	$L_h > 60$ km	0
	1st	2.5
	2nd	2.0
	3rd	1.5
	Others	1
	Contains railway station	2.5
	$L_h \leq 30$ km	2.0
Railways	$30 \text{ km} < L_h \leq 60$ km	1.0
	$L_h > 60$ km	0
Airports	Contains airport	2.0
	$L_h \leq 30$ km	1.0
	$30 \text{ km} < L_h \leq 60$ km	0.5
	$L_h > 60$ km	0

Note. L_h refers to buffer distance from the transportation infrastructure.

large. The spatial pattern is expressed as High–Low differentiation or Low–High differentiation [14]. The equation of local Moran's I is shown as follows:

$$I_i = \frac{(x_i - \bar{x})}{S^2} \sum_j W_{ij}(x_j - \bar{x}), \quad (4)$$

where the definitions of S^2 , X_i , X_j , and W_{ij} are the same as equation (3).

In order to analyze the correlation between multiple variables, related scholars further extended the global and local autocorrelation of bivariate based on Moran's I, and provided a feasible method to reveal the correlation of spatial distribution of different features. The definition is as follows:

$$I_{lm}^i = z_l^i \sum_{j=1}^n W_{ij} z_m^j = \frac{X_l^i - \bar{X}_l}{\sigma_l} \sum_{j=1}^n W_{ij} \frac{X_m^j - \bar{X}_m}{\sigma_m}. \quad (5)$$

In equation (5), X_l^i is the eigenvalue of the attribute l in spatial unit i , X_m^j is the eigenvalue of the attribute m in spatial unit j , σ_l , σ_m are the variances of eigenvalues of l and m , respectively. The meanings of other parameters are the same as the preceding ones.

5. Results

5.1. Distribution of Night Light over the Qinghai–Tibet Plateau. According to the spatial distribution of night light data, the features of human activities in the Qinghai–Tibet Plateau show a spatial distribution of “strong in the southeast and weak in the northwest.” Xining and its surrounding area of Hehuang Valley, Lhasa and its surrounding area of Yarlung Zangbo River with its two tributaries, and the three Parallel Rivers Area of Yunnan part are the areas with high intensity of human activity. The northwest side of Qinghai–Tibet Plateau, mainly including western Tibet, Qinghai, and

Xinjiang Provinces, are regions with low intensity of human activities. Regarding the standard deviation of night light data (as shown in Figure 7), the areas with large differences in light intensity within counties are mainly distributed in the southeast of Qinghai–Tibet Plateau. The southeast is still the main region of urbanization and human activities in the Qinghai–Tibet Plateau, and the difference in human development levels within the region is also the most obvious.

5.2. Calculation of Night Light Development Index in the Qinghai–Tibet Plateau. The *NLDI* of the Qinghai–Tibet Plateau is calculated based on equation (1) and plotted with the county scale, as shown in Figure 8. The most developed areas are concentrated in the southeast of the Qinghai–Tibet Plateau. The southeast has the highest level of urbanization, the most concentrated population distribution, the highest level of infrastructure construction and public services, and the highest brightness of night light.

In terms of global spatial autocorrelation, the Moran's I is 0.149, which is greater than 0. It also passes the test at the significance level of 0.001, which indicates that the *NLDI* in the Qinghai–Tibet Plateau presents a robust spatial autocorrelation and shows a significant agglomeration distribution trend. The human development levels in adjacent counties influence each other, and the Z value is 5.849, indicating that *NLDI* is mainly concentrated in the Qinghai–Tibet Plateau with a High-Value.

As shown in Figure 9, from the perspective of local spatial autocorrelation, the *NLDI* in the Qinghai–Tibet Plateau gives a spatial agglomeration pattern and displays spatial heterogeneity. In the local Moran's I spatial pattern, the Low–Low agglomeration areas are mainly distributed in 22 counties, including Hezuo, Gangca, Kangding, Ledu, etc. The High–High agglomeration areas are mostly in 21 counties, including Hotan, Rutog, Zanda, Akto, etc. The High–Low agglomeration areas are concentrated primarily in 20 counties, including Shiqu, Tianjun, Gonghe, Huzhu, Guinan, etc.

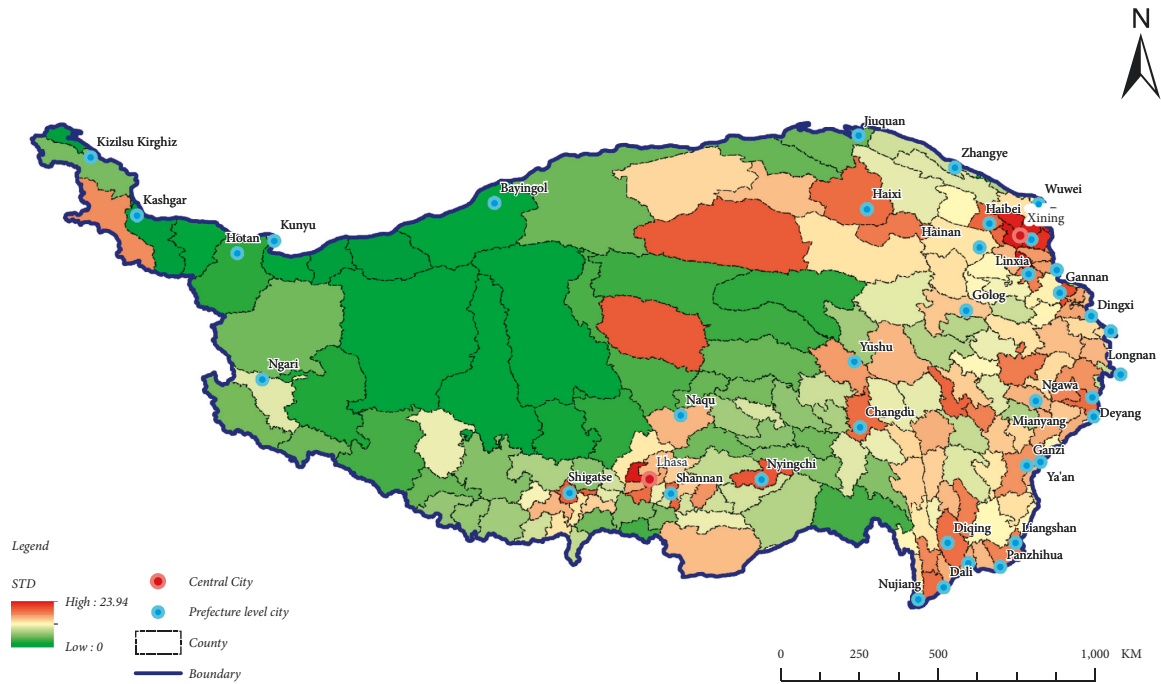


FIGURE 7: Spatial distribution of night light standard deviation.

