

Topographical relief characteristics and its impact on population and economy:

A case study of the mountainous area in western Henan, China

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Abstract: Topographical relief is a key factor that limits population distribution and economic development in mountainous areas. The limitation is especially apparent in the mountain-plain transition zone. Taking the transition zone between the Qinling Mountains and the North China Plain (i.e. the mountainous area in western Henan Province) as an example and based on the 200-m resolution DEM data, we used the mean change-point analysis to determine the optimal statistical unit for topographical relief, and thereafter extracted the relief degree. Taking the 1:100,000 land use data, township population and county-level industrial data, population and economic spatial models were constructed, and 200-m resolution grid population and economic density maps were generated. Afterwards, statistical analysis was carried out to quantitatively reveal the impact of topographical relief on population and economy. In addition, the impacts of other topographical factors were discussed. The results showed the following. (1) The relief degree in western Henan is generally low, where 58.6% of the regional topography does not exceed half the height of a reference mountain (relative elevation ≤ 250 m). Spatially, the relief degree is high in the west while low in the east, and high in the middle while low in the north and south. There is a positive correlation between relief degree and elevation, and a much stronger correlation between relief degree and slope. (2) The linear fitting degree between the population and economic validation data and the corresponding simulation data are 0.943 and 0.909, respectively, indicating that the spatialized results can reflect the actual population and economic distribution. (3) The impact of topographical relief on population and economy was stronger than that of other topographical factors. The relief degree showed a good logarithmic fit relationship with population density (0.911) and economic density (0.874). Specifically, 88.65% of the population lives in areas where the topographical relief is ≤ 0.5 and 88.03% of the gross regional product was from areas where the relief is ≤ 0.3 . Compared with the population distribution, the economic development showed an obvious agglomeration trend towards low relief areas.

Keywords: topographical relief; population and economy; land use; spatialization; grid; western Henan mountainous area

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1 Introduction

Topography greatly impacts on agricultural production, population distribution, urban construction and economic development (Meybeck *et al.*, 2001; Baumann *et al.*, 2011; Li *et al.*, 2015; Fang and Ying, 2016; Shi *et al.*, 2018). At a global scale, the mountains have been classified based on surface roughness and elevation, and the impact of different types of mountain on water resources and population distribution have been analyzed (Meybeck *et al.*, 2001). At the country level, the mountains in China have been classified based on elevation, relative height and slope (Fang and Ying, 2016). Taking county as the basic unit, the economic development in mountainous areas was classified into 4 major types and 23 sub-types, suggesting that the difference in economic development between mountainous and plain areas was one of the primary reasons for unbalanced economic development in China (Fang and Ying, 2016). From two different scales (grid scale and county scale), the impact of topographical relief on population distribution and economic development has been discussed, and relief, as an important factor for the suitability assessment of human settlements, has been suggested (Feng *et al.*, 2007, 2011). Moreover, many studies have quantitatively analyzed the impact of topographical relief on population and economy from small to medium scale. The results showed that topographical relief also has a high practical application in the suitability assessment of human settlements at the small and medium scales (Wei *et al.*, 2013; Yu *et al.*, 2015; Xi *et al.*, 2018). Using a geographical detector model to investigate the mechanism of poverty in village scale, Liu and Li (2017) concluded that surface slope was a dominant factor for poverty.

Previous studies have demonstrated that topographical factors are important limiting factors that influence population distribution and economic development. Topographical factors should be fully taken into consideration when selecting regional settlement sites, improving living environments and establishing economic development policies. However, previous small-medium scale studies were mostly based on statistical data of administrative units, which often conceal the internal spatial difference in population distribution and economic development, and thus potentially distort the results. A quantitative study at the grid scale, based on spatial data, can therefore better highlight the practical significance. With the support of geographic information system (GIS) and remote sensing (RS) technologies, especially the high resolution images, the spatialization and refinement of socioeconomic factors have become the hot topic of geographic research. The use of these technologies greatly improved the spatial resolution and precision of social and economic data (Kan, 2007; Zhao *et al.*, 2017; Li *et al.*, 2018). Commonly used spatial socioeconomic models include the spatial interpolation model, land use impact model and remote sensing inversion model. Factors that impact population and economic distribution mainly include climate, transportation, land use, residential area, and the distance to rivers and other cities. In particular, land use is most closely related to social and economic activities. Other impact factors also show a close relationship with population and economic distribution (Zhuang *et al.*, 2002; Hu *et al.*, 2017; Huang *et al.*, 2018). Therefore, the land use impact model is widely used in the spatialization of population and economic data.

The western Henan mountainous area is located in the transition area between the second and the third steps in the topography of China, and between the Qinling Mountains and the Huanghuai Plain. The area is characterized by a complex topography and is classified as

underdeveloped due poor transportation infrastructure, and delayed social and economic development (Zhang *et al.*, 2017; Zhu and Li, 2017; Zhu *et al.*, 2019). Social and economic scholars have investigated the probable reasons for the underdevelopment in this area from various aspects such as social structure, resources and condition, policies and management (Li, 2002; Du, 2015). However, the impact of topographical relief on population distribution and economic development in this area has rarely been studied. Significant relief is the main topographical feature of the study area. Topographical relief plays an important role in the formation of population and economic patterns. In addition, complex topographical conditions lead to more significant differences in population and economy within administrative units. Thus, it is of practical value to study the impact of topographical relief on population and economy at the grid scale. Topographical relief is a quantitative index to characterize topographic fluctuations and it can directly reflect geomorphological characteristics (Liu *et al.*, 2015). However, the calculation of topographical relief involves inherent uncertainty and is dependent on the calculation scale. As such, scientifically defining the calculation scale (or the optimal statistical unit) is the key to determining regional topographical relief (Liu *et al.*, 2010; Zhang *et al.*, 2018). According to previous studies, the mean change-point analysis as a non-manual discriminate method can rapidly and accurately calculate optimal statistical units (Prima *et al.*, 2006; Zhang and Dong, 2012). Thus, this method was used to determine the optimal statistical unit for topographical relief in western Henan mountainous area. Thereafter, the extraction method, based on the suitability assessment of human settlements (Feng *et al.*, 2007), was used to calculate the topographical relief. Based on the land use impact model, the population and economic spatial models were constructed, and the 200-m resolution grid population and economic density maps were generated. Statistical analyses, based on grid units, were carried out to quantitatively reveal the impact of topographical relief on population and economy. In addition, the impacts of other topographical factors were analyzed as well. The ultimate goal is to explore mechanisms for reducing poverty and to implement targeted measures in alleviating poverty, and thereby provide a scientific basis and decision-making support for the coordinated development of population, resources and environment, and socioeconomics in the study area.

