

Quantifying and Evaluating the Cultivated Areas Suitable for Fallow in Chongqing of China Using Multisource Data

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Abstract: The quantitative evaluation of the suitability of land fallow is of great significance to the effective implementation of fallow system in rural China. The purpose of this study is to systematically evaluate the cultivated areas suitable for fallow in Chongqing, China. The results show that: (1) a comprehensive index of cultivated land fallow (ILF) was developed by employing a series of multi—source data, and the ILF has been proven as an effective proxy to identify the cultivated areas suitable for fallow; (2) cultivated land with ILF values above the average value accounts for 34.38% (9902 km²) of the total cultivated land; (3) the ILF is negatively correlated with the population density, transportation proximity, and proportion of inclined area. This study argued that the ILF can reflect the cultivated areas suitable for fallow in Chongqing and can provide guidance for the spatial distribution of cultivated land fallow. The findings indicated that the differences in geographical elements between karst and non—karst areas must be further investigated, and the evaluation accuracy of the cultivated areas suitable for fallow must be improved.

Keywords: cultivated land fallow; suitability evaluation; land use change; multisource data; Chongqing; China



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1. Introduction

Global land productivity is declining at an unprecedented rate [1,2], rooted in the fact that more and more land is unsuitable for cultivation and that the main source of human food is being lost [3]. Over the past forty years, land erosion and pollution led to the loss of nearly 33% of arable land [4]. Landscape changes, soil erosion, and depletion of land fertility have greatly reduced the function of land as a living and ecological guarantee for people [5,6]. In order to reverse the development model of resource consumption and environmental pollution in the early stage, the Chinese government has sought the ecological and sustainable development path from the perspective of the top—level design of the country, and distributed the ecological development model from the perspective of five—in—one, which is the master plan for a balanced development, economically, politically, culturally, socially, and ecologically.

Land is fundamental for providing material and space for the ecological and sustainable development. However, the prospects for the ecological environment in China are not optimistic because of soil erosion, soil pollution, and other ecological resource challenges [7,8]. The quality of cultivated land resources in China is generally low, and intensive land exploitation is a crucial approach to China's future food security [8–11]. To safeguard the natural characteristics of ecosystems, it is necessary to protect cultivated land and habitats for species at the risk of extinction. The government has established systematic approaches and innovations in a top—down manner. The Ministry of Agriculture emphasized that cultivated land protection through the fallowing of cultivated land is

the most important mission. In order to effectively implement the cultivated land fallow system, the most important thing is to identify areas suitable for fallow [12,13]. Therefore, it is urgent for policy and academic circles to carry out regional fallow adaptability research.

In recent years, many studies have shown land use and its changes for crop production in China [14–18]. However, few studies have dissected the spatial suitability of land fallow in China, which would undermine the implementation of the land fallow system [13,19–21]. Thus, measuring of land fallow suitability in different regions become an important research agenda about cultivated land fallow systems [12,21]. The suitability evaluation of cultivated land fallow is based on spatial zoning through the Geographic Information System (GIS) platform and by comprehensively analyzing natural factors, socioeconomic factors, and location factors. The evaluation of the cultivated areas suitable for fallow usually depends on the degree of land suitability for cultivation. In areas with intensive tillage, measures for land fallow should be taken to restore soil fertility [13,22]. Currently, several researchers have measured the cultivated areas suitable for fallow based on administrative units using statistical data [19,20,23]. However, because statistical data cannot provide accurate spatial details, since these data sources are questionable, they fail to play a guiding role for related policies. To address this problem, studies have lately used high— to moderate—resolution remote sensing images to map out the spatial distribution of fallow on the scale of a village or town [13].

However, most of these studies focused on the evaluation of a single dimension of the environmental characteristics of cultivated land fallow, which cannot easily reflect the comprehensive conditions of cultivated land [24,25]. The choice of cultivated land fallow area is a multidimensional process with interactions among natural factors, socioeconomic factors, and location factors. Some studies have adopted multisource remote sensing images and other data to conduct suitability evaluations from a multidimensional perspective. For example, the suitability of cultivated land consolidation [26] and the quality of regional human settlements [27] have been evaluated. These factors made it possible to evaluate cultivated land from a multidimensional perspective using multisource images.

