# Evaluation of the production-living-ecology space function suitability of Pingshan County in the Taihang mountainous area, China

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**Abstract:** A rational utilization of land is a matter of importance in sustainable development of mountainous area. The land function in mountainous areas has a close connection with space structure of ecology, production and living. To promote a harmonious development of the relationship between people and nature in mountainous areas, it is necessary to coordinate their relationships of space functions. Suitability evaluation of basic unit function associated with multi-scale space analysis is a prerequisite to a reasonable optimization of land function structure. In this study, an optimized evaluation index system of combination functions was introduced into the assessment of ecological spatial functional suitability in ecological fragile regions by adding three indicators, namely, soil erosion sensitivity, landscape ecological risk and ecological sensitivity. The principle of “taking high” (referred to a function with high suitability to be regarded as the main function of an evaluation unit) and ecological priority (referred to the case, supposing the suitability of a unit’s three functions is consistent, the main function is determined to be the ecological function) were used to determine the main function of an evaluation unit. Pingshan County, China, located at the eastern foot of the Taihang Mountain, was targeted in this case study. The production-living-ecology space (PLES) function in Pingshan was identified by applying our improved valuation indexes. Further, the functional suitability distribution of the combination of elements was obtained by using overlapping comprehensive analysis method, considering the tradeoff of the functional suitability of combination elements. The regions suitable for production/living were distributed in relatively flat

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piedmont plains, whereas the regions suitable for ecology were distributed in the mountain areas of middle and low altitudes. Therefore, to maintain a sustainable development in mountainous areas, an improved scheme of development for Pingshan should be to delineate ecologically fragile areas, to build ecological industrial parks near existing scenic spots, to protect basic agricultural production areas, and to increase investment in science and technology, including reasonable ecological compensation. This study can provide reference for the planning of sustainable development in the Taihang Mountain area and similar regions.

**Keywords:** Taihang Mountain Area; Space of production-living-ecology; Functional tradeoff; Suitability evaluation

## Introduction

According to the European Union Compendium of Spatial Planning Systems and Policies (CEC 1999), spatial planning is based on domestic planning systems and considers the methods used to influence the spatial distributions of activities (Harris et al. 2002). Spatial planning systems vary by country according to the characteristics of the natural environment, economy, social mores, political system, culture and heritage. For example, the British government proposed the National Planning Policy Framework, while for the United States in 2050, strategic spatial planning is more focused on special planning, including infrastructure planning, mega-city regional planning, development lagging regional planning, and large-scale landscape protection planning (Zhai and Gu 2018). The Chinese government proposed establishing a spatial planning system at the Third Plenary Session of the 18th Central Committee in 2013 and further proposed to delimit the development control boundary of production-living-ecology space (PLES) in 2015.

Land use suitability evaluation and land use pattern optimization are key issues related to sustainable land utilization (Peng et al. 2007) and land use planning. Similarly, spatial suitability evaluation and spatial pattern optimization are key issues for spatial planning. Spatial suitability, which is based on land suitability (Gong et al. 2012; Liu et al. 2006), refers to the suitability of a given type of space to support defined behaviors such as ecological protection and agricultural production (Nong et al. 2020). Due to differences in evaluation objects, spatial suitability is significantly different from land use suitability. However, while there is little ongoing research on spatial suitability, many researchers still perform land suitability evaluations (Reshmidevi et al. 2009; Gong et al. 2012) or policy research related to spatial planning (Oranje and Merrifield 2010; Federico 2013; Galle et al. 1997). Since the 2015 proposal by the Chinese government mentioned above, some Chinese scholars have researched spatial suitability. Wu et al. (2016) quantitatively evaluated the suitability of creating national space in Ningbo from the perspective of PLES functions. Nong et al. (2020) conducted a suitability evaluation of agricultural production, urban construction and ecological protection in terms of resource background and land use status. These city-scale studies provide a reference for constructing the evaluation index of PLES functional suitability. However, the spatial suitability evaluation indexes of different types of natural areas, such as mountainous areas and watersheds, are quite different. Constructing spatial suitability evaluation indexes for different types of natural areas can provide a theoretical reference for the spatial suitability evaluation of those types of natural areas.

Due to their inherent fragility, mountainous areas are particularly susceptible to anthropogenic activities; thus, mountain areas are special areas with weak ecological environments (Yang et al. 2008). Therefore, there is growing environmental concern for mountain land use, and sustainable mountain development should be promoted in developing regions (Buckley et al. 1999; Saffrey 1999; Tonderayi 1999; Arrowsmith and Inbakaran 2002; Nepal 2002). Moreover, for the spatial planning of mountainous areas, ecological functions should be given priority.

A spatial system is a system with multiple (possibly conflicting) functions (Montanari et al. 2014; Tudor et al. 2014), such as eco-environment protection and economic development in mountainous areas (Yang et al. 2008). Therefore, spatial suitability evaluations and spatial function optimization (tradeoff) are used to resolve spatial function conflicts, such as PLES functions (Zhou et al. 2017). Therefore, the objectives of the case study in Pingshan County of the Taihang Mountain in Hebei Province are as follows: (1) to develop an index system for evaluating the suitability of the PLES function in mountainous areas; (2) to propose the principle of PLES function tradeoff; and (3) to provide a theoretical basis for spatial planning and development in mountain areas.

## 1 Connotation and Suitability Evaluation Method of PLES Functions

### 1.1 What is the 'production-living-ecology spatial function'?

Traditional sustainable land use evaluation focused on economic sustainability, social sustainability and ecological sustainability (Yang et al. 2008) based on the five principles of sustainable land use proposed by FAO (1993). A land use system is composed of economic, social, and ecological subsystems (Bach et al. 2015; Verstegen et al. 2016) that generally separately perform production, living, ecological functions (Zhou et al. 2017). Due to environmental issues and natural disasters, greater attention must be focused on ecological construction; therefore, the production-living-ecology function must be further studied. At the 18th National Congress, the Chinese government stated an aim to "promote production space and maintain a moderately livable environment" and noted that "ecological space is beautiful." Furthermore, during the 19th National Congress of the Chinese government, the "human-land relationship" was referred to as the "human-environment relationship" which is more in line with the times and highlights a focus on systematic ecological protection. Thus, the human-environment relationship can serve as a new basis for research on PLES functions.

PLES functions are interconnected and mutually unified (Forman 1995; Verburg et al. 2009; Cai et al. 2017; Tasser et al. 2007). A production space aims to intensively and efficiently use space to produce goods such as industrial products, agricultural products and service products (Huang et al. 2017). A living space aims to provide convenient services and promote livability through residential space and space dedicated to consumption, leisure and entertainment (Huang et al. 2017). An ecological space aims to provide beautiful scenery, protect the natural environment, and provide ecological products and services (Huang et al. 2017). Of the three types of spaces, the production space is the foundation, the ecological space is the support, and the living space is the purpose (Zhou et al. 2017).