2 Overview of the study area

The western Henan mountainous area comprises the residuals of the Qinling Mountains in Henan Province. The area expands in a fan shape and includes Funiu Mountain in the southwest, Xiaoshan, Xiong'er and Waifang mountains in the northeast, and Songshan and Xiaoqinling mountains in the east-west direction (Zhang *et al.*, 2017), which covers an area of 4.95×10^4 km² and includes 29 county-level administrative units in Sanmenxia, Luoyang, Nanyang, Pingdingshan and Zhengzhou (Figure 1). The topographical relief gradually decreases from west to east and the elevation ranges between 29–2372 m. The landscape changes gradually from middle and low mountains to hills, tableland, plains and basins. At the end of 2014, the total population in the area was 17.908 million and the urbanization rate was 43.9%, which was lower than the average in Henan (45.2%). The gross regional product in 2014 was 853.03 billion yuan, accounting for 24.1% of the province's total. Since the land area accounts for 30% of Henan, it is generally considered underdeveloped.

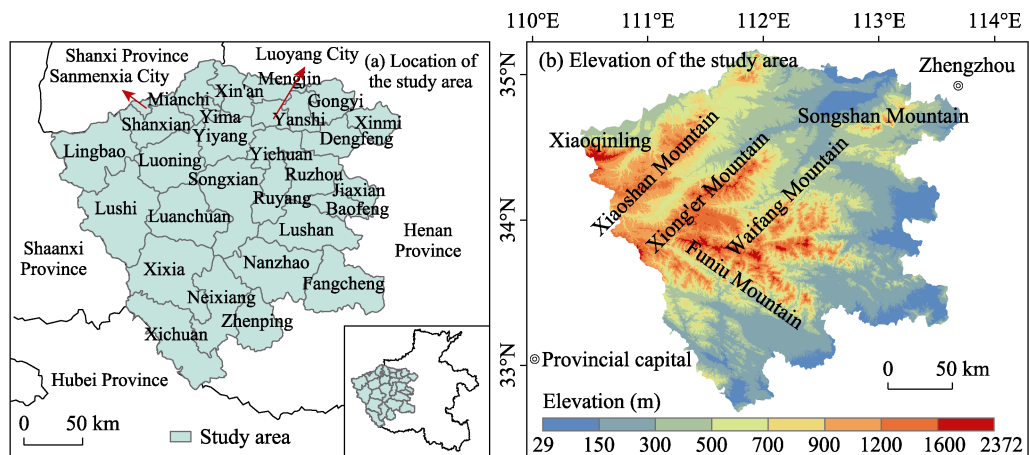


Figure 1 Location and elevation map of the western Henan mountainous area, China

Note: In this study, the municipal districts of every city were all considered in the total city area.

3 Data sources and processing, and research method

3.1 Data sources and processing

The digital elevation model (DEM) data were from ASTER GDEM, with a spatial resolution of 30 m. After splicing, projection, clipping and re-sampling, the 200 m resolution DEM of the study area was generated.

The 2014 population data were from the 2015 China Statistical Yearbook (Townships). After removing invalid data, 408 township units were reserved and 70 were randomly selected as validation samples for the results of population spatialization. The 2014 economic data were from the 2015 Henan Statistical Yearbook, which included the output values of different industries in 29 county-level units. The gross regional products of Songxian, Yichuan, Yiyang and Ruyang counties in Luoyang and Gongyi in Zhengzhou were from the 2015 statistical yearbook of all cities or counties. After removing invalid data, 68 township units were retained, which were used as validation samples for the results of economic spatialization. The population and economic data were divided by the area of the corresponding statistical unit to obtain the population density and economic density of every sector.

The 1:100,000 land use and vector diagrams of county and township boundaries in 2013 were from the National Science & Technology Infrastructure of China, Data Sharing Infrastructure of Earth System Science–Data Center of Lower Yellow River Regions (<http://henu.geodata.cn>). The land use data were divided into 6 primary types and 25 secondary types. As for the study area, the land use data consisted of 6 primary types and 16 secondary types.

3.2 Method

3.2.1 Extraction of topographical relief

1) The calculation of topographical relief has scale dependence. In this study, the moving window method was used to calculate the relief at different scales. The maximum and minimum elevation of every neighborhood grid in each window was collected, and the difference between the two represents the topographical relief of the corresponding grid. The

equation is as follows:

$$M = H_{\max} - H_{\min} \quad (1)$$

where M is the topographical relief value of the central grid in the window; H_{\max} is the maximum elevation and H_{\min} is the minimum elevation in the window.

Based on the above equation, $n \times n$ windows with $n = 2, 3, \dots, 30$ pixel sizes were sequentially applied to the DEM data. The average topographical relief under different windows was calculated. The variation in topographical relief with the window area shows a logarithmic relationship, and the fitting was 0.98 (Figure 2a). As can be seen in Figure 2a, there is a point on the curve between 2 and 8 km² where the slope decreased sharply, this point is called the change-point. The window size corresponding to the change-point is the optimal statistical unit.

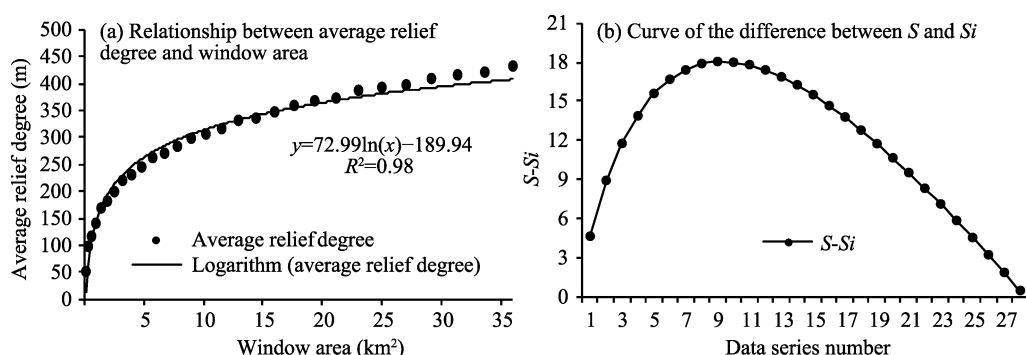


Figure 2 Relationship between the average relief degree and the window area (a), and the curve of the difference between S and S_i (b)

In this study, the mean change-point method was used to calculate the optimal statistical unit for topographical relief in western Henan mountainous area. The method is able to identify the sudden change-point in a dataset and is most effective in conditions where there is only one change-point (Zhang *et al.*, 2018). The procedure is as follows:

(1) The average topographical relief under different windows was divided by the area of the corresponding window to obtain the relief value per unit area for each window, T_i ; and afterward taking its logarithm, the sequence of numbers $\{X_i\}$ was obtained (Equation 2). The variance of the sequence S is 25.02:

$$X_t = \ln T_t \quad (2)$$

where t is the number of windows ($X = 1, 2, 3, \dots, 29$).