This study has two main aims: (1) Using multisource data to quantify the suitability of fallow land on a large scale from natural, social, and locational dimensions, and (2) evaluating the cultivated areas suitable for fallow over multiple scales. Specifically, this study presented the methods for developing an indicator aimed at the spatial suitability of fallow land in areas subjected to great environmental pressures. The indicator was developed for spatial ex—ante evaluations of fallow land in areas subjected to great environmental pressures, although it may also be used for other spatial evaluations, such as groundwater funnel areas and heavy metal pollution areas. The indicator was based on the relationships between cultivated land and natural, social, and location conditions. The index systematically quantifies and evaluates the cultivated areas suitable for fallow in different ecological regions to provide guidance for cultivated land fallow in China.

2. Study Areas and Data Sources

2.1. Study Areas

This study takes Chongqing as the study case. Chongqing is located in southwestern China within the upper reaches of the Yangtze River and the southeast Sichuan Basin. The study area crosses 105°11′–110°11′ E longitude and 28°10′–32°13′ N latitude and covers an area of approximately 8.24×10^4 km². The region is primarily hilly and mountainous, and karst landforms are widely distributed. In addition, the uneven seasonal distribution of rainfall and the spatial diversity of soil types contribute to cause strong regional and local soil erosion, debris flow, and other geological hazards [28]. Under the combined influence of various factors, the deterioration of the ecological environment, including soil fertility decline, soil erosion, and rocky desertification, has become increasingly prominent in the region. In addition, due to the flourishing nonagricultural economy and the continuous labor emigration, cultivated land has been seriously marginalized in Chongqing. To slow down the speed of cultivated land abandonment [29], the Pilot Project to explore the

implementation of a Crop Rotation and Cultivated Land Fallow System (PEICRCLFS) articulated the importance of cultivated land protection again and urged local governments and peasants to take actions. According to the PEICRCLFS proposed by the CPC Central Committee and the State Council in 2016, the karst rocky desertification area in Southwest China is a typical area of cultivated land degradation. Additionally, Chongqing is a key ecological construction area in the Yangtze River economic belt and should be a key area for cultivated land fallow [30].

To further effectively identify and evaluate the cultivated areas suitable for fallow in Chongqing, the whole city has been divided into six areas: Daba Mountain area in northeastern Chongqing (NE), Wuling Mountain area in southeastern Chongqing (SE), Yuzhong parallel ridge valley area (MC), urban main city area (UC), south—central mountain area (SC), and Chongqing western mountain and hilly area (WC) (Figure 1).