### 1.2 Evaluation method

#### *1.2.1 Construction of the functional suitability evaluation index system for PLES*

Based on spatial relationships between humans and nature (Figure 1), the relationships among people, land, site conditions, etc. were evaluated, and relevant research results were considered (Peng et al. 2019; Wang et al. 2016; Ma et al. 2014; Gao et al. 2018).

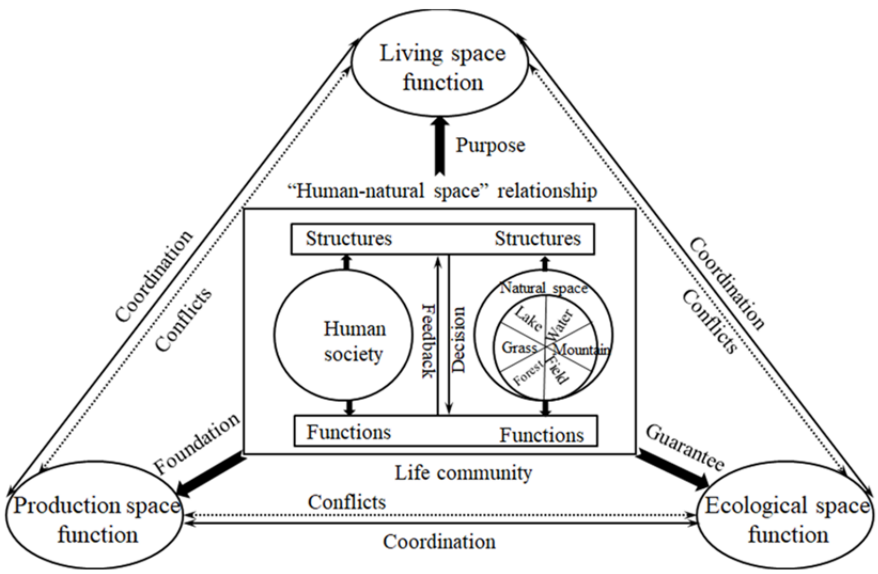


**Figure 1** "Human-natural space" relationship and relationships among production-living-ecology space functions.

**Table 1** Evaluation index system of production-living-ecology space function suitability

| Evaluating Indicator | | Calculation Formula/Operating Software | Trend | Weight | Data Sources |
|---|---|---|---|---|---|
| Production space function | GDP per area | Total GDP/land area | + | 0.23 | Pingshan County Statistical Yearbook (2016) |
| | Population density | Total population/land area | + | 0.22 | |
| | Fruit yield per area | Fruit yield/land area | + | 0.12 | |
| | cultivated land proportion | Cultivated land area/total land area | + | 0.24 | |
| | Grain yield | Total grain yield/cultivated land area | + | 0.03 | |
| | Cultivated land area per capita | Cultivated land area/total population | + | 0.06 | |
| | Second & service production rate | Second & service production/total population | + | 0.11 | |
| Living space function | Traffic density | Intra-region total length of the road /region area | + | 0.15 | Road Vector Map of Pingshan County (2015) |
| | Distance from the railway | (the farthest distance + the closest distance)/2 | - | 0.05 | |
| | Distance from the national road or provincial road | (the farthest distance + the closest distance)/2 | - | 0.04 | |
| | Distance from the county road | (the farthest distance + the closest distance)/2 | - | 0.03 | |
| | Income per capita | Total gross income/total land area | + | 0.17 | Pingshan County Statistical Yearbook (2016) |
| | Housing area per capita | Total housing area/total land area | + | 0.17 | Land use classification map (2015); Field investigation |
| | Urbanization rate | Urban population/total land area | + | 0.39 | Pingshan County Statistical Yearbook (2016) |
| Ecological space function | Slope | ArcGIS 10.2 | + | 0.35 | DEM |
| | Distance from the river/lake | ArcGIS 10.2 | - | 0.03 | Water Vector Map of Pingshan County (2015) |
| | Altitude | ArcGIS 10.2 | + | 0.07 | DEM, generates elevation Digital Model from elevation data |
| | Sensitivity of soil erosion | ArcGIS 10.2 | + | 0.23 | DEM |
| | Aspect | ArcGIS 10.2 | | 0.09 | DEM |
| | Net Primary Productivity | - | + | 0.11 | MOD17A3 (2014, https://ipdaac.usgs.gov) |
| | Landscape ecological risk index | ArcGIS 10.2, Fragstats 3.4 | + | 0.08 | High score 1 satellite image (2015) |
| | Ecological Sensitivity | - | + | 0.05 | Literature (Guo et al. 2016) |

**Notes:** "+" means that the larger the index value, the higher the suitability; "-" indicates that, the higher the index value, the lower the suitability.

Seven production space indicators, seven living space indicators, eight ecological space indicators, and twenty-two impact factors were selected to construct the PLES function suitability evaluation indicator system of the Taihang Mountain (Table 1).

(1) Ecological sensitivity

Ecological sensitivity is the sensitivity of an ecosystem to external disturbances, and it is an important indicator for studying ecological suitability (Suffling 1980). Due to the acceleration of urbanization and the government's vigorous support of agricultural production, cultivated land, garden land, forestland and construction land in Pingshan County have increased significantly. The land use intensity has increased by 7.6% in the past 20 years (Guo et al. 2016), therefore, this paper considered human influence. Regarding the calculation results (2013, Table 2) of Guo et al. (2016), ecological sensitivity was defined as the ratio of the change rate of ecosystem service value (ESV) in Pingshan County to the change rate of the land use intensity index in the corresponding time period. The greater the eco-sensitivity index value, the more sensitive the response of Pingshan ESV to land use change.

(2) Landscape ecological risk index

The landscape ecological risk index refers to the variability in landscape ecological risk caused by disturbance in the external environment.

Referring to Zan (2016), an ecological risk index (ERI) calculation model of the landscape ecological risk index in Pingshan County was established.

$$ERI = \sum_{j=1}^{n} \frac{A_j}{A} \times LLI_j \tag{1}$$

where ERI is the landscape ecological risk index of Pingshan County, $A_j$ is the patch area of land category $j$ (obtained by Fragstats 3.4, which is a landscape ecology software program), A is the total area of Pingshan County, $LLI_j$ is the landscape ecological loss index of land category $j$ (Formula 2), and $n$ represents the number of land classes.

$$LLI_j = LVI_j \times LDI_j \tag{2}$$

$LVI_j$ is the landscape vulnerability index of category $j$ in Pingshan County, and $LDI_j$ is the landscape disturbance index of category $j$ in Pingshan County (Formula 3).