(2) Let $i = 2, 3, \dots, 29$, each i divides the sequence into two parts: $\{X_1, X_2, \dots, X_{i-1}\}$ and $\{X_i, X_{i+1}, \dots, X_{29}\}$. The arithmetic mean X_{i1} and X_{i2} of each part and their statistic S_i were then calculated respectively.

$$S_i = \sum_{t=1}^{i-1} (X_t - X_{i1})^2 + \sum_{t=i}^{29} (X_t - X_{i2})^2 \quad (3)$$

(3) The difference between S and S_i was calculated. When the difference reaches the maximum, the corresponding window area is the optimal statistical unit.

It can be seen from Figure 2b that the maximum difference (18.04) is reached at the 9th

point (i.e. $i = 10$), and the corresponding window area at this point is 11×11 pixels. Therefore, it can be concluded that by using 200 m resolution DEM, the optimal statistical unit size of the topographical relief in western Henan mountainous area is 4.84 km^2 .

2) Calculation of topographic relief. Due to topographical relief serving different purpose in different fields, there exist different extraction methods. This study explores the impact of topographical relief on population and economy, therefore, the extraction method proposed by Feng *et al.* (2007), based on the suitability assessment of human settlements, was used to calculate the topographical relief. The equation is as follows:

$$RDLS = \{[\text{Max}(H) - \text{Min}(H)] \times [1 - P(A) / A]\} / 500 \quad (4)$$

where *RDLS* refers to “relief degree of land surface”, which is also called the topographical relief degree; $\text{Max}(H)$ and $\text{Min}(H)$ are the maximum and minimum elevation in the area (m), respectively. The difference between them is the relative elevation. $P(A)$ is the flat land in the study area (km^2). From the 200-m resolution DEM data, the average slope of the study area is 7.7° . In this study, areas with a slope of $\leq 2^\circ$ were defined as flat land. A is the total area of the study area, also referred to the size of the optimal statistical unit (4.84 km^2). Feng *et al.* (2007) calculated relief degree using 500 m as the height of China’s reference mountain, which gave the concept geographic meaning. In brief, when $RDLS = 1$, the relief degree is lower than the height of a reference mountain, but when $RDLS = x$, the relief degree is x times the height of a reference mountain.

3.2.2 Spatialization of population and economic data

In this study, the land use impact model was used to spatialize the population and economic data. For population density, based on town statistical data, X_1 (farmland), X_{21} (forestland), X_{22} (shrubland), X_{23} (sparse forestland), X_{24} (other forestland), X_{31} (high-coverage grassland), X_{32} (medium-coverage grassland), X_{33} (low-coverage grassland), X_{51} (urban land), X_{52} (rural residential area) and X_{53} (construction land) were selected for spatialization. For economic density, a study has shown that spatialization per industrial sector may help improve accuracy (Han *et al.*, 2012). However, the gross regional products of town level industries are difficult to obtain. Thus, the county-level data were used to select X_{11} (paddy field), X_{12} (dryland), X_{21} , X_{22} , X_{23} , X_{24} , X_{31} , X_{32} , X_{33} , X_{41} (river and channel) and X_{43} (reservoir and pond) for economic density spatialization of the primary industry. For spatialization of the secondary and tertiary industries, X_{51} , X_{52} and X_{53} were selected. The index of each type of land use is X_i , i.e. the proportion of each land use type in the statistical unit. It should be noted that the area of paddy field at the town level is generally small, thus different types of farmland were not subdivided during population spatialization. When determining the grid size, since the data resolution is limited, it is difficult to verify the simulation results obtained at a very small scale. Moreover, smaller grids will inevitably lead to data redundancy. Therefore, a grid size of $200 \text{ m} \times 200 \text{ m}$ is commonly selected. The spatialization steps are as follows:

Firstly, the county and town boundaries were superimposed on the land use map to calculate the land use type index in every county and town. Next, a multiple regression model was established by taking the population density data of 338 towns, and the economic density data of different sectors in 29 counties as the dependent variables, and their corresponding land use type indices as the independent variables. Based on the Liao’s study the constant term was set to 0 (Liao *et al.*, 2015). The regression function is shown in Table 1, it can be seen that the correlation coefficients are high, indicating good fitting effects.

Table 1 Relationship between population density, economic density and the corresponding land use type indices

Type	Regression equation	Relative coefficient
Population density	$Y = 455.22X_1 + 49.341X_{21} + 12.222X_{22} - 181.338X_{23} + 338.556X_{24} - 192.647X_{31} - 64.721X_{32} + 351.082X_{33} + 2982.149X_{51} + 2453.164X_{52} + 779.709X_{53}$	0.937
Economic density of the primary industry	$Y = 1171.513X_{11} + 383.519X_{12} + 36.694X_{21} + 432.508X_{22} + 719.687X_{23} - 3094.677X_{24} - 345.41X_{31} + 179.08X_{32} - 7331.019X_{33} - 1755.961X_{41} + 380.34X_{43}$	0.990
Economic density of the secondary and tertiary industries	$Y = 54053.11X_{51} + 14161.954X_{52} + 31699.782X_{53}$	0.975

Secondly, a 200 m × 200 m grid was constructed and superimposed on the land use type data. The percentage of each land type in every grid was recorded. In the data layer attribute table, a new field was created for each land type. Using the “Select By Attribute” function, the regression coefficients were inputted. Using the “Field Calculator” tool, the regression operation was carried out. The results were fused as such that every grid represented a regression value. At this point, the gridding of population density and economic density of the primary, secondary and tertiary industries were completed. By superpositioning the economic density of every industry, the gridding of economic density was completed. Finally, the results were converted to the grid format, thereby generating the 200 m resolution population density and economic density maps.