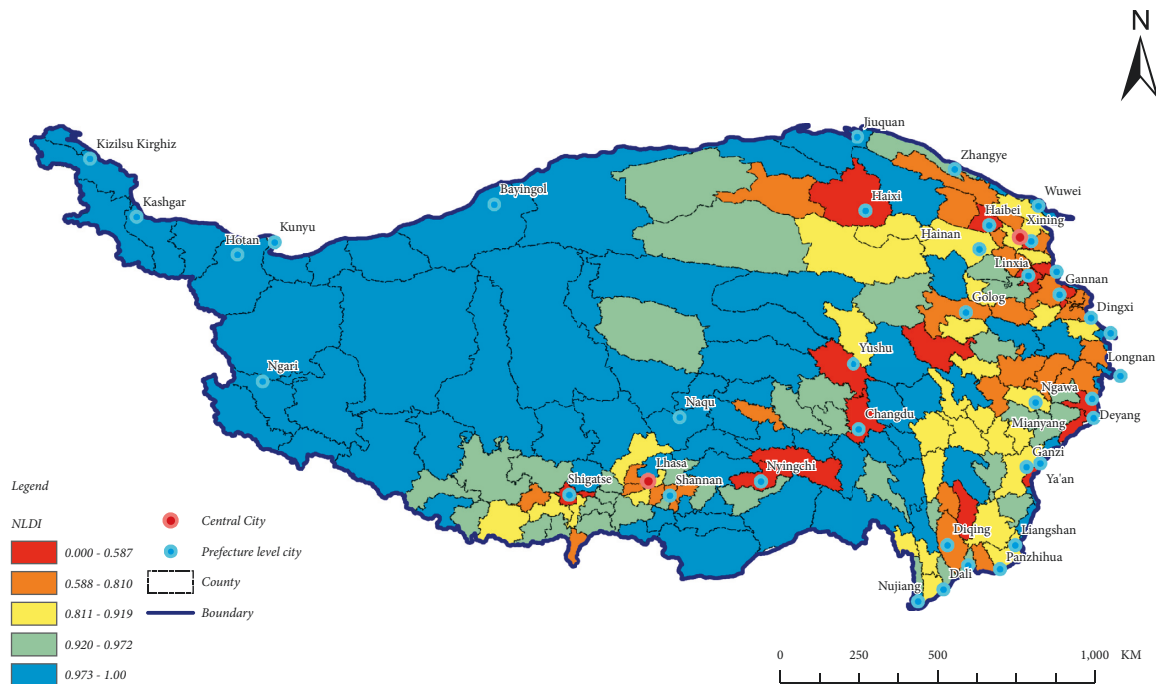
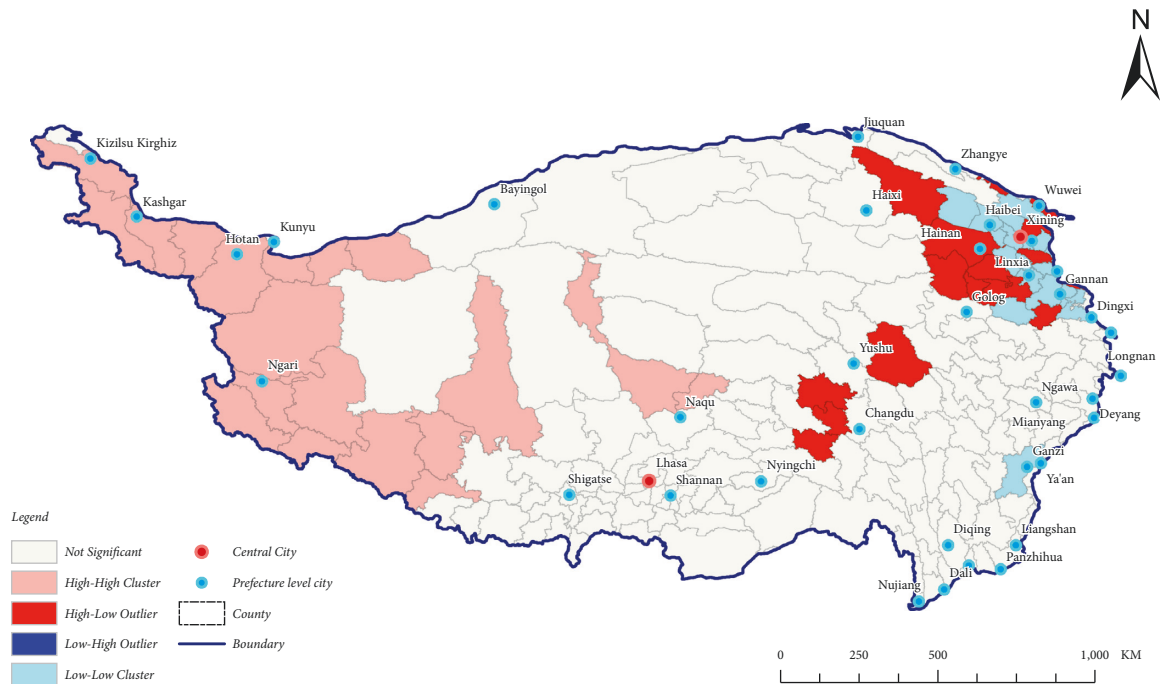
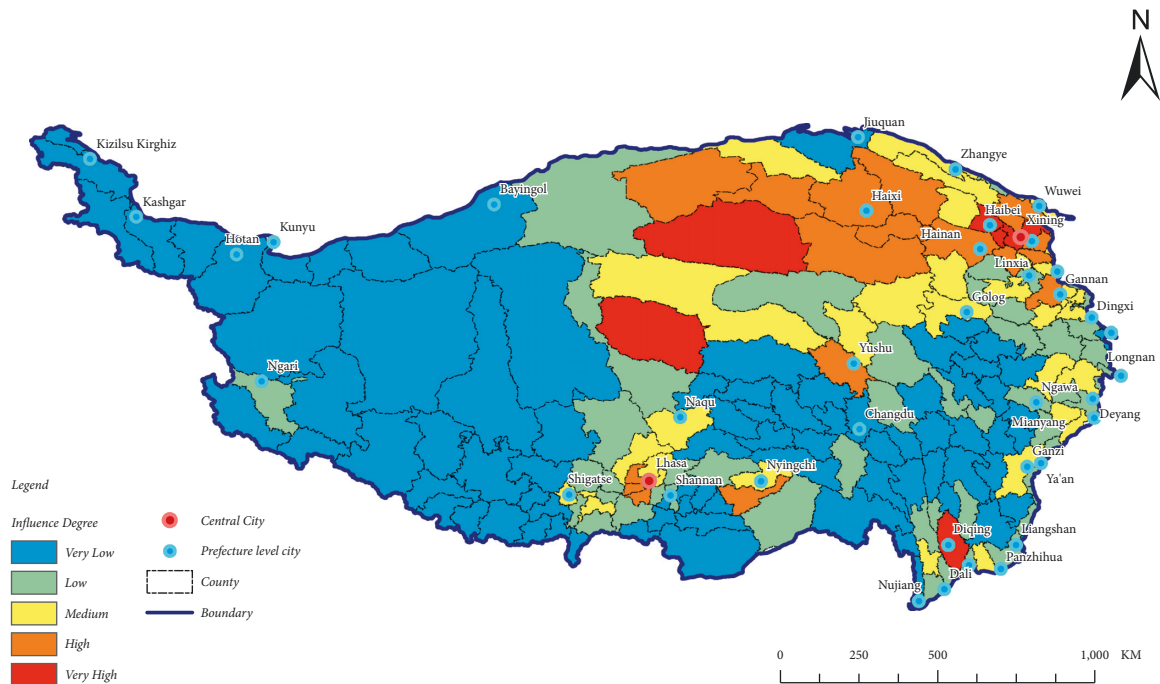