In Jing (2008), 17 risk receptors (land use types) were graded: bare land (grade 8); rivers and lakes (grade 7); woodland and shrub woodland (grade 6); sparse woodlands and other woodlands (grade 5); paddy fields, reservoirs, pits and beaches (grade 4); grassland with high coverage, medium coverage and 1ow coverage (grade 3); dry land and rural residential land (grade 2); and urban land and industrial construction land (grade 1). The landscape vulnerability index ($LVI_j$) was obtained after normalization (Table 2):

$$LDI_j=\alpha C_j+\beta ED_j+\gamma F_j \tag{3}$$

where $C_j$ is the fragmentation degree of category $j$ in Pingshan County (Formula 4), $ED_j$ is the boundary density of category $j$ in Pingshan County (Fragstats 3.4), and $F_j$ is the separation degree of category $j$ in Pingshan County (Formula 5). $\alpha$, $\beta$ and $\gamma$ represent the weight values of the three indexes, which are calculated by the entropy weight method (Table 2).

$$C_j = \frac{N_j}{A_j} \tag{4}$$

where $N_j$ is the number of patches in category $j$ in Pingshan County (Fragstats3.4) and $A_j$ is the patch area of category $j$ in Pingshan County.

$$F_j = \frac{D_j}{PL_j} \tag{5}$$

where $PL_j$ is the area index of category $j$ in Pingshan County (Fragstats 3.4) and $D_j$ is the distance index of category $j$ in Pingshan County

**Table 2** Ecological sensitivity (ES) and risk index of the ecological landscape in Pingshan County

| Towns | ES | $\alpha$ | $\beta$ | $\gamma$ | Landscape disturbance index | Landscape vulnerability index | Landscape ecological loss index | Ecological risk index |
|---|---|---|---|---|---|---|---|---|
| Beiye | 4.16 | 0.26 | 0.36 | 0.38 | 13.39 | 0.70 | 0.74 | 17.68 |
| Donghuishe | 3.33 | 0.21 | 0.34 | 0.45 | 16.56 | 0.66 | 0.63 | 12.45 |
| Dongwangpo | 2.98 | 0.31 | 0.27 | 0.42 | 11.67 | 0.61 | 0.54 | 8.99 |
| Gangnan | 1.11 | 0.30 | 0.26 | 0.44 | 13.63 | 0.56 | 0.67 | 8.74 |
| Guyue | 2.55 | 0.23 | 0.37 | 0.40 | 17.92 | 0.82 | 1.02 | 26.62 |
| Hehekou | 3.79 | 0.23 | 0.39 | 0.38 | 17.39 | 0.44 | 0.99 | 45.72 |
| Jiaotanzhuang | 2.11 | 0.21 | 0.44 | 0.35 | 13.49 | 0.49 | 0.90 | 39.98 |
| Lianghe | 2.11 | 0.23 | 0.39 | 0.38 | 14.34 | 0.32 | 0.56 | 12.32 |
| Mengjiazhuang | 2.42 | 0.18 | 0.53 | 0.29 | 22.95 | 0.72 | 1.45 | 42.63 |
| Nandian | 2.63 | 0.24 | 0.35 | 0.41 | 12.37 | 0.37 | 0.39 | 12.55 |
| Pingshan | 0.94 | 0.28 | 0.42 | 0.30 | 17.80 | 0.52 | 0.59 | 11.57 |
| Shangguanyintang | 1.04 | 0.26 | 0.41 | 0.33 | 13.20 | 0.44 | 0.79 | 38.36 |
| Shangsanji | 2.29 | 0.33 | 0.27 | 0.40 | 9.47 | 0.27 | 0.32 | 9.99 |
| Sujiazhuang | 1.29 | 0.39 | 0.23 | 0.38 | 9.79 | 0.37 | 0.52 | 15.30 |
| Wentang | 1.62 | 0.22 | 0.48 | 0.30 | 24.66 | 0.76 | 1.31 | 32.10 |
| Xiahuai | 2.92 | 0.32 | 0.34 | 0.34 | 12.76 | 0.76 | 0.76 | 30.82 |
| Xiakou | 2.82 | 0.26 | 0.43 | 0.31 | 19.11 | 0.70 | 1.17 | 30.24 |
| Xiaojue | 1.87 | 0.19 | 0.40 | 0.41 | 14.46 | 0.77 | 0.87 | 25.58 |
| Xibaipo | 1.77 | 0.34 | 0.40 | 0.26 | 16.24 | 0.46 | 1.04 | 34.63 |
| Xidawu | 1.07 | 0.43 | 0.24 | 0.33 | 8.67 | 0.27 | 0.32 | 7.04 |
| Yangjiaqiao | 1.28 | 0.26 | 0.34 | 0.40 | 13.58 | 0.65 | 0.86 | 22.56 |
| Yingli | 1.85 | 0.23 | 0.41 | 0.36 | 13.23 | 0.55 | 0.90 | 32.15 |
| Zhaibei | 0.94 | 0.24 | 0.34 | 0.42 | 15.89 | 0.68 | 0.88 | 24.26 |

(Formula 6).

$$D_j = \frac{1}{2}\sqrt{PD_j} \tag{6}$$

where $PD_j$ is the patch density of category $j$ in Pingshan County (Fragstats 3.4). The calculation results are shown in Table 2.

### *1.2.2 Evaluation index weights*

(1) Productive and living functions

We selected the entropy method to determine the productive and living function suitability evaluation weights.

1) Data standardization (extremum method):

$$r_{ij} = \begin{cases} \frac{X_{ij}-min\{X_{ij}\}}{max\{X_{ij}\}-min\{X_{ij}\}}, & Trend = "+" \\ \frac{max\{X_{ij}\}-X_{ij}}{max\{X_{ij}\}-min\{X_{ij}\}}, & Trend = "-" \end{cases} \tag{7}$$

where $r_{ij}$ is the standard value of the $j$th administrative township on the $i$th evaluation index, $r_{ij} \in [0,1]$, and $X_{ij}$ is the $i$th index of the $j$th administrative township.

2) Calculate entropy

If there are m indicators for evaluating a function in Pingshan County and n evaluated objects ($n$=23), then the entropy of the $i$th index is defined as follows:

$$H_i = -\frac{1}{\ln n}\sum_{j=1}^{n} f_{ij}\ln f_{ij}, \quad i = 1,2,\dots,m \tag{8}$$

$$f_{ij} = \frac{X_{ij}}{\sum_{j=1}^{n} X_{ij}} \tag{9}$$

3) Calculate the index weight

$$W_i = \frac{1-H_i}{\sum_{i=1}^{m}(1-H_i)} \tag{10}$$

(2)Ecological function

For ecology function suitability, the basic assessment unit is a grid, and we invited 10 experts specializing in land ecological use and familiar with Taihang Mountain areas who worked at universities and the Chinese Academy of Sciences to score 8 indicators of ecological function. The Analytic hierarchical Process (AHP) (Saaty 1980) method is used to construct the judgment matrix and determine its index weight by finding the maximum approximate eigenvalue of the judgment matrix.