4 Results and analyses

4.1 Distribution of topographical relief degree

As can be seen from Figure 3a, the topographical relief degree of western Henan mountainous area shows a spatial pattern of high relief degree in the west and low in the east, and high relief degree in the middle and low in the south and north. The highest values are distributed in the main ridge area of the Xiaoqinling, Funiu and Xiong’er mountains. The second highest values are distributed in the southeastern Taihang, Waifang, Songshan and Xiaoshan mountains. The lowest values are distributed in Jiaxian and Baofeng counties in the eastern part of the study area, in city proper of Luoyang in the northeastern part, and in

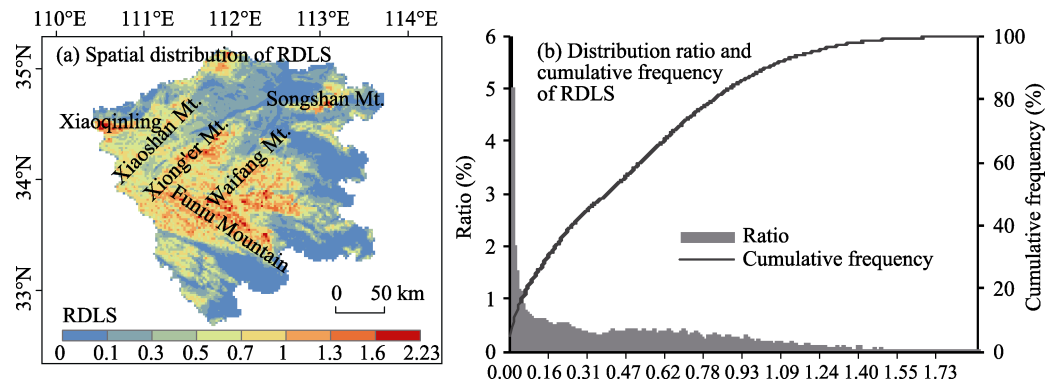


Figure 3 RDLS of western Henan mountainous area (a), and RDLS distribution ratios and area cumulative frequencies (b)

Fangcheng, Zhenping and Xichuan counties in the southeastern part.

The distribution ratios and the cumulative frequencies of RDLS in the study area are shown in Figure 3b. It can be seen that the topographical relief degree is low generally. From Table 2, it can be seen that areas with a relief degree of 0–0.1 account for the largest proportion (24.21%), the average relative elevation is only 48.98 m and the area of flat land is the largest (70.41%). Areas with a relief degree above 1.6 account for only 0.49% of the study area, the average relative elevation is 864.74 m and the area of flat land is minimal (0.20%). Thus, as the relief degree increases, the relative elevation gradually increases and the proportion of flat land gradually decreases. From Figure 3b and Table 2, when the relief degree reaches 0.5, the average relative elevation does not exceed 250 m and the cumulative frequency reaches 58.6%. When the relief degree reaches 1, the average relative elevation is ≤ 500 m and the cumulative frequency reaches 89.76%. When the relief degree reaches 1.6, the average relative elevation is ≤ 800 m and the cumulative frequency reaches as high as 99.51%.

Table 2 Main RDLS parameters of western Henan mountainous area

RDLS		[Max (H) – Min (H)]	P (A) /A
Range	Proportion (%)	Average (m)	Average (%)
0–0.1	24.21	48.98	70.41
0.1–0.3	19.86	122.56	44.78
0.3–0.5	14.53	217.88	7.25
0.5–0.7	15.05	307.59	2.80
0.7–1	16.11	424.10	1.31
1–1.3	7.57	568.53	0.62
1.3–1.6	2.18	707.43	0.35
1.6–2.23	0.49	864.74	0.20

From Figures 4a and 5a, RDLS shows a strong positive correlation with both elevation and slope, with a linear fitting degree of 0.926 and 0.934, respectively. In particular, RDLS shows a stronger correlation with slope. When the elevation is less than 150 m, there is some inconsistency between the trend of RDLS and elevation. This is possibly due to the fact that there are some ravine and gorge areas with low elevation but relatively high relief degree. When the elevation is under 1800 m or the slope is $<30^\circ$, the variation in RDLS is low. For areas with >1800 m elevation or $>30^\circ$ slope, the variation in RDLS increases since the areas are located at the main ridge area of Xiaoqinling, Funiu and Xiong'er mountains, which have large land relief and significant fragmentation. From Figures 4b and 5b, with changes in elevation and slope, the proportion of the variation in RDLS in different areas can be classified into three types: continuous decrease (with changes of 0–0.2); first increase and then decrease (the changes include 0.2–0.5 and 0.5–0.8 in different elevations, and on different slopes, the changes include 0.2–0.5, 0.5–0.8 and 0.8–1.2); continuous increase (the changes include 0.8–1.2 and ≥ 1.2 in different elevations, and on different slopes, the changes only include ≥ 1.2). In summary, low RDLS areas are mainly located in the low elevation and low slope areas, and high RDLS areas are located in high elevation and high slope areas. With increasing elevation and slope, the proportion of high RDLS areas gradually increases and shows relatively strong consistency with elevation and slope.

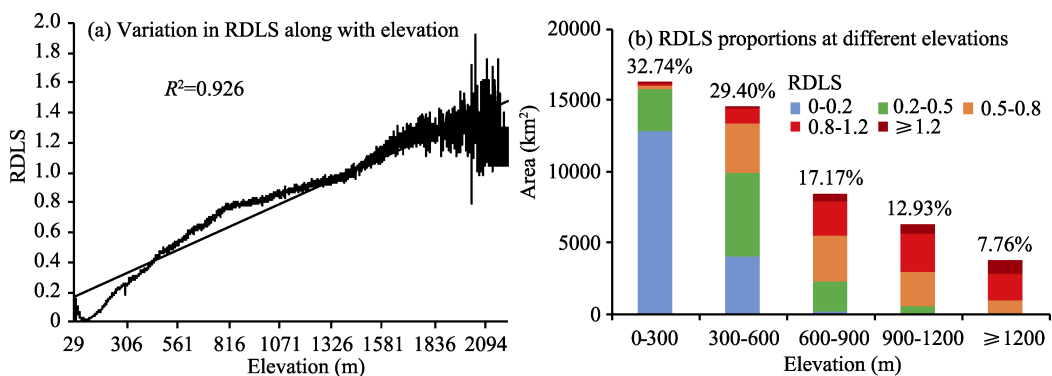


Figure 4 Variations in RDLS along with elevation (a), and RDLS proportions at different elevations (b)