FIGURE 8: Spatial distribution of NLDI.

5.3. Evaluation of Transportation Infrastructure Influence Degree in the Qinghai-Tibet Plateau. Based on the method described in Section 4.2, *TIID* is evaluated and is divided into five levels, including areas with Very High, High, Medium, Low, and Very Low, as is shown in Figure 10 and Table 2.

The overall level of *TIID* in the Qinghai-Tibet Plateau is relatively low. The *TIID* between counties is different, showing a trend of sparseness from east to west, from central cities to remote areas. Among them, areas of very high level are Golmud City in the middle and the urban agglomeration areas in the east with Xining as the

FIGURE 9: Local spatial autocorrelation of *NLDI*.FIGURE 10: Spatial distribution of transportation infrastructure influence degree (*TIID*).

center. Most of the surrounding areas of very high level are areas with high level. Areas with medium-level areas are mainly connected to high-level areas from the east, northeast, and southwest. Most of the areas with low levels and very low level are distributed in the western and southern areas.

As shown in Table 2 above, there are nine counties with very high influence degree in Qinghai-Tibet Plateau, accounting for 4.31% of the total counties in the study area, and the land area is 134671.1 km², accounting for 5.19% of the total area of the study area. There are 20 counties with High influence degree in Qinghai-Tibet Plateau, accounting

TABLE 2: Statistics of transportation infrastructure influence degree (*TIID*) in Qinghai-Tibet Plateau.

Level	Threshold	Number of counties	Proportion of total number (%)	Area (km ²)	Proportion of total area (%)
Very low	0.00–0.20	96	45.93	1441988	55.55
Low	0.21–0.40	50	23.92	239127.9	9.21
Medium	0.41–0.60	34	16.27	425239.2	16.38
High	0.61–0.80	20	9.57	354848.3	13.67
Very high	0.81–1.00	9	4.31	134671.1	5.19

for 9.57% of the entire counties in the study area. The land area is 354848.3 km², accounting for 13.67% of the total area of the study area. There are 34 counties with medium influence degree, accounting for 16.27% of the whole counties in the study area, and the land area is 425239.2 km², accounting for 16.28% of the total area of the study area. There are 50 counties with low influence degrees, accounting for 23.92% of the total counties in the study area, and the land area is 239127.9 km², accounting for 9.21% of the total area of the study area. There are 96 counties with very low influence degree accounting for 45.93% of the total counties in the study area, and the land area is 1441988 km², accounting for 55.55% of the total area of the study area.

From the perspective of spatial pattern, there is a strong spatial autocorrelation of *TIID* in the Qinghai-Tibet Plateau. In terms of global spatial autocorrelation, the Moran's *I* is 0.749, which is much greater than 0. It also passes the test at significance level of 0.001, indicating that the *TIID* in the Qinghai-Tibet Plateau presents a strong spatial autocorrelation with a significant agglomeration distribution trend. In addition, the *Z* value is 28.289, meaning that the *TIID* mainly presents the characteristics of high-value agglomeration in the Qinghai-Tibet Plateau. At county scale, the spatial aggregation degree of *TIID* was significantly higher than that of *NLDI*.