A 9-scale scoring table was used to make pairwise comparisons of eight indicators (Saaty 1980). According to the degree of importance, the results were divided into five grades, each with an assignment of 1, 3, 5, 7, or 9, which tended to result in the assignment of 2, 4, 6, or 8 between two levels. After the calculation, the consistency test result (CR) of the expert score was 0.02, which satisfied the consistency test; thus, the scoring result was reasonable (Table 3).

### *1.2.3 Calculate suitability indexes and grading standards*

(1) Calculate the productive and living space function suitability indexes

$$SI_j = \sum_{i=1}^{m} r_{ij} W_i \tag{11}$$

Here, $SI_j$ is the suitability index of the $j$th administrative township (production or living), $r_{ij}$ is the standard value of the $j$th administrative village on the $i$th evaluation indicator, and $W_i$ is the weight of the $i$th indicator.

(2) Ecological space function suitability indexes

1) Each suitability value of the ecological function evaluation indexes

Each indicator was divided into three levels (i.e., high suitability, general suitability, and low suitability for values of 3, 2 and 1, respectively). The grading standards for 6 factors, including slope, aspect, distance from the river, elevation, vegetation NPP, and soil erosion sensitivity, referred to the study results of the ecological-

**Table 3** Judgment matrix and weights of ecological space functional suitability assessment indexes

| | Falling gradient | Distance* | Altitude | SSE | Aspect | NPP | LER index | ES | Weight |
|---|---|---|---|---|---|---|---|---|---|
| Falling gradient | 1 | 8 | 6 | 2 | 5 | 4 | 6 | 7 | 0.35 |
| Distance* | 1/8 | 1 | 1/2 | 1/5 | 1/3 | 1/4 | 1/3 | 1/2 | 0.03 |
| Altitude | 1/6 | 2 | 1 | 1/4 | 1/2 | 1/2 | 1 | 2 | 0.07 |
| SSE | 1/2 | 5 | 4 | 1 | 3 | 3 | 4 | 5 | 0.23 |
| Aspect | 1/5 | 3 | 2 | 1/3 | 1 | 1 | 1 | 2 | 0.09 |
| NPP | 1/4 | 4 | 2 | 1/3 | 1 | 1 | 2 | 2 | 0.11 |
| LER index | 1/6 | 3 | 1 | 1/4 | 1 | 1/2 | 1 | 2 | 0.08 |
| ES | 1/7 | 2 | 1/2 | 1/5 | 1/2 | 1/2 | 1/2 | 1 | 0.05 |

**Notes:** Distance*= Distance from the river/lake; SSE=Sensitivity of soil erosion; NPP=Net Primary Productivity; LER index=Landscape ecological risk index; ES=Ecological Sensitivity.

**Table 4** Grading standards of the production-living-ecology space functional suitability for Pingshan County

| Grade | | Standard value of suitability | | |
|---|---|---|---|---|
| | | High suitability | Moderate suitability | Low suitability |
| Production space function | | ＞0.52 | 0.29-0.52 | ＜0.29 |
| Living space function | | ＞0.38 | 0.24-0.38 | ＜0.24 |
| Ecological space function | | ＞2.14 | 1.81-2.14 | ＜1.81 |
| Ecological space function | Aspect | South slope | Northeast slope / southwest slope / northwest slope / northeast slope / west slope / east slope | North slope |
| | Sensitivity of soil erosion (°) | ＞8 | 5-8 | ＜5 |
| | Distance from the river/lake (m) | ＜3000 | 3000 -8000 | ＞8000 |
| | Altitude (m) | ＞1500 | 700-1500 | ＜700 |
| | Falling gradient (°) | ＞25 | 10-25 | ＜10 |
| | Net Primary Productivity | ＞300 | 200-300 | ＜200 |
| | Ecological risk index | ＞33 | 20-33 | ＜20 |
| | Ecological Sensitivity | ＞3.1 | 2-3.1 | ＜2 |

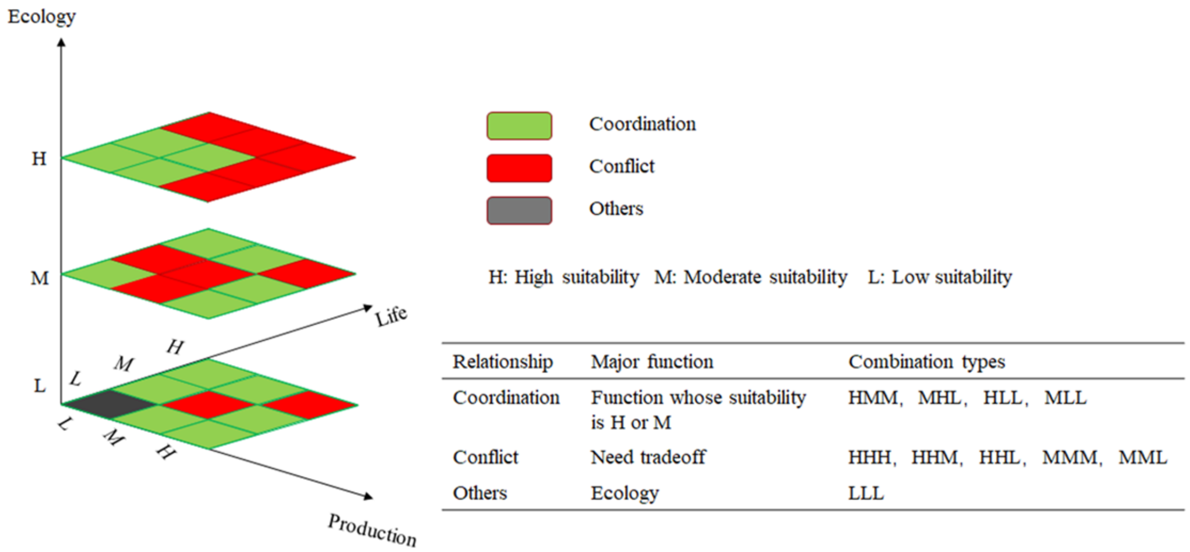


**Figure 2** Tradeoff principle of the production-living-ecology space functions of the same research unit.

spatial function of the mountain system (Gao et al. 2018). The index data for the landscape ecological risk and ecological sensitivity were divided into 3 grades by using a score frequency histogram; the results are provided in Table 4.