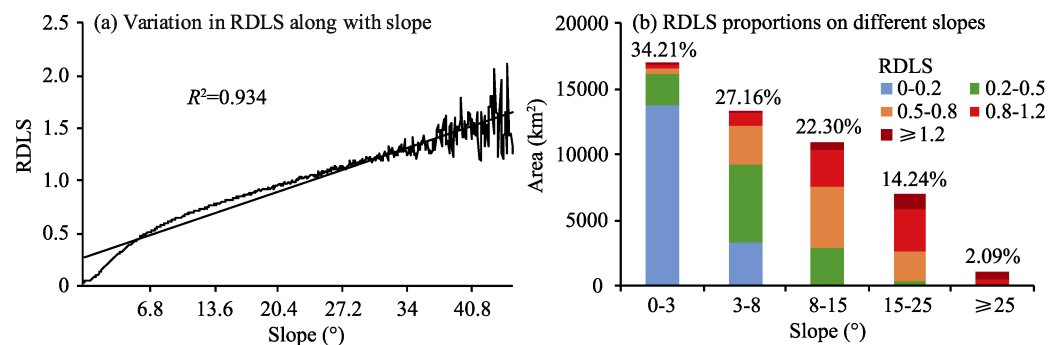


Figure 5 Variations in RDLS along with slope (a), and RDLS proportions on different slopes (b)

4.2 Results of population and economic spatialization analyses

4.2.1 Accuracy verification

To verify the reliability and accuracy of the regression model, the population and economic data selected for validation were linearly fitted to the corresponding simulated values (Figure 6). The fitting degree between the statistical and simulated values of population and economic data are 0.943 and 0.909, respectively, indicating that the simulation results are accurate and the accuracy in population density is higher than that in economic density. Thus, the 200 m \times 200 m population and economic densities obtained from the proposed model are able to reflect the actual population and economic distribution in western Henan mountainous area.

4.2.2 Differences in spatial distribution of population and economy

As can be seen in Figure 7, population and economic densities have certain spatial coupling

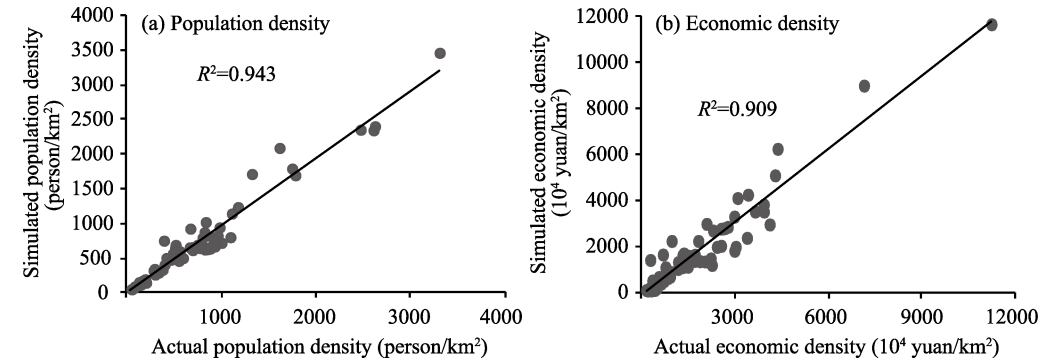


Figure 6 Relationship between simulated and statistical values

characteristics. At the grid scale, the correlation between population density and economic density is 0.787 ($p < 0.05$), indicating that population distribution and economic development in western Henan mountainous area were in coordination at the 200 m grid level. Both densities increased from the central-western part to the northern, eastern and southern parts. The low value areas were all distributed in Lushi, Luanchuan and Xixia counties in the central-western part, where the population density was below 100 people/km² and the economic density was under 3 million yuan/km². The high value areas were mainly concentrated in the northeastern (e.g. Zhengzhou and Luoyang) and the northern part (e.g. Sanmenxia and Lingbao), as well as in some scattered counties and townships. The population density in high value areas was >800 people/km² and the economic density was >20 million yuan/km².

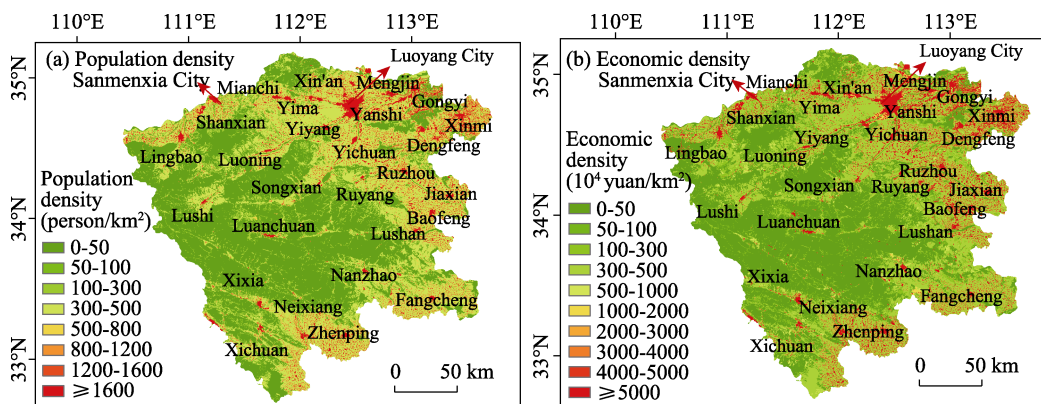


Figure 7 Spatial distribution of population density and economic density at a resolution of 200 m × 200 m

4.3 Impact of topographical relief on population and economy

4.3.1 Comparison with the impact of other topographical factors

In order to compare the differences between topographical relief and other factors in terms of their impact on population and economy, a regional statistical analysis model was used to collect the topographical relief degree, elevation, slope, population density and economic density at the grid level. Logarithmic fitting was then carried out (Figure 8). There are some similarities in the impact of various topographical factors on population and economy. Among these factors, RDLS had the strongest impact, followed by slope, and elevation had the lowest impact. From Figures 8b and 8e, it can be seen that in some low elevation areas, the population and economic densities are low as well. This is because these areas mostly comprise remote ravines and gorges, and although the elevation is low, the slope and RDLS are relatively large. Thus, social and economic activities are still limited. The fitting degree between topographical relief degree and population and economic densities are 0.911 and 0.874, respectively. Compared with other factors, RDLS showed a strong limitation towards population and economic development. From Figures 8a and 8d, it can be seen that the change-point for population and economic densities was at the relief degree of 0.7 and 0.5, respectively. Beyond the change-point, there was no significant change in the population and economic densities, which suggests that 0.7 and 0.5 are critical values for RDLS-dependent variations in population and economic densities.