As shown in Figure 11, from the perspective of local spatial autocorrelation, the *TIID* in the Qinghai-Tibet Plateau presents a spatial agglomeration pattern and shows strong spatial heterogeneity. In the local Moran's *I* spatial pattern, the High-High agglomeration areas are mainly concentrated in 42 counties (e.g., Delingha, Dulan, Gonghe, Huzhu, Modoi). The Low-Low agglomeration areas mainly cover 48 counties (e.g., Sog, Zadoi, Hotan, Akto). The Low-High agglomeration areas are only concentrated in 7 counties (e.g., Henan, Guinan, Bange).

We further analyze the spatial aggregation patterns of *TIID* within the buffer area of about 60 km from the highway (freeway), highway (ordinary highway), railway, and airport in the Qinghai-Tibet Plateau. As shown in Figure 12, the High-High area around highway (freeway) accounts for the highest proportion of 48.75%. The influence of railway is second only to the highway (freeway), and the proportion of High-High area around railway is 47.69%. It can be seen that, as the main frame of transportation infrastructure systems in Qinghai-Tibet Plateau, highway (freeway) and railway have played a key role in improving the level of transportation infrastructure and structure of the transportation network. They have also improved and promoted the location conditions of the surrounding areas along the

line. At the same time, we also found that the highway (freeway) has gradually replaced the dominant position of the railway in the comprehensive transportation system of the Qinghai-Tibet Plateau by virtue of its high efficiency and speed.

5.4. Relationship between Transportation Infrastructure and Human Development Level in the Qinghai-Tibet Plateau.

Based on the previous calculation, this study first analysis the statistics between *TIID* and *NLDI* at the county scale. As shown in Figure 13(a), there is a significant negative correlation between *TIID* and *NLDI*. The value of *R*² is 0.98. At county scale, with the improvement of the *TIID*, the mean of the *NLDI* shows a downward trend, reflecting the upward movement of human development overall.

As shown in Figure 13(b), this study further analyzes the characteristics of *NLDI* distribution under different grades of *TIID*. With the improvement of *TIID*, the spatial aggregation of *NLDI* is constantly improving, and the spatial differentiation continues to decrease. For example, in counties with the influence degree of very high, high, medium, and low grade, the proportions of *NLDI* showing Low-Low aggregation mode are 66.67%, 35%, 20.58%, and 4%, respectively. However, in counties of very low grade, there is no Low-Low aggregation pattern in the distribution of *NLDI*. The trend of decline is noticeable overall. On the contrary, the proportions of *NLDI* showing a nonsignificant pattern are 22.22%, 50%, 61.67%, 80%, and 76.04%, respectively, showing a significant increasing trend.

Based on the bivariate spatial autocorrelation method, the spatial weight matrix is established to calculate the global spatial autocorrelation index between the *TIID* and *NLDI*, and a strong negative correlation is found. The value of Moran's *I* is −0.157. According to the scatter diagram (see Figure 14), most of the points fall in quadrants II and IV, while fewer points fall in quadrants I and III, which indicates that the *TIID* and *NLDI* tend to converge at High-Low or Low-High. That is, the better the *TIID*, the easier it is for clustering units with low *NLDI*. On the contrary, the worse *TIID*, the easier it is for units with high *NLDI* to aggregate.

Local Indicators of Spatial Association (*LISA*) plot can further clarify the specific locations of these clusters or anomalies. There are four spatial agglomeration relationships between the *TIID* and *NLDI*, with significant differences (see Figure 15).

In general, spatial distribution has four major relationships between the *TIID* and *NLDI*.

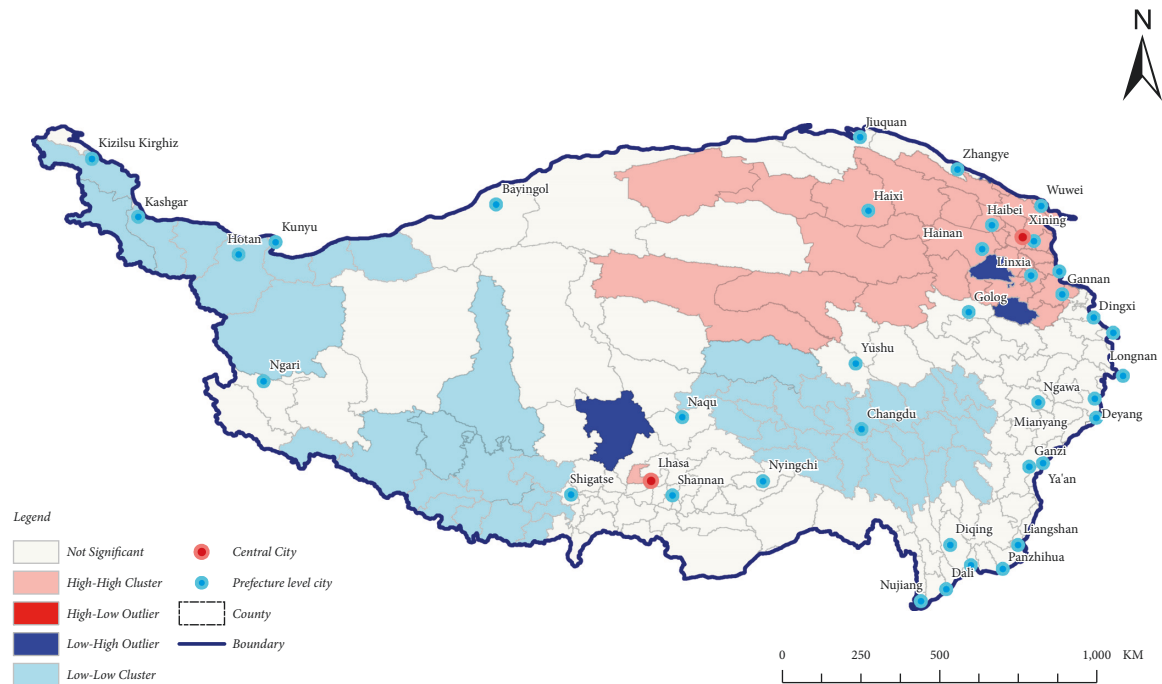


FIGURE 11: Local spatial autocorrelation of *TIID*.