2) Evaluation index of ecological spatial function suitability:

$$SI_j^g = \sum_{i=1}^{m} r_{ij}^g W_i \quad (12)$$

where $SI_j^g$ is the suitability index (ecology) of the jth grid unit, $r_{ij}^g$ is the value of the $i$th index of the $j$th grid unit (3, 2, or 1), and $W_i$ is the weight of index $i$.

(3) Grading standards

The suitability evaluation index of the living and ecological space functions was divided into 3 grades by using a score frequency histogram (Table 4). Because the suitability indexes of the production space function in 5 of the 23 townships in Pingshan County were much higher than those in the other townships, the 5 townships were classified as "high suitability", and the other 18 townships were divided into 2 grades by using the score frequency histogram. Thus, the classification standard of the production space function suitability was obtained (Table 4).

## 1.3 PLES functional tradeoff

In this study, the PLES functional tradeoff can be described as follows (Figure 2). (1) If only one kind of spatial function was labeled as high (H) in the regional PLES function, then the dominant function of this region was defined as having an H characteristic. (2) Regarding conflict analysis, if a region had two or more spatial functions with H or moderate (M) characteristics, then it was necessary to carry out conflict analysis to determine the leading function. During the tradeoff process, the positioning function of study area functional zone of the main body should be considered first, which means that it is necessary to ensure the status of the key ecological spaces of the Taihang Mountain. (3) Finally, regarding the ecological priority principle, if the suitability of the production, living, and ecology spaces of a region were low (L), then the dominant function of this area was defined as the ecological space function.

## 2 Case Analysis

### 2.1 Study area

The Taihang Mountain area in Hebei Province is the ecological barrier and water conservation area of the Beijing-Tianjin-Hebei area, which is China's political and economic center; therefore, environmental protection and steady development of the Taihang Mountain area is extremely important. However, the Taihang Mountain area has faced slow economic development and serious damage to the environment due to extensive land use, and mountain protection and mountain development are often in conflict. As such, it is urgent to explore reasonable ways to maximally utilize the space.

We select Pingshan County of Hebei Province, which includes 23 town-level districts and is located at the eastern foot of the Taihang Mountain along the upper reaches of the Hutuo River (113°31′–114°51′ E; 38°9′–38°45′ N) as the case study area (Figure 3). Pingshan covers 2617 km$^2$, and mountainous land accounts for 74.8% of the total land area; this area is a typical mountain region consisting of 0.2% subalpine area, 13.1%

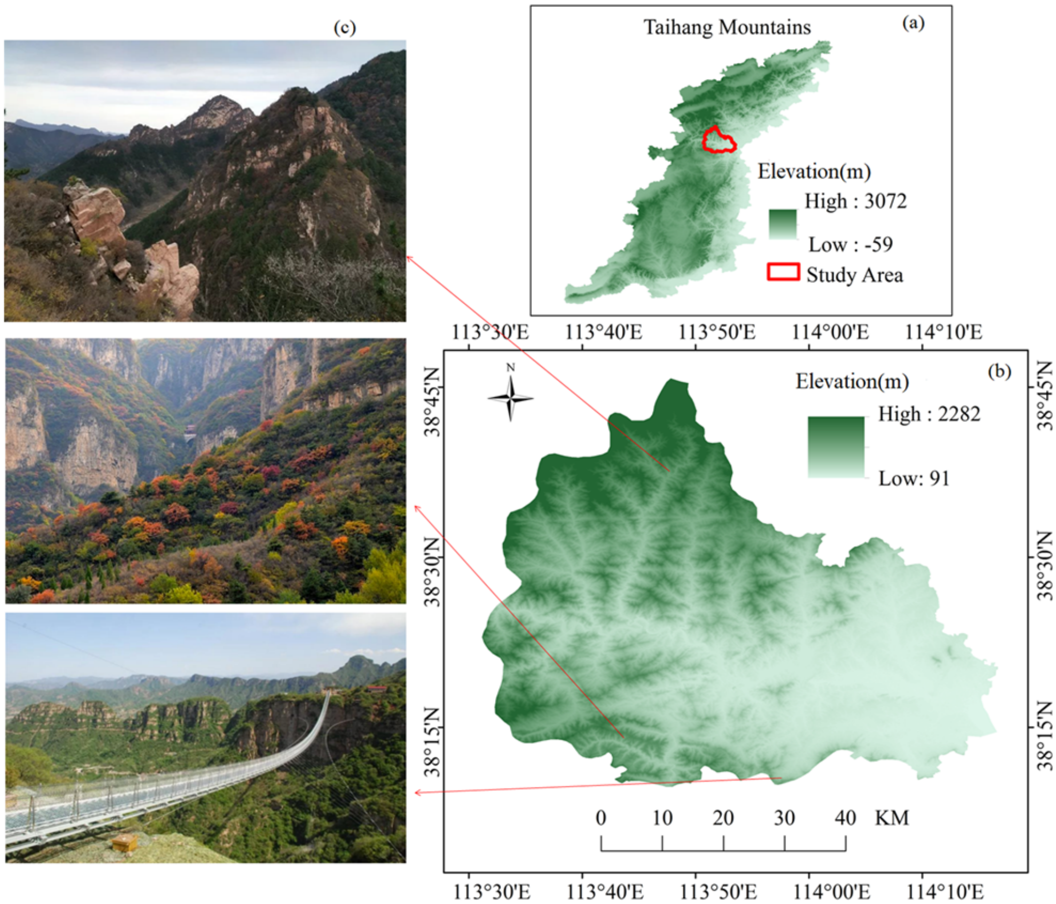


**Figure 3** Map of the study area. (a) The location of the study area in the Taihang Mountain; (b) Digital elevation map of Pingshan County; and (C) Representative pictures of the study area.

middle mountain area, 35.5% low mountain area, 26.5% hills, and 25.2% piedmont plain area, and the altitude varies greatly from 111–2281 m (The People's Government of Pingshan County 2019, http://www.xbp.gov.cn/index.html). Pingshan County also has various geomorphologic types, such as terraces, hills, valleys and depressions. Moreover, this area is the drinking water source of Shijiazhuang, the capital of Hebei Province. Therefore，planning the main functional area of Hebei Province, Pingshan County was positioned as a key ecological area because it has outstanding ecological spaces.

Pingshan County has a temperate semihumid continental monsoon climate with hot summers and cold winters[1]. The annual precipitation in Pingshan County is unevenly distributed in time and space, with an average precipitation of 530–690 mm. The precipitation from July to August is the largest, accounting for 65%–70% of the precipitation of the whole year, and the spatial and temporal distributions of surface runoff are extremely uneven, with an average annual runoff of 1.8 billion cubic meters (The People's Government of Pingshan County 2019, http://www.xbp.gov.cn/index.html). The registered population of Pingshan County was 505 thousand, including 400 thousand in rural areas in 2016 (The statistical bureau of Pingshan County 2016). The ratio of the primary, secondary and tertiary industries in 2018 was 6.8:51.4:41.8, and the total regional GDP was 21.9 billion yuan in 2018. Pingshan County was listed as a national poverty county in 1986 but removed from the poverty county list in 2018 (https://www.thepaper.cn/newsDetail_forward_2490422).