Moreover, it is apparent that the correlations between various factors and population density were higher than that for economic density, and the critical value for population density

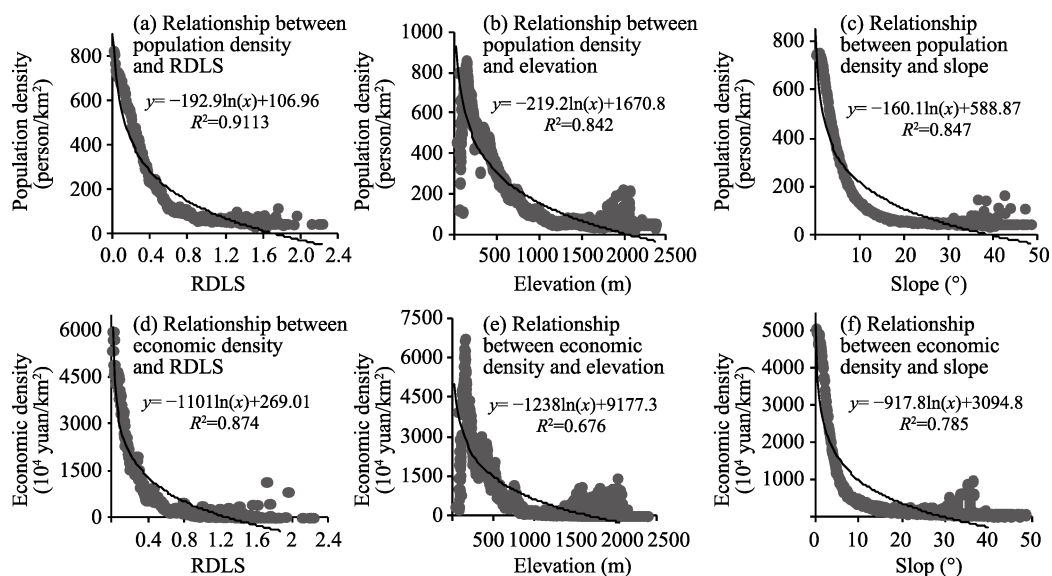


Figure 8 Relationships of RDLS, elevation and slope with population density and economic density

was also higher than that for economic density. This suggests that the impact of topography on population was stronger than that on economy. This is likely due to the advantages that relatively flat terrain areas offer in terms of local financial budget, infrastructure and investment. The economic agglomeration effect is stronger than the population agglomeration effect, resulting in concentrated gross regional product values in these areas and thus unbalanced economic development.

4.3.2 Relationship between RDLS and distribution of population and economy

Figure 9 shows the variations in cumulative frequencies of total population, gross regional product and land area with changes in RDLS. With increasing RDLS, it can be seen that the cumulative frequency of gross regional product first reached the critical value (0.5), followed by total population (0.7) and land area (1.3). This indicates that the majority of population and gross regional product in western Henan are distributed in areas with a flat terrain, and that the population agglomeration degree lags behind the economic agglomeration degree. The population and economy were in a moderately coupled state. However, the coupling relationship with land area was weak. When the RDLS is 0 (i.e. flat; slope $\leq 2^\circ$), the cumulative frequencies of population and gross regional product accounted for 10.35% and 13.04%, respectively, while that of land area was only 4.98%. When the RDLS is 0.5 (i.e. relative elevation < 250 m), the cumulative frequencies of population and gross regional product were 88.65% and 94.39%, respectively, and that of land area was 58.6%. When the RDLS > 1 (i.e. relative elevation > 500 m), the cu-

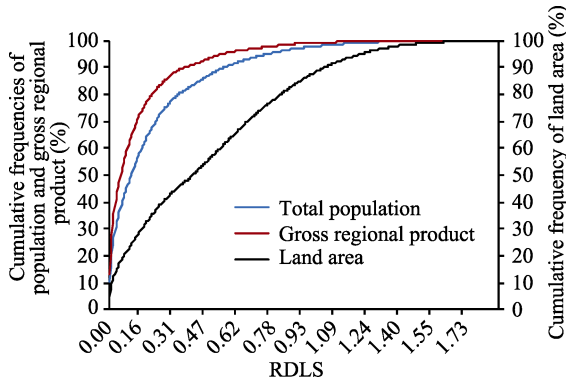


Figure 9 Variations in cumulative frequencies of population, gross regional product and land area with changes in RDLS

mulative frequency of land area accounted for 10.24% while that of population and gross regional product accounted for 1.84% and 0.75%, respectively.

As the RDLS increased, population density, economic density, total population and gross regional product all decreased sharply (Table 3). When the RDLS is 0–0.1, the population and economic densities peaked at 728.91 people/km² and 45.43 million yuan/km², respectively. The total population and gross regional product were 8.9242 million and 570.736 billion yuan, respectively. About 49.86% of the population lived in 25% of the study area and generated 64.07% of the gross regional product. When the RDLS increased from 0–0.1 to 0.3–0.5, the decrease in population and economic densities was the largest, with a decrease of 49.3% and 61.9%, respectively. The total population and gross regional product dropped by 3.28 million and 156.636 billion yuan, respectively. When the RDLS is 0.5–0.7, the decrease in population and economic densities gradually slowed, and the cumulative frequencies of population and gross regional product reached about 95%. When the RDLS ranged 1.6–2.23, the population and economic densities were 45.46 people/km² and 0.604 million yuan/km², respectively, and the total population and gross regional product accounted for 0.07% and 0.02% of that of the whole study area, respectively. In summary, 88.65% of the population in the study area lived in regions where the RDLS is < 0.5, which accounts for 58.6% of the total area. In terms of gross regional product, 88.03% was distributed in regions where the RDLS is < 0.3, which accounts for 44.07% of the total area. Therefore, the study area is characterized by unbalanced population distribution and strong economic agglomeration effect.