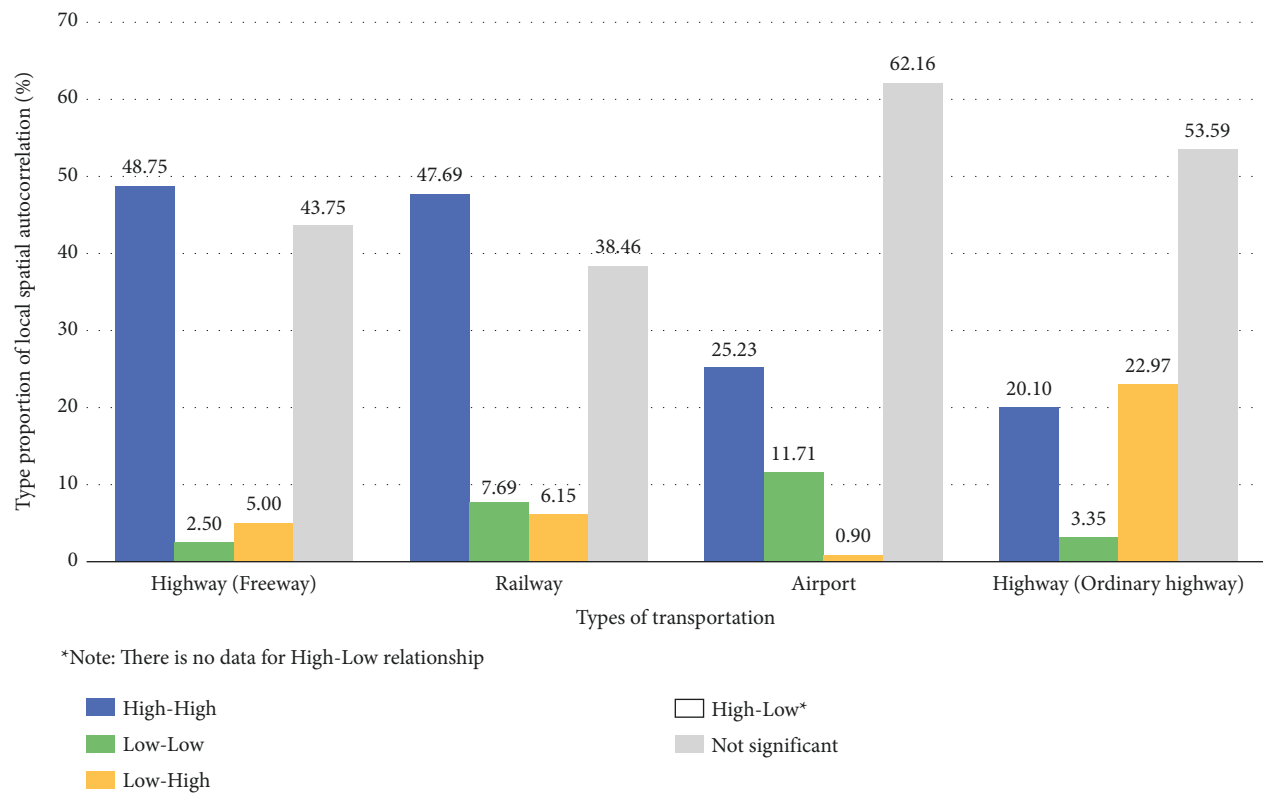
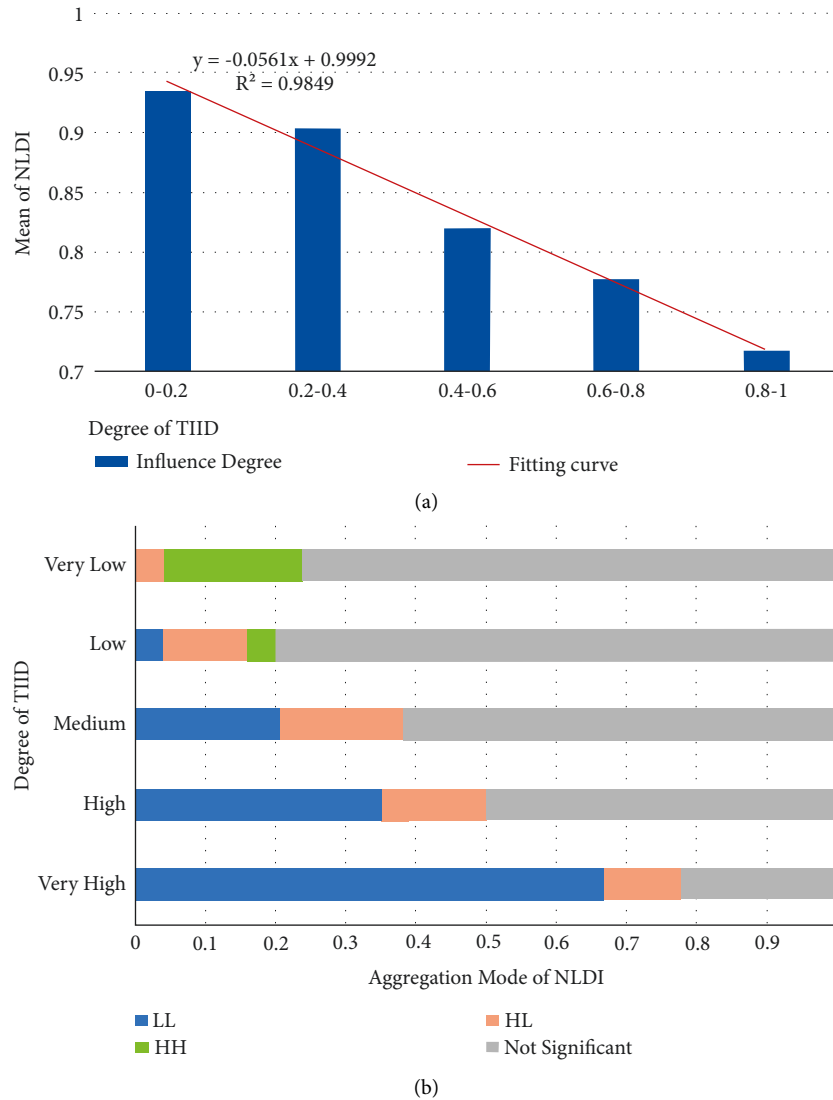