The land reclamation rate of Pingshan County is approximately 70%, and the main land use types are forestland and cultivated land, accounting for 33% and 18% of the total area, respectively (Guo et al. 2016). That is, the land in Pingshan County is mainly ecological-productive land. In recent years, due to the reduction in farmers' willingness to cultivate, the area of cultivated land in Pingshan County has decreased. To ensure food supply and social stability, it is imperative to ensure a certain amount of cultivated land resources. Due to ecological environment protection and water source conservation positioning, the development and utilization of unused land must protect the environment in a rational way.

### 2.2 Data collection

The basic evaluation unit in this study was either the natural area unit (ecological space), with an accuracy of 30 m × 30 m, or the township administrative unit (production space and living space). Social and economic data were derived from the Pingshan County Statistical Yearbook (2016). Digital elevation model (DEM) data were derived from the Geospatial Data Cloud Platform of the computer network information center of the Chinese Academy of Sciences (http://www.gsc1oud.cn), which consisted ASTER GDEM V2 data with a spatial resolution of 30 m. Vegetation net primary productivity (NPP) data were obtained from MOD17A3 (2014) data released by the University of Montana (https://ipaac.usgs.gov); the spatial resolution was 1 km, and the temporal resolution was 1 year. Image splicing, projection and resampling were performed by using MRT (MODIS reprojection tools) software, and ArcGIS 10.2 was used to extract the effective values. Data on township boundaries, traffic and water areas were derived from NavInfo (http://www.navinfo.com/), and the data were from 2015. The basic data for the land use classification map (required for calculating the landscape ecological risk index) were based on a 2015 Gaofen-1 satellite image obtained by the project team through visual interpretation. Moreover, images with high spatial resolutions (DEM data and Gaofen-1 satellite images) were resampled according to images with low spatial resolution (NPP data) when performing the overlay analysis.

### 2.3 Results

#### *2.3.1 Evaluation results of PLES functional suitability in Pingshan County*

(1) Production spaces

The functional suitability areas of the high, moderate, and low production spaces in Pingshan County were 319.68 km$^2$, 341.60 km$^2$, and 1955.73 km$^2$, respectively, of which 74.73% was not suitable for production (specifically in the western part of Pingshan County and in the hinterland of Taihang Mountain) but was suitable for ecological space (Figure 4a). The areas with the highest functional suitability for production space were located in 5 townships in the eastern part of Pingshan County

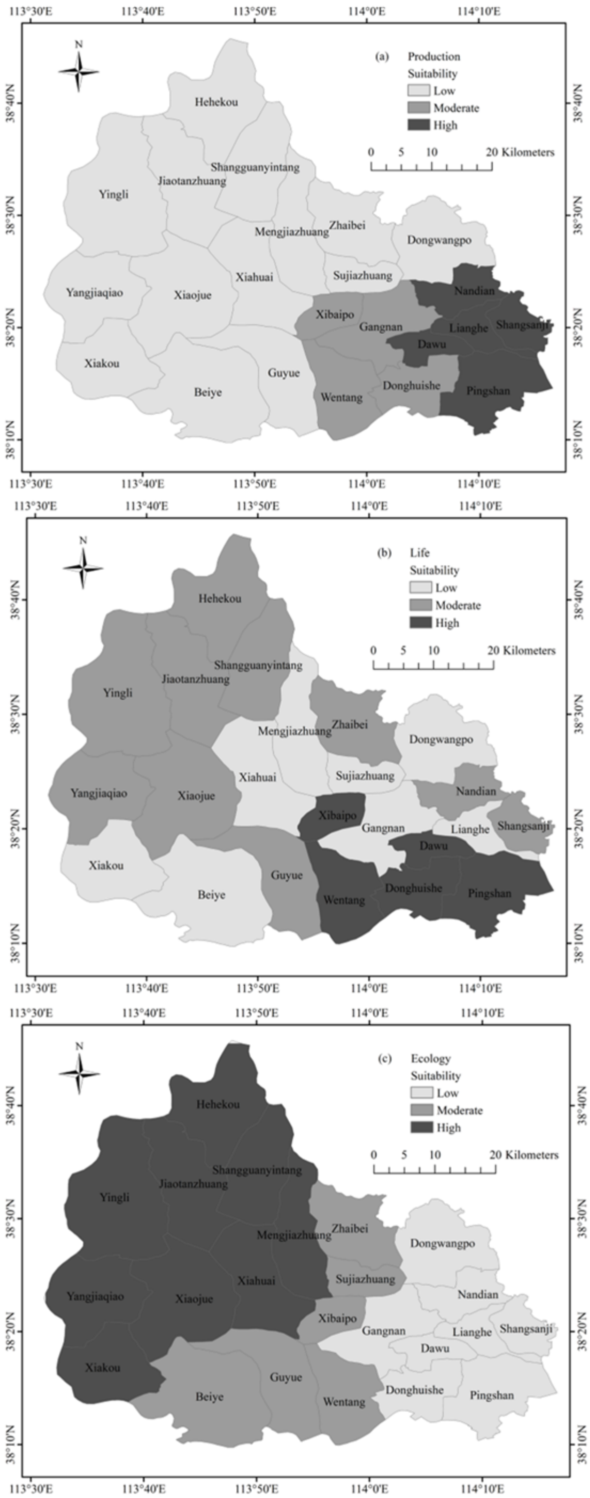


**Figure 4** Distribution of production-living-ecology space functional suitability in Pingshan County.

(Figure 4a). Pingshan Town, the capital of Pingshan County, has primary, secondary and tertiary industries; the average land GDP is 45 million yuan/km², which is more than twice those of other townships (except Dawu Township). For the other four townships, the cultivated land area was relatively large, and the proportion of cultivated land was more than 10 times those of most villages and towns in the western part of the county. Therefore, this area was suitable for classification as the main grain-producing area of the county.