Table 3 Statistics of land, population and economy at different RDLS

RDLS	Land		Population density (person/km ²)	Economic density (10 ⁴ yuan/km ²)	Population		Gross regional product		Cumulative frequency of population (%)	Cumulative frequency of gross regional product (%)
	Area (km ²)	Percentage (%)			Total (10 ⁴ people)	Percentage (%)	Total amount (10 ⁸ yuan)	Percentage (%)		
0–0.1	11900.80	24.21	728.91	4542.99	892.42	49.86	5707.36	64.07	49.85	64.07
0.1–0.3	9760.52	19.86	511.11	2106.84	511.43	28.57	2133.51	23.95	78.43	88.03
0.3–0.5	7143.16	14.53	259.13	802.51	183.02	10.23	567.15	6.37	88.65	94.39
0.5–0.7	7399.40	15.05	132.73	349.79	98.93	5.53	255.89	2.87	94.18	97.27
0.7–1	7920.08	16.11	88.11	214.55	71.25	3.98	176.93	1.99	98.16	99.25
1–1.3	3720.68	7.57	67.63	143.66	25.23	1.41	53.59	0.60	99.57	99.85
1.3–1.6	1070.84	2.18	58.90	94.24	6.44	0.36	11.23	0.13	99.93	99.98
1.6–2.23	238.48	0.49	45.46	60.36	1.19	0.07	1.77	0.02	100.00	100.00

5 Discussion and conclusions

5.1 Discussion

(1) Discussion on the spatialization process

Existing research on the spatialization of population and economy, using the land use impact model, mostly used grid data layers during computation, i.e. one grid layer for every land use type (Han *et al.*, 2012). This method may cause information loss or damage in the process of data extraction and conversion. By contrast, we used the grid land use vector data (recording the percentage of every type in a grid). Based on the “Select by Attribute” and

“Field Calculator” tools, the grids of population and economic data were obtained. Compared with other studies, the present study successfully avoided potential errors that may be introduced during the vector and grid data conversion. The results show large improvement in accuracy and calculation efficiency.

(2) Analysis of the spatialization results

As shown in 4.2.1, the spatialization results of population and economic data have good accuracy and are reliable. The simulation accuracy for population density was higher than that for economic density. According to the results, the average population density was 364.17 people/km², and the economic densities of primary, secondary and tertiary industries were 1.99 and 16.14 million yuan/km², respectively. In order to further verify the accuracy of the results and deviation from the actual values, the simulated data of population, output of each industry and gross regional product were compared with the corresponding statistics (Table 4). It can be seen that the relative error of total population was the lowest (0.66%), indicating that the land use impact model works well in population simulation. Some researchers have simulated the spatial distribution of population density in Henan using geostatistic methods and have reported that western Henan mountainous area is sparsely populated. The high and low population density areas are consistent with the results of this study (Zhang *et al.*, 2016). The relative error of the primary industry was the second lowest (1.39%). However, the simulation accuracy for the second and tertiary industries was relatively low, resulting in low accuracy for the gross regional product. Thus, there are some limitations in spatializing economic data solely based on land use data. With the development of RS and GIS technologies, the remote sensing inversion of economic data and multi-source data fusion models have emerged (Zhao *et al.*, 2017). Thus, we will integrate remote sensing data, land use and other geographic data in future studies, and use the principal component analysis method to detect information redundancy in various factors. Accordingly, the spatial economic data model will be constructed from the aspect of different rural-urban areas and different industries.

Table 4 Error analysis of simulated results

Type	Simulated data	Statistical value	Residual error	Relative error (%)
Total population (10 ⁴ people)	1802.64	1790.8	11.84	0.66
Primary industry (10 ⁸ yuan)	989.7	976.09	13.61	1.39
Secondary and tertiary industries (10 ⁸ yuan)	7988.51	7554.16	434.35	5.75
Gross regional product (10 ⁸ yuan)	8978.21	8530.25	447.96	5.25

(3) Impact of RDLS on population and economy

In western Henan mountainous area, the impact of RDLS on population was stronger than that on economic development (Figures 8a and 8d). Correlation analysis showed that RDLS is negatively correlated with both population and economy at the significance level of 0.01, with correlation coefficients of −0.784 and −0.687, respectively. This result is consistent with a study by Yu *et al.* (2015), which showed that the correlation between RDLS and population in the Three Gorges Reservoir area was −0.821, higher than that between RDLS and economic development (−0.663). This may be due to the advantages of flat terrain areas in terms of financial budget, infrastructure and investment. The strong economic agglomeration effect, as compared to the population agglomeration effect, resulted in highly concentrated gross regional product and unbalanced economic development.

Compared with previous studies on the impact of medium-small scale topographical factors (Wei *et al.*, 2013; Yu *et al.*, 2015; Xi *et al.*, 2018), this study discussed the limitation of RDLS on population distribution and economic development in western Henan mountainous area. However, previous studies mostly focused on statistical data of administrative units, which often concealed the internal spatial difference and potentially distorted the results. In this study, first the spatialization of population and economic data was conducted and then the quantitative analysis at the grid scale was performed, which better highlights the practical significance and enables comparison with other topographical factors. Thus, helps reveal the formation of population and economic patterns in the mountain-plain transition zone. However, due to some limitations in this study such as the resolution problem in land use data and the low accuracy in economic data when using county-level sub-industry data, the results may have some uncertainty. In addition, the spatial variation in RDLS, population and economic data have certain scale dependency. However, this study only focused on the 200 m resolution grid scale, which may also introduce some uncertainty. On the basis of improving data resolution, future research should explore the scale effect while analyzing the impact of RDLS on population and economy, and thereby more accurately demonstrate the relationship between RDLS and socioeconomic factors, and provide a scientific basis for the implementation of poverty alleviation projects in mountainous areas.

5.2 Conclusions

(1) RDLS in western Henan mountainous area is dominated by low values. Specifically, the topography in 58.6% of the area is below half the height of a reference mountain (relative elevation ≤ 250 m). Flat land (slope $\leq 2^\circ$) accounted for 46.06% of the area. The spatial pattern is characterized by “low in the east and high in the west” and “high in the middle and low in the north and south”. RDLS is positively correlated with elevation and slope, while the correlation with slope is higher than that with elevation.

(2) The linear fitting degrees between population and economic data and simulated data were 0.943 and 0.909, respectively, suggesting that the spatialization results can reflect the actual population and economic distribution. Both population and economic densities increased from the central-western to the northern, eastern and southern parts. The low value areas are generally distributed in Lushi, Luanchuan and Xixia counties in the central-western part. The high value areas are mainly concentrated in Zhengzhou and Luoyang in the northeast, and Sanmenxia and Lingbao in the north, as well as in several scattered counties and townships.

(3) The impact of RDLS on population and economy was stronger than that of other topographical factors. There is a logarithmic relationship between RDLS and population and economic densities, the fitting degrees are 0.911 and 0.874, respectively. In western Henan mountainous area, 88.65% of the population lived in areas with a RDLS < 0.5 (58.6% of the total area) and 88.03% of the gross regional product was generated in areas with a RDLS < 0.3 (44.07% of the total area). Compared with population distribution, economic development agglomerates more obviously in low RDLS areas.