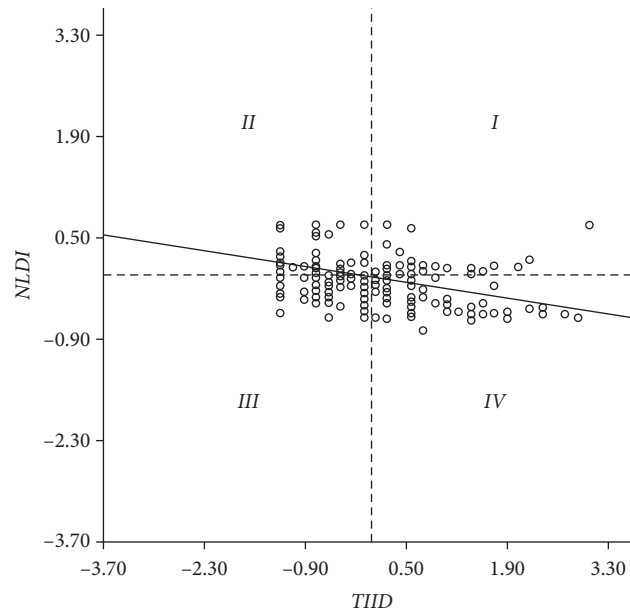
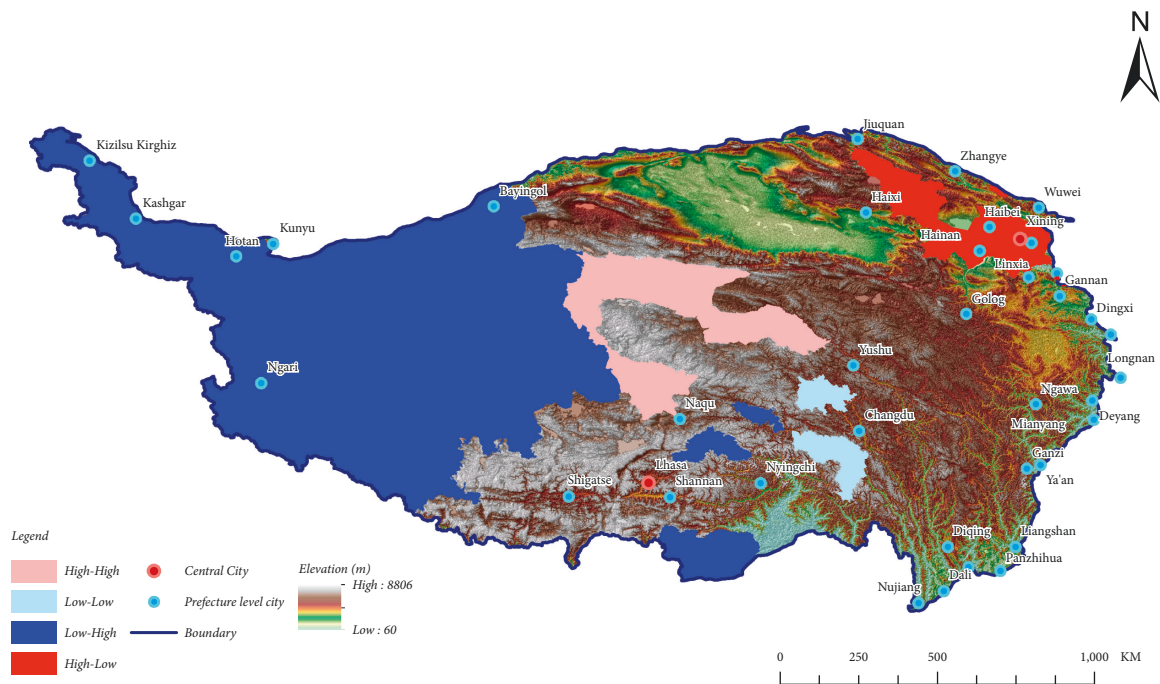
FIGURE 12: Influence of different types of transportation on spatial pattern of *TIID* in Qinghai-Tibet Plateau. *Note: There is no data for the High-Low relationship.

FIGURE 13: Statistics between *NLDI* and *NLDI* at the county scale.

(1) *High-Low*. It refers to the areas with higher *TIID* but lower *NLDI*, according to the surrounding areas, mainly distributed in 18 counties, such as Tianjun, Gonghe, and Haiyan. These counties are primarily located in the Lanxi urban agglomeration area, including the eastern part of Qinghai, the north of Xiqing mountains, the Qilian mountains, and the Gannan area in the upper Taohe River. These areas have excellent geographical locations and convenient transportation. The freeways of Gougyu, Pinga, Beijing-Tibet, G6, G0611, G109, G316, G315, S101, S307, S202, S301, S204, S310, and Qinghai-Tibet railway are crisscrossed with dense crowds. The population density and economic condition of these areas with better development potential in the Qinghai-Tibet Plateau are much higher than those of the surrounding areas. For such areas, we suggest that the integrated development of urban and rural transport should be further promoted. Rural

transportation infrastructure should be upgraded, and the integrated planning, construction, and management of urban-rural transportation infrastructure should be realized to improve the equalization of transport public services.