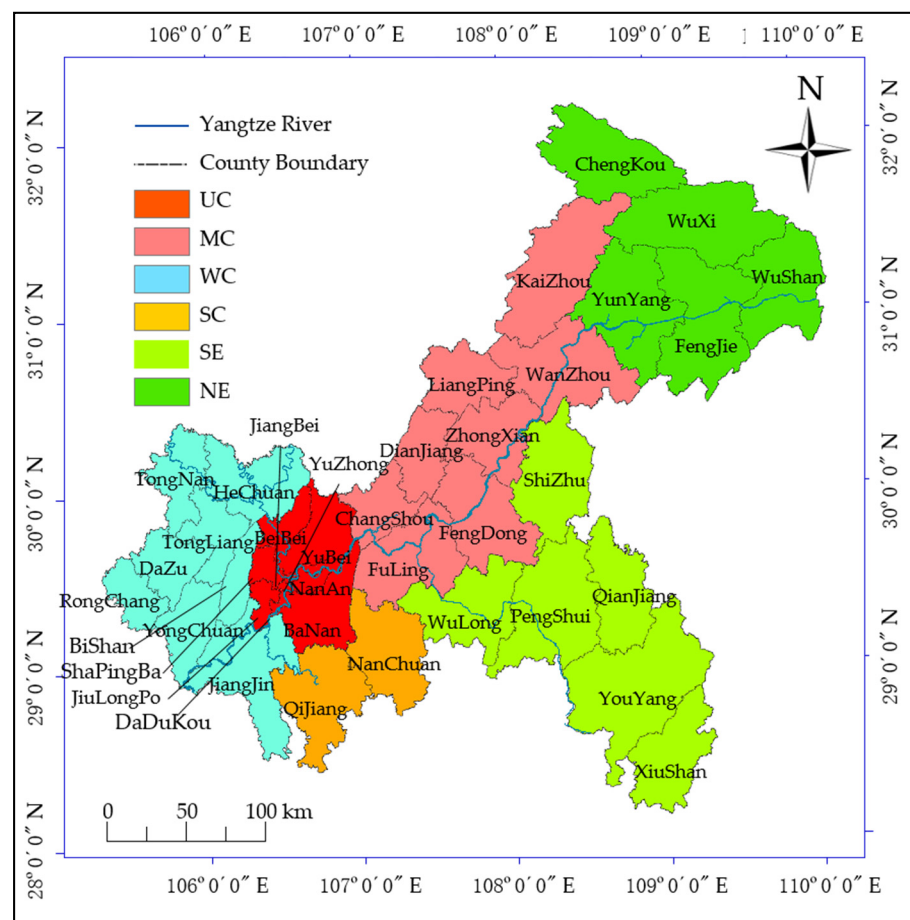


Figure 1. Spatial location of the study area. Note: UC represents the metropolitan region of Chongqing, MC represents the central region of Chongqing, WC represents the western region of Chongqing, SC represents the southern region of Chongqing, NE represents the northeastern region of Chongqing, SE represents the southeastern region of Chongqing.

2.2. Data Sources and Data Preprocessing

Land use/cover data, digital elevation model (DEM) data, karst area data, soil erosion data, precipitation data, temperature data, demographic maps, gross domestic product (GDP) data, nighttime light composite data from the Visible Infrared Imaging Radiometer Suite (VIIRS) Day–Night Band (DNB) carried by the Suomi National Polar—orbiting Partnership (NPP) Satellite, administrative boundaries, and statistical data were used in this study, and their basic information is showed in Table 1 and Figure 2.

Table 1. Basic information of the data used in this study.

Data Name	Data Description	Source
Land use/cover data	National land use/cover data with a spatial resolution of 30 m in 2015.	District and County Land Bureau in Chongqing
Digital elevation model (DEM)	Digital elevation data with a spatial resolution of 30 m in 2005.	Geospatial data clouds (http://www.gscloud.cn)
Karst area data	Vector files of karst areas for Southwest China in 2015.	Karst Scientific Data Center (http://www.karstdata.cn/)
Soil erosion data	Average annual soil erosion data was modeled at 30 m spatial resolution with different erosion types in 2010.	Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn/)
Temperature data	Average annual temperature data with a spatial resolution of 30 m.	RESDC (http://www.resdc.cn/)
Precipitation data	Average annual precipitation data with a spatial resolution of 30 m.	RESDC (http://www.resdc.cn/)
Gross domestic product (GDP)	Average annual GDP data with a spatial resolution of 1 km in 2015.	RESDC (http://www.resdc.cn/)
Demographic data	Average annual population data with a spatial resolution of 1 km in 2015.	RESDC (http://www.resdc.cn/)
National Polar—orbiting Partnership/Visible Infrared Imaging Radiometer Suite (NPP—VIIRS) nighttime light data	Annual nighttime light composite data with a spatial resolution of approximately 15 arc—seconds in 2015.	Earth Observation Group of National Oceanic and Atmospheric Administration’s National Geophysical Data Center (NOAA/NGDC) (https://www.ngdc.noaa.gov/eog/dmsp/downloadV4composites.html)
Statistical data	Annual statistical data at the prefecture level: total population (10^4) and production area of cultivated land (10^4 hm ²) in 2015.	Chongqing Statistical Yearbook
Administrative boundaries	Vector files of provinces and counties in Chongqing in 2015.	National Geomatics Centre of China (http://ngcc.sbsm.gov.cn/article/en/)

The land use/coverage data in 2015 were derived from the land use status of the District and County Land Bureau in Chongqing (Figure 2a).

The DEM data were downloaded from a geospatial data cloud and distributed jointly by METI (Japan) and NASA (USA). The data provide a major advancement in the accessibility of high—quality elevation data with a 1 rad/s spatial resolution (approximately 30 m) (Figure 2b).

The karst area data in 2015 were derived from the Institute of Geochemistry, Chinese Academy of Sciences. The data were interpreted based on Landsat—7 Enhanced Thematic Mapper Plus (ETM+) images (spatial resolution of 30 m). Taking into account the characteristics of the slope, soil cover, and vegetation, this study classified rocky desertification into four levels: class 0 (no rocky desertification), class 1 (mild rocky desertification), class 2 (moderate rocky desertification), and class 3 (intense rocky desertification) [31] (Figure 2c).