(2) Living spaces

The high, moderate, and low functional areas for living spaces in Pingshan County were 319.59 km², 1320.11 km², and 905.30 km², respectively, and 50.44% of the areas belonged to moderately suitable living areas. The most suitable areas were located in five villages and towns in the southeastern part of Pingshan County, and the moderately suitable areas were mostly located in the western mountainous area of the county and three townships in the northeastern part of the county (Figure 4b). Among the many factors that affected the land suitability for living, the urbanization level contributed the most (with a weight of 0.39), followed by income level, housing area and traffic density. Urbanization level (the urbanization rates in Pingshan Town, Donghuishe Town, and Dawu Township were greater than 50%), income level (Wentang Town) and traffic density (Xibaipo Town) had the greatest impacts on determining high areas. The areas with good economic development were suitable for living spaces. Housing area had the greatest influence on the moderate areas, which was mainly because the populations of villages and towns in the western mountain area are small and the per capita housing area is relatively large. Furthermore, residential areas in the western mountain area are distributed throughout the region, which can effectively alleviate the difficulty of human survival in the ecological space, and these areas have little impact on the key ecological areas in Pingshan County.

(3) Ecological spaces

The high, moderate, and low areas for ecological space in Pingshan County were 1333.64 km², 650.14 km², and 633.22 km², respectively, with 50.96% of the area designated as high area, which is in line with the key ecological spaces in Pingshan County. Overall, the distribution of ecological spatial suitability in Pingshan County was the opposite of that for the production space, and the suitability gradually increased from east to west (Figure 4c).

### *2.3.2 Balancing PLES functions in Pingshan County*

According to the PLES functional tradeoff principle (chapter 1.3), a PLES functional balance map was obtained for Pingshan County (Figure 5a). The western mountainous area of Pingshan County was suitable for ecological space, the eastern plain area was suitable for production space, and the middle of the county was suitable for living space. However, there were conflicts for four townships. Pingshan Town and Dawu Township in the southeastern part of Pingshan County were classified as high for living space and production space suitability, while Zhaibei Township and Guyue Town were designated as moderate for living space and ecological space suitability.

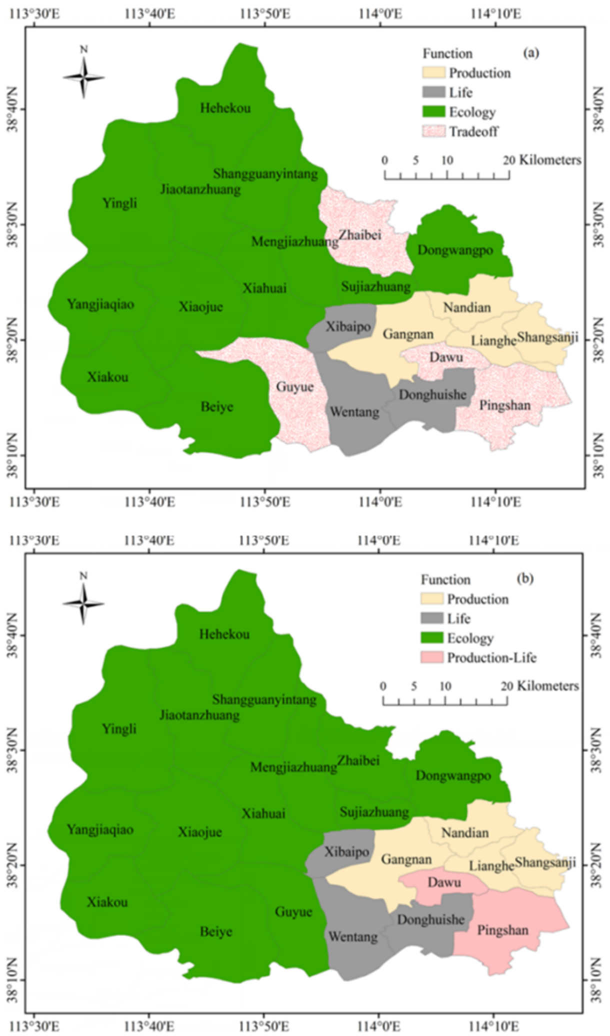


**Figure 5** Tradeoff results of production-living-ecology space function for Pingshan County. (a) tradeoff map; (b) distribution map of functional suitability.

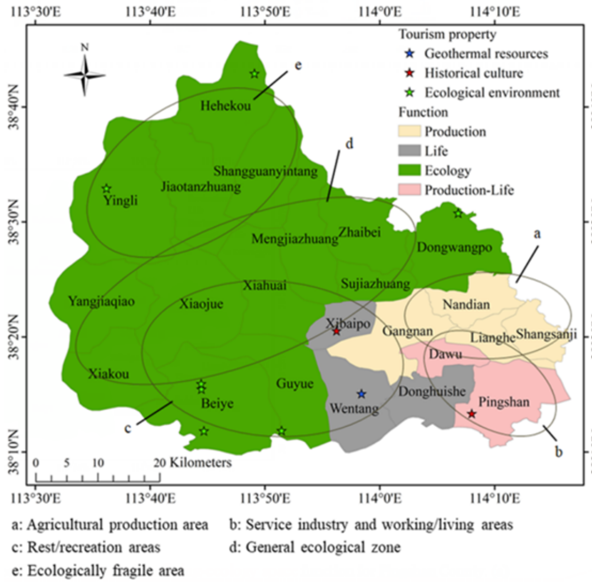


**Figure 6** Detailed spatial distributions for Pingshan County based on production-living-ecology space functional suitability.

The suitability of Zhaibei Township as a living space was moderate, and the population (13600 people) and population density (1.34 people/hm$^2$) were relatively small (approximately 1/10 that of Pingshan Town). All three surrounding villages and towns were suitable for ecological space. Therefore, the land in Zhaibei Township is relatively more suitable for ecological space. Guyue Town and its three surrounding villages and towns (Beiye Township, Wentang Town and Xibaipo Town) are rich in tourism resources (Figure 6). With the help of existing tourist spots, tourist attractions can be built in these areas, the green transformation of the industrial structure in Pingshan County can be realized, the value of characteristic agricultural products in mountainous areas can be improved, and employment opportunities can be created. In this scenario, the land in Guyue Town is relatively suitable for living space.

The suitability indexes of the production space and living space of Pingshan Town and Dawu Township were highest and second highest, respectively. Based on a single index, the urbanization rates of the two townships were greater than 50%, the proportion of cultivated land was greater than 40%, and the population density and average land GDP were in the top 2. Moreover, Pingshan Town and Dawu Township were located in the transitional zone between the area suitable for production space and the area suitable for living space. In this study, Pingshan Town and Dawu Township were positioned as production-living composite space functional areas.

According to the above results, the functional suitability distribution map of the PLES in Pingshan County (Figure 5b) was obtained: land in the subalpine and middle mountain areas in the western and northwestern regions was suitable for ecological space, the eastern plain hilly area was suitable for production space, dense tourist areas in the central and southern regions were suitable for living space, and the transitional production-living space was created for both production and living. The suitable land area for the ecological space function in Pingshan County was 1566.96 $km^2$, accounting for 59.88% of the total area of Pingshan County. The functional land areas classified as production and living space accounted for 13.80% and 18.71% of the total area, respectively.