(2) *Low-High*. It refers to the areas with lower *TIID* but higher *NLDI*, according to the surrounding areas. They are mainly distributed in 26 counties, for example, Wuqia, Gar, Pishan, etc. These counties are mainly located in the western Qinghai-Tibet Plateau, including the Qiangtang plateau, Kunlun Alpine plateau, and the mountainous desert area of Ali. Due to the numerous rivers and lakes, extensive glaciers and frozen soil, and poor natural conditions, there are extremely backward transportation infrastructures, such as G219, S206, S207, and other high-grade highways, which are sparsely distributed. For such regions, it is necessary to improve the support capacity of major

FIGURE 14: Scatter diagram of global spatial autocorrelation between *TIID* and *NLDI*.FIGURE 15: Distribution of spatial agglomeration relationships between the *TIID* and *NLDI*.

infrastructure, and increase the construction of urban transportation facilities. An accessible and safe transportation system should be built based on the highway network.

- (3) *High-High*. It refers to the areas with higher *TIID* and higher *NLDI* according to the surrounding areas. The regions are mainly distributed in the counties of

Amdo and Zhiduo. These areas mainly include Qingnan plateau and the eastern part of Qiantang plateau. They are mainly pure pastoral areas for grazing yaks and sheep. Especially in sparsely populated regions such as Hoh Xil and Altun Mountain Nature Reserve in Qinghai, the intensity of human activities is relatively low. However, G109, G215, S224, S313, and other high-grade highways and the

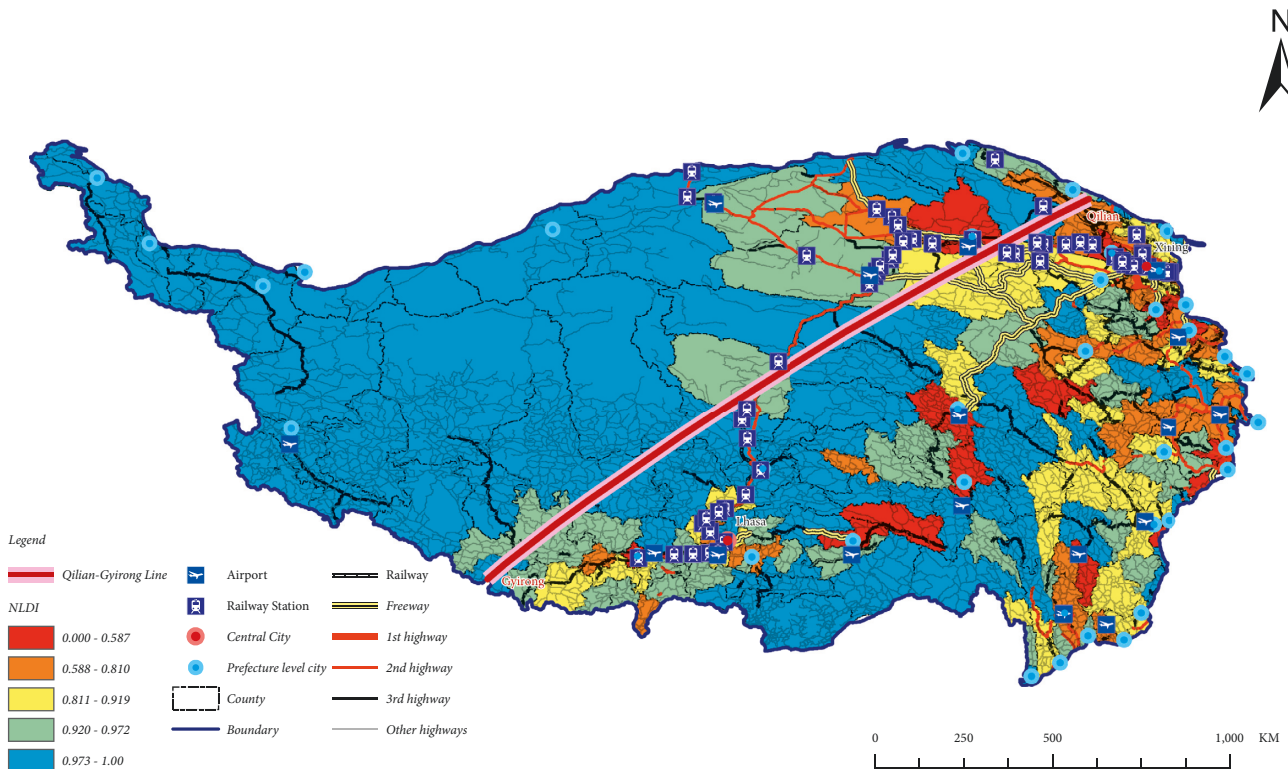


FIGURE 16: Spatial distribution of NLDI (showing the “Qilian-Gyirong Line”).

Qinghai-Tibet railway pass through the border, with obvious geographical advantages. For such areas, we suggest that full consideration should be given to the transportation hubs and main roads in ecological protection areas. Coordination between transportation infrastructure and ecological space should be promoted to maximize the protection of important ecological function areas. In addition, we recommend promoting the overall planning and construction of transportation infrastructure and energy (new energy) facilities, taking into account the characteristics of various energy transmissions, improving facility utilization efficiency, and reducing energy resource consumption.

- (4) *Low-Low*. It refers to the areas with lower *TIID* and lower *NLDI* according to the surrounding areas. They are mainly distributed in the counties of Nangqian, Basu and Lhorong, etc. The valleys in eastern Sichuan and Tibet are natural areas with mountains and valleys as the main body. Although G214, G318, S303, and other high-grade highways pass through this area, the overall progress of transportation infrastructure construction is relatively slow, and the network layout is imperfect due to the violent terrain undulation, severe climate change, complex distribution of rivers, strong internal and external dynamic geological interaction, and high incidence of seismic activities in this area. At the same time, there are rich tourist resources in

this area, such as Nangqian, known as “secret land,” Bangda grassland, Ranwu Lake, and Jiayu Grand Canyon. The unique natural scenery and rich cultural landscape make this area a tourist attraction with high intensity of human activities. For such regions, we suggest that the fundamental role of transportation in promoting tourism development should be considered. And the planning and construction of tourist scenic routes and tourist transportation systems should be accelerated to build a natural landscape line. In addition, the functions of tourism service facilities along transportation networks should be improved, and the construction of transportation infrastructure related to rural tourism, vacation, and self-driving travel should be supported.