Soil erosion data were downloaded from the Data Centre for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC), and the amount of soil that was eroded and displaced per unit area and unit time was expressed by the soil erosion modulus. Soil erosion in Chongqing was mainly caused by hydraulic erosion according to the soil erosion classification and classification standard (SL190—2007). The erosion modulus was classified into six grades: no erosion (1), slight erosion (2), moderate erosion (3), high erosion (4), severe erosion (5), and very serious erosion (6) [32]. These grades can effectively represent soil erosion in Chongqing (Figure 2d).

The temperature and precipitation data were also downloaded from the RESDC. The data, which were obtained from 37 meteorological stations in Chongqing, were developed at a 30 m spatial resolution using Anusplin interpolation software [33]. The average annual precipitation data were produced from the arithmetic means of natural daily 24 h average precipitation (Figure 2e,f).

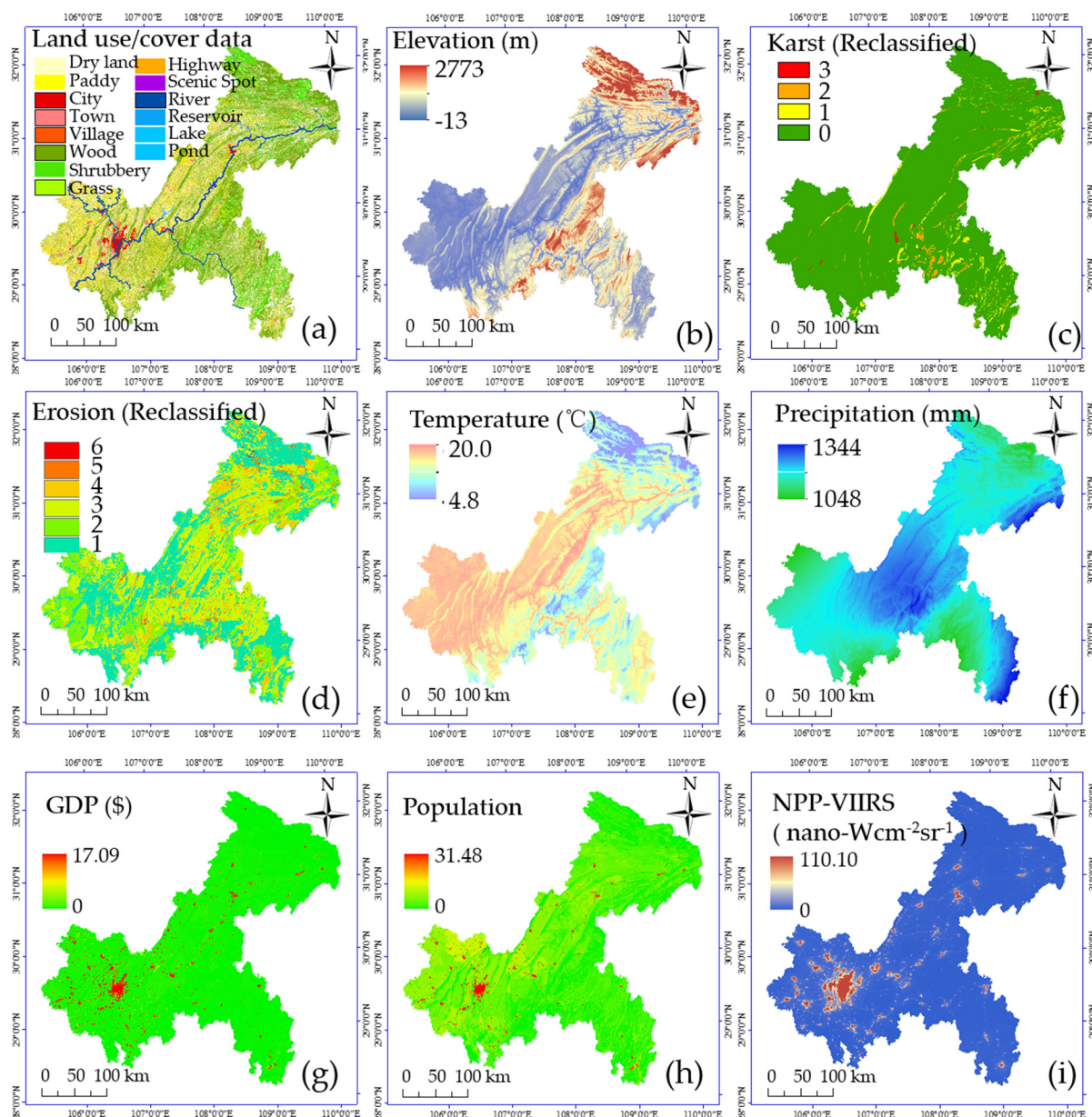


Figure 2. Spatial distribution of the data used in this study—(a) Land use/cover data; (b) Elevation; (c) Karst (Reclassified); (d) Erosion (Reclassified); (e) Temperature; (f) Precipitation; (g) GDP; (h) Population; (i) NPP-VIIRS. Note (Figure 2a): The second national land survey divides residential land into urban residential land (City), town residential land (Town), and rural residential land (Village) according to the urban–rural system.

On the basis of the county GDP statistical data (acquired from the RESDC), the data were calculated based on the weighting of various data in accordance with their influence. The spatial resolution of the statistical GDP data is 1 km (Figure 2g).

The demographic data were downloaded from the RESDC. Based on the land use type obtained from remote sensing imagery and demographic data, the spatial distribution model of demographic data was constructed by using the spatial analysis function of GIS. The spatial resolution of the statistical demographic data is 1 km (Figure 2h).