References

- Baumann M, Kuemmerle T, Elbakidze M *et al.*, 2011. Patterns and drivers of post-socialist farmland abandonment in Western Ukraine. *Land Use Policy*, 28(3): 552–562.
- Du Junwei, 2015. Study on rural poverty alleviation and development of three mountains and one beach area in

- Henan Province [D]. Wuhan: Central China Normal University. (in Chinese)
- Fang Y P, Ying B, 2016. Spatial distribution of mountainous regions and classifications of economic development in China. *Journal of Mountain Science*, 13(6): 1120–1138.
- Feng Zhiming, Tang Yan, Yang Yanzhao *et al.*, 2007. The relief degree of land surface in China and its correlation with population distribution. *Acta Geographica Sinica*, 62(10): 1073–1082. (in Chinese)
- Feng Zhiming, Zhang Dan, Yang Yanzhao, 2011. Relief degree of land surface in China at county level based on GIS and its correlation between population density and economic development. *Jilin University Journal Social Sciences Edition*, 51(1): 146–151. (in Chinese)
- Han Xiangdi, Zhou Yi, Wang Shixin *et al.*, 2012. GDP spatialization in China based on DMSP/OLS data and land use data. *Remote Sensing Technology and Application*, 27(3): 396–405. (in Chinese)
- Hu L, He Z, Liu J, 2017. Adaptive multi-scale population spatialization model constrained by multiple factors: A case study of Russia. *The Cartographic Journal*, 54(3): 265–282.
- Huang D, Yang X, Dong N *et al.*, 2018. Evaluating grid size suitability of population distribution data via improved ALV method: A case study in Anhui Province, China. *Sustainability*, 10(1): 41. doi: 10.3390/sul0010041.
- Kan K, 2007. Residential mobility and social capital. *Journal of Urban Economics*, 61(3): 436–457.
- Li L, Li J, Jiang Z *et al.*, 2018. Methods of population spatialization based on the classification information of buildings from China's first national geoinformation survey in urban area: A case study of Wuchang District, Wuhan City, China. *Sensors*, 18(8): 2558. doi: 10.3390/s18082558.
- Li Xiaojian, 2002. The role of rural household behavior in economic development of less developed rural area: A case study of Western Henan mountains and hilly region, China. *Acta Geographica Sinica*, 57(4): 459–468. (in Chinese)
- Li Y, Yang X, Cai H *et al.*, 2015. Topographical characteristics of agricultural potential productivity during cropland transformation in China. *Sustainability*, 7(7): 96–110.
- Liao Shunbao, Ji Guangxing, Hou Pengmin *et al.*, 2015. Discussion on two key problems of multivariable linear regression models for spatialization of grain yield. *Journal of Natural Resources*, 30(11): 1922–1932. (in Chinese)
- Liu C, Sun W, Wu H, 2010. Determination of complexity factor and its relationship with accuracy of representation for DEM terrain. *Geo-spatial Information Science*, 13(4): 249–256.
- Liu Y, Deng W, Song X Q, 2015. Relief degree of land surface and population distribution of mountainous areas in China. *Journal of Mountain Science*, 12(2): 518–532.
- Liu Yansui, Li Jintao, 2017. Geographic detection and optimizing decision of the differentiation mechanism of rural poverty in China. *Acta Geographica Sinica*, 72(1): 161–173. (in Chinese)
- Meybeck M, Green P, Vörösmarty C, 2001. A new typology for mountains and other relief classes: An application to global continental water resources and population distribution. *Mountain Research and Development*, 21(1): 34–45.
- Prima O D A, Echigo A, Yokoyama R *et al.*, 2006. Supervised landform classification of Northeast Honshu from DEM-derived thematic maps. *Geomorphology*, 78(3): 373–386.
- Shi Z, Deng W, Zhang S, 2018. Spatio-temporal pattern changes of land space in Hengduan Mountains during 1990–2015. *Journal of Geographical Sciences*, 28(4): 529–542.
- Wei W, Shi P, Zhou J *et al.*, 2013. Environmental suitability evaluation for human settlements in an arid inland river basin: A case study of the Shiyang River Basin. *Journal of Geographical Sciences*, 23(2): 331–343.
- Xi C, Qian T, Chi Y *et al.*, 2018. Relationship between settlements and topographical factors: An example from Sichuan Province, China. *Journal of Mountain Science*, 15(9): 2043–2054.
- Yu H, Luo Y, Liu S Q *et al.*, 2015. The influences of topographic relief on spatial distribution of mountain settlements in Three Gorges area. *Environmental Earth Sciences*, 74(5): 4335–4344.
- Zhang Haixia, Niu Shuwen, Qi Jinghui *et al.*, 2016. Geological statistics analysis of population distribution at township level in Henan Province. *Geographical Research*, 35(2): 325–336. (in Chinese)
- Zhang J, Zhu W, Zhao F *et al.*, 2018. Spatial variations of terrain and their impacts on landscape patterns in the transition zone from mountains to plains: A case study of Qihe River Basin in the Taihang Mountains. *Science China Earth Sciences*, 61(4): 450–461.
- Zhang Jingjing, Zheng Hui, Zhu Lianqi *et al.*, 2017. Multi-dimensional changes of vegetation NDVI and its response to climate in Western Henan Mountains. *Geographical Research*, 36(4): 765–778. (in Chinese)
- Zhang X R, Dong K, 2012. Neighborhood analysis-based calculation and analysis of multi-scales relief amplitude. *Advanced Materials Research*, 468–471: 2086–2089.
- Zhao M, Cheng W, Zhou C *et al.*, 2017. GDP spatialization and economic differences in South China based on NPP-VIIRS nighttime light imagery. *Remote Sensing*, 9(7): 673. doi: 10.3390/rs9070673.
- Zhu W, Li S, 2017. The dynamic response of forest vegetation to hydrothermal conditions in the Funiu Mountains of western Henan Province. *Journal of Geographical Sciences*, 27(5): 565–578.
- Zhu W, Zhang X, Zhang J *et al.*, 2019. A comprehensive analysis of phenological changes in forest vegetation of the Funiu Mountains, China. *Journal of Geographical Sciences*, 29(1): 131–145.
- Zhuang D, Liu M, Deng X, 2002. Spatialization model of population based on dataset of land use and land cover change in China. *Chinese Geographical Science*, 12(2): 114–119.