6. Discussion

The spatial distribution of population in the Qinghai-Tibet Plateau is uneven, with a general spatial distribution of “dense in the southeast and sparse in the northwest.” Qi et al. [47] proposed that the characteristics of population differentiation on the Qinghai-Tibet Plateau can be reflected through the “Qilian-Gyirong Line,” connecting Qilian county and Gyirong county, as shown in Figure 16. After calculation, the area on both sides of the “Qilian-Gyirong Line” is roughly the same, but the population ratio between the southeast and northwest is 93:7. This study further

analyzes the level of construction of transportation infrastructure and human development on both sides of “Qilian-Gyirong Line.”

Taking county as the statistical unit, the average value of *NLDI* on the east side of “Qilian-Gyirong Line” is 0.87, the average value of *NLDI* on the west side is 0.96. The variance of *NLDI* on the east side of “Qilian-Gyirong Line” is 0.17, and the variance of *NLDI* on the west side is 0.12. The average value of *TIID* on the east of “Qilian-Gyirong Line” is 4.98. And the average value of *TIID* on the west is 3.93. It can be noticed that the construction and development of transportation infrastructure in the Qinghai-Tibet Plateau are relatively backward as a whole. The “Qilian-Gyirong Line” is the dividing line, and the southeast part is slightly higher than the northwest part. Correspondingly, the level of human development in the Qinghai-Tibet Plateau is not high, with the “Qilian-Gyirong Line” as the dividing line, and the southeast part is also slightly higher than the northwest part.

Transportation infrastructure in the Qinghai-Tibet Plateau is closely related to social and economic development and is one of the critical factors affecting the regional human development level. Based on the above analysis, we can find that the Qinghai-Tibet Plateau takes “Qilian-Gyirong Line” as the dividing line, the population proportion difference between the southeast and northwest is very large. But the difference among construction and development levels of transportation infrastructure, human development levels, and so on are not very small. We can see that the construction and development of transportation infrastructure in the Qinghai-Tibet Plateau region is a key factor restricting the level of human social development and achieving high-quality sustainable development.

7. Conclusions

The scientific and reasonable evaluation of the relationship between regional transportation infrastructure and human development level is significant to support sustainable planning and management. The Qinghai-Tibet Plateau is the unique ecology-transportation unit on the Earth. The construction and improvement of transportation infrastructure in the research area can bring spatial and temporal convergence effect to the region, which in turn will have a profound impact on regional economic development, industrial layout and spatial structure, and promote the coordinated development of man-land relationship [47]. Based on the night light data and population data, this study builds the night light development index (*NLDI*) to monitor the human development level, and then estimates the transportation infrastructure influence degree (*TIID*) in the Qinghai-Tibet Plateau by using the transportation infrastructure data, including highways, railways, and airports. Finally, this study analyzes the unbalanced spatial variation characteristics of human development level with the spatial distribution influence of transportation infrastructures by using the bivariate spatial autocorrelation method. The main conclusions are as follows:

- (1) This article utilizes *NLDI* to monitor the level of human development at the county scale in response to data collection and variable homogeneity, which may reduce spatial comparability. It provides a scientific and practical reference for policy-making about sustainable development in Qinghai-Tibet Plateau.
- (2) On the views of spatial county scale in the Qinghai-Tibet Plateau, *NLDI* presents a “southeast-northwest” spatial distribution pattern with apparent characteristics of unbalanced spatial variation. The spatial pattern of human development level in the Qinghai-Tibet Plateau is radially distributed along with the transportation infrastructures, such as the freeways of Gougyu, G316, G315, G318, etc. According to the calculation of global spatial autocorrelation, the Moran's *I* of *NLDI* is 0.149, which has a relatively significant characteristic of spatial aggregation. According to the calculation of local spatial autocorrelation, the spatial variation of *NLDI* in the Qinghai-Tibet Plateau is obvious. There are spatial aggregation patterns of Low-Low and High-Low in the southeast. And there is only a spatial aggregation pattern of High-High in the northwest. It can be checked that the human development level of the Qinghai-Tibet Plateau has obvious characteristics of spatial polarization and center-periphery structure. The high-value regions of human development level are concentrated in the Lanxi agglomeration area, while the low-value areas are focused on the northwest of the Qinghai-Tibet Plateau, with large variation.
- (3) The construction and development of transportation infrastructure are closely related to the level of human development in the Qinghai-Tibet Plateau. Although the spatial disequilibrium of human development level is significant, the spatial distribution of the number, grade, type, and structure of transportation infrastructure has a significant matching. From the perspective of the entire study area, there are four types of spatial relationships between *TIID* and *NLDI*. The Lanxi agglomeration area and the western part of the Qinghai-Tibet Plateau have significant spatial coordination with the level of human development. In the central region of the Qinghai-Tibet Plateau, spatial coordination is declining to a certain extent. Amdo, Zhiduo, etc., are located in essential traffic arteries but the level of human development is low, due to their special ecological environment and population distribution restrictions. Although Nangqian, Basu, Lhorong, etc. are in high mountains and valleys with relatively poor transportation infrastructure, they are rich in natural resources, especially tourism resources, which are highly developed and have a high level of human development.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Zhiheng Wang was responsible for conceptualization, methodology, formal analysis, original draft preparation, reviewing and editing, and visualization. Tao Xing was responsible for methodology, data curation, and visualization. Daikun Wang was responsible for validation, reviewing and editing, and supervision. Hongkui Fan was responsible for software and data curation. Dongchuan Wang was responsible for conceptualization, formal analysis, resources, project administration, and funding acquisition. Yanwang Wu was responsible for project administration. Qiaozhen Guo validated the study. Lina Xiu investigated the study. All authors have read and agreed to the published version of the manuscript.

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