The NPP-VIIRS nighttime light data for 2015 were obtained from NOAA/NGDC (http://ngdc.noaa.gov/eog/viirs/download_viirs_ntl.html). The data mainly reflect stable lighting from rural areas and can be a powerful tool for modeling socioeconomic indicators [34,35]. The radiometric resolution is 14 bit with a spatial resolution of approximately 15 arc—seconds. (Figure 2i).

To ensure spatial consistency, all the spatial data were projected into an Albers Conic Equal Area Projection with reference D_Krasovsky_1940 and resampled to a spatial resolution of 30 m based on the nearest—neighbor resampling algorithm (excluding management boundaries).

3. Methods

The quantification and evaluation of the cultivated areas suitable for fallow in different ecological regions involve a complex and integrative process. Especially on a fine scale, the suitability is affected by natural and social factors, including topography, heat, population, and economy. The purpose of this study is to develop an index of cultivated land fallow (ILF) for the spatial evaluation of cultivated land, which considers several impact indicators. Generally, the ILF involves three major factors: natural, social, and location factors.

Specifically, natural factors mainly include two categories: the ecological environment and tillage quality [36,37]. The social factors are closely related to food security and represent an important foundation for the continuous and effective implementation of fallowing [38]. Location factors, including traffic conditions, affect the labor and transportation costs of inputs as well as the economic benefits and mechanization operations. When selecting single indicators, it is important to follow the principles of stability, dominant spatial variability, and accessibility of each index [39] (Figure 3).

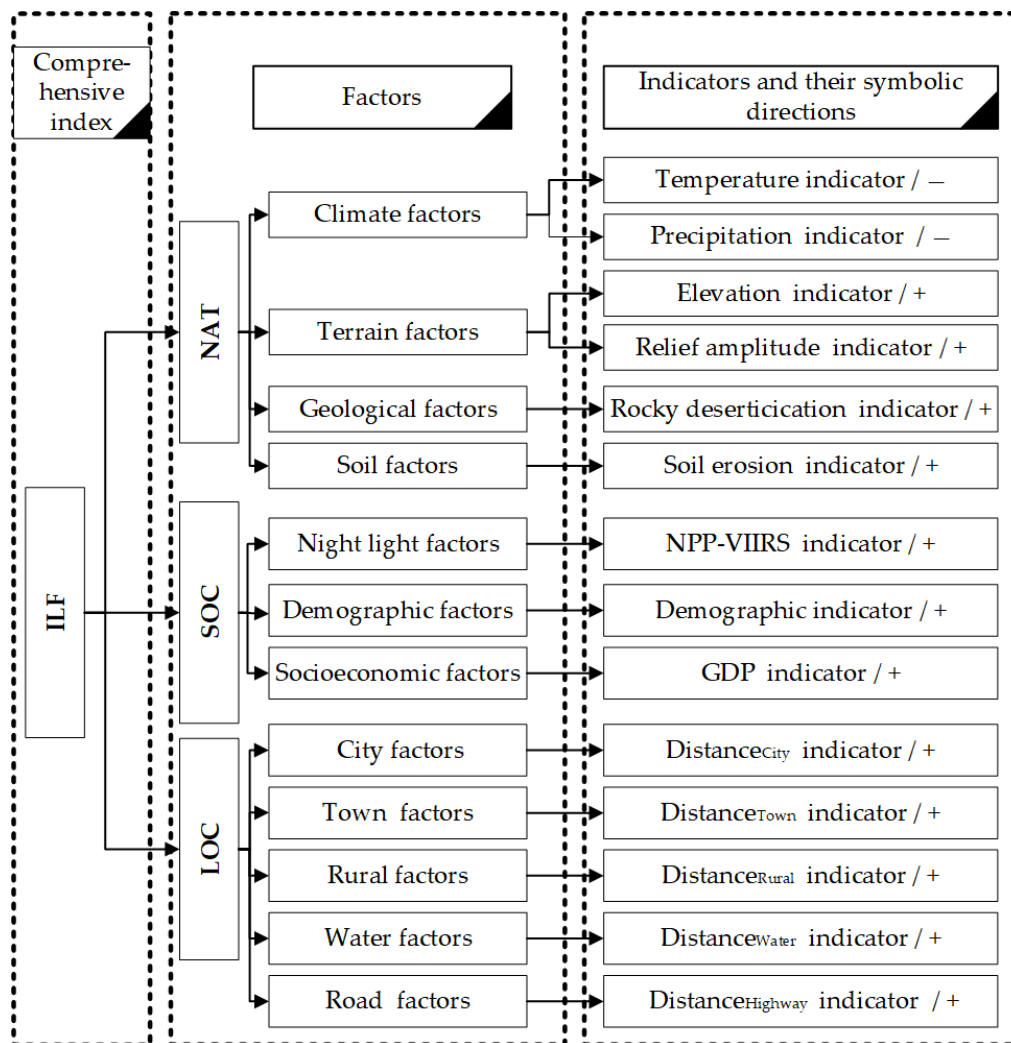


Figure 3. Cultivated land fallow index and its corresponding indicators. Note: NAT represents natural factors, SOC represents social factors, and LOC represents location factors. “+” represents a positive indicator. “—” represents a negative indicator.

3.1. Selection of the Suitability Evaluation Index for Cultivated Land Fallow

3.1.1. Natural Factors

The natural factors include climatic factors, terrain factors, rocky factors, and soil factors [40].

(1) Climate factors. These factors include temperature, precipitation, and other indicators. Among the climate factors, water and heat play decisive roles in the development and growth of organisms. These factors are stable and can represent the differences in a wide range of land natural production, which determines crop production. Therefore, indicators such as temperature and precipitation are not only prerequisites for agricultural production [41] but also basic factors for quality evaluation [42].

(2) Terrain factors. These factors include elevation and “relief amplitude” indicators and play an important role in the energy exchange of water and heat conditions in the region and directly affect soil formation and plant growth and development. Terrain factors largely determine the direction of land use and the development of cultivated land infrastructure, technological facilities for land transformation, and land development and utilization. Terrain factors are among the important factors for the suitability evaluation of cultivated land fallow [43].

The relief amplitude represents the height difference between the highest point and the lowest point in a specific area. This characteristic affects the production of cultivated land in the region. Compared with other indicators, the relief amplitude needs further preprocessing. In this study, the relief amplitude is calculated via a window analysis [44]. The formula is as follows:

$$RA_i = E_{max} - E_{min} \quad (1)$$

where RA_i represents the relative height difference in the window, with the i th pixel at the center; and E_{max} and E_{min} denote the highest and lowest points in the window, respectively [45]. In this study, based on a 30 m raster resolution, a window size of 0.56 km² is most appropriate [45].

(3) Geological factors. Ecological deterioration and environmental deterioration caused by rocky desertification lead to intensified soil erosion and reduced land resources for cultivation [46]. Karst landforms are widely distributed in Chongqing. Carbonate rocks are mainly distributed near the Daba Mountains in the NE and Wuling mountainous areas in the SE, and they account for 37% of the total area of Chongqing [47]. The demographic carrying capacity in karst areas makes them important areas for cultivated land fallow. Therefore, we adopted the rocky desertification indicator for representing the hilly characteristics in this study.

(4) Soil factors. Various soil factors are associated with soil nutrients and should be considered in cultivated land fallow. Soil type is also a reflection of the basic soil properties and fertility level [48]. The soil erosion process can directly affect the distribution of soil nutrients. Based on relevant research at the provincial scale and the data acquisition problem, we also adopted the soil erosion indicator to reflect the environment of cultivated land [49,50].

3.1.2. Social Factors

The social factors of cultivated land include demographic, GDP, and night lighting indicators [51–53].

(1) Demographic indicators. Demographic indicators are the main driver of land use and land cover change (LUCC), and they directly affect the spatial and temporal differentiation of LUCC [10,54–56]. Under the combined action of these factors, the decrease in cultivated land per capita will lead to the scarcity of cultivated land resources [57,58]. This condition directly affects the motivation of farmers in the region to practice cultivated land fallow [59].

(2) GDP indicator. Socioeconomic development has a significant impact on cultivated land change, and agricultural GDP has a significant positive impact on cultivated land [53]. A relatively high GDP is very helpful for farmers to choose economic crops [60]. At the

same time, the more developed the agriculture is, the more cultivated land is used for farming, the greater the load of cultivated land, and the stronger the demand for fallow.

(3) Nighttime light indicator. The nighttime light indicator can effectively reflect the social and economic activities of human beings. There are many quantitative analyses of the correlation between nighttime light data and socioeconomic parameters [61–64]. Human activity is key to the effective management of cultivated land fallow because nighttime lights are one of the major indicators of cultivated land fallow in Southwest China [19,35]. NPP–VIIRS has exhibited positive responses to regional GDP and electricity consumption of urban and rural residents, which can represent the impact of human activities [51,52].

3.1.3. Location Factors

The location factors of cultivated land include the distance from the city center, towns, rural settlements, highways, and water bodies [65–68].

(1) $Distance_{City}$ is the distance from the city center. There is a belt pattern around a city—centered agricultural location, and the distance to the city center is great [65,69]. During the rapid conversion of cultivated land in urban and suburban areas, very rare cultivated land resources are sufficiently used in modern agricultural production modes. The intensity of cultivated land use and the protection of cultivated land tend to increase with increased distance to the city center [70]. Therefore, in areas farther from the central urban area, cultivated land requires a higher fallowing degree.

(2) $Distance_{Towns}$ is the distance from towns. In the process of urbanization, the agricultural facilities of the cultivated land around towns are better than those far from towns [67]. At the same time, the development of regional agricultural modernization has increased the investment in agricultural infrastructure, and agricultural mechanization has gradually replaced manpower; thus, the production capacity of surrounding cultivated land has been improved [71]. However, some of the high—quality cultivated land has changed greatly; therefore, the cultivated land far from a town requires a high fallowing degree.

(3) $Distance_{Rural}$ is the distance from rural settlement areas. The difference in natural surface conditions in Chongqing is obvious. Not only is cultivated land fragmented, but rural settlements are also scattered. The distance between the cultivated land plots and the central rural settlement areas is also variable. Moreover, the difficulty of commuting and the cost of labor are also higher in rural areas. The relationship between the distance of cultivated areas from the rural settlements, and the rate of abandonment has been found through studies at the plot scale [29].

(4) $Distance_{Highway}$ is the distance from a highway. The construction and improvement of transport infrastructure not only promotes the adjustment of the planting structure in the region but also greatly reduces the influence of the geographical distance between the production land and the central consumer land on the choice of agricultural production space. A reasonable cultivation radius is also an important factor for farmers to decide whether fallowing is required. In modern agricultural development, under a higher level of agricultural mechanization, the degree of agricultural intensification increases correspondingly, and the degree of cultivated land conversion is high. Less distance to a road corresponds to a lower probability that farmers will implement fallowing; therefore, these areas are the less suitable for fallowing.

(5) $Distance_{Water}$ is the distance from water bodies. The advantage of a regional water source is high for cultivated land, the quality of the water environment is good, and the output quality of cultivated land is high [68]. Less distance to a water source corresponds to a lower probability that farmers will implement fallowing; therefore, these areas are less suitable for fallowing.

3.2. Measurement of the ILF

To ensure that the data of each indicator are comparable, it is necessary to carry out dimensionless processing