## 3 Discussions

### 3.1 Suggestions for the development and planning of mountainous areas

Based on the analysis of the functional suitability distribution characteristics of PLES and the current space utilization in Pingshan County, the development planning recommendations for different land types are summarized (Table 5).

(1) Agricultural production area. Basic farmland that must be protected in the piedmont plain area is suitable for crops and surrounded by vegetable plantations. Moreover, the investment in agricultural science and technology should be increased to improve agricultural production efficiency and to ensure food demand due to increased population.

(2) Industrial production area. In past decades, the exploitation and utilization of mineral resources was the main source of economic development of mountainous areas, such as Pingshan County, the contribution to GDP of secondary industry, which was dominated by the steel industry, still exceeded 50% in 2018. However, the fragility of the environment and the number of disasters in mountainous areas are caused by the extensive exploitation of mineral resources; therefore, improving mineral resource exploitation projects and implementing industrial transformations (e.g., eco-tourism) are key to the sustainable development of mountainous areas, and it is worth noting that reasonable ecological compensation should be considered.

(3) Service industry and working/living areas. These two areas, which generally overlap, are mainly distributed in the county center or town

**Table 5** Proposals for land spatial development planning in different types of spaces

| Space types | | Features | Proposal about Land Spatial Development Planning |
|---|---|---|---|
| Production | Agricultural production area | The altitude is low, the foothills are located, and the soil is relatively fertile | Mainly for protection, delineate the basic farmland protection red line |
| | Industrial production area | The altitude is relatively low, and mineral resources are available for development and use | Ecological restoration and cleaner production |
| | Service industry | The altitude is relatively low, the transportation is more convenient, and the infrastructure is complete | Improve facilities; suggest that the service industry shift to ecotourism |
| Living | living and working area | The altitude is relatively low, the transportation is more convenient, and the infrastructure is complete | Improve facilities, improve environment, introduce e high-tech industries and attract talents |
| | Resting area/Recreational tourism area | Moderate altitude, most ecotourism attractions, and convenient transportation | Improve facilities, integrate scattered tourist spots, and establish ecotourism industrial parks |
| Ecology | General ecological zone | Moderate altitude, there are usually attractions | While protecting the ecological environment, comprehensive development is carried out in combination with the rest function of the living space |
| | Ecologically fragile area | Altitude is relatively high, mineral mining area, water conservation area | Mainly for protection and restoration, delineated as an ecological red line area, prohibiting or restricting human activities |

center. The government should improve the quality of facilities and the environment and introduce high-tech industries to attract talent.

(4) Rest/recreation areas. Mountain ecosystems display unique natural beauty, varied landscapes, and rich biodiversity; thus, they can be used for a wide spectrum of tourism activities (Mahapatra et al. 2012), which represent a great opportunity. Based on existing tourist spots and planned tourist spots, comprehensive ecotourism gardens with central recreation areas will be built. Infrastructure and supporting facilities to improve standard of living will be centrally located in recreation areas; in regions outside the garden area, the status quo will be maintained and the environment will be protected.

(5) General ecological zone. Here, appropriate development activities based on ecological protection are encouraged. Because there are many existing tourist attractions in this area, recreational tourism and ecological functions are the main functions of the region.

(6) Ecologically fragile area. Human activities should be limited in ecologically important areas and forbidden in extremely important zones to protect mountainous environments.

Based on the above perspectives, a detailed spatial distribution map of the PLES in Pingshan County (Figure 6) was obtained. The five areas in Figure 6 have overlapping parts due to the overlapping of functions in specific space, such as the overlap between rest/recreation areas and general ecological zones, which reflect the overlap between the production function of the tourism industry and the ecological function. The development of green tourism promotes the coordination of PLES in the southern part of the county. Relying on existing tourist spots, Xibaipo Town, Bei Ye Township, Guyue Town and Wentang Town are turned into multifunctional tourism resorts with red, green, and blue tourism: red tourism focuses on education (Xibaipo Red Revolution Education Base), green tourism focuses on leisure and fitness (Beiye and Guyue) and blue tourism focuses on health and preservation (Wentang geothermal resources). Tourists mainly eat and live in Guyue Town and Wentang Town, which protects the ecological environment of Beiye Township in the west and facilitates the production of grain in the east.

### 3.2 Improving evaluation indexes

In this study, the "human-environment relationship" was the basis for constructing an index system for functional suitability evaluation. However, because the definition of space has been improved, the evaluation index also needs to be improved. PLES is key to land space governance, and there have been many studies on PLES. Based on the research objectives of previous studies, PLES functions have been divided in different ways. For example, Zhang (2017) defined this space according to the sustainable development of an economic society and the resource environment, and Hu et al. (2016) explored the definition of PLES from the perspective of spatial regions, such as towns and villages. Jin (2014) divided PLES according to sustainable and balanced development and conducted scientific research by investigating land at different scales by using national planning and construction management statistics. When selecting evaluation indicators, we mainly considered the PLES functions in mountainous areas and the future development goals of Pingshan County, while we ignored urban-rural differences. In addition, some indicators have multiple attributes; for example, GDP has both social and economic attributes. A method for handling these multiattribute indicators is a problem that needs further discussion.

## 4 Conclusions

Environmental degradation and geological disasters in mountainous areas are becoming increasingly serious due to inappropriate human behaviors. Therefore, the land in mountainous areas needs to be optimized, and functional suitability assessment is a prerequisite for spatial structure optimization. Traditional assessment is carried out considering economic, social and ecological aspects of production and living. Based on the concepts proposed by the Chinese government, PLES has been expanded. On this basis, by taking Pingshan County in the Taihang Mountain area as an example, we carried out a functional suitability assessment from which the following preliminary conclusions can be drawn:

1) The index system for evaluating the

suitability of the PLES function in mountainous areas was constructed based on spatial relationship between humans and the environment. To protect ecologically fragile areas, indicators such as soil erosion sensitivity, landscape ecological risk and ecological sensitivity have been added to the ecological function suitability assessment subsystem.

2) The PLES functional tradeoff was proposed. In general, the function with high suitability is regarded as the major function in the region; ecological priority is considered when there are PLES conflicts.

3) A new development and planning perspective for mountainous areas is provided; specifically, ecologically fragile areas are to be delineated, comprehensive ecotourist gardens are to be built by relying on existing scenic spots, basic agricultural production areas are to be protected and investment in science and technology is to be increased. Finally, on this basis, red, green and blue tourism are used to promote education (red), leisure and fitness (green) and health and preservation (blue), and multifunctional tourism resorts are proposed to be built in Pingshan County.

The idea of ecological priority will promote the sustainable development of mountain ecosystems, and this study offers the technological support and a new development perspective for the Taihang Mountain and similar regions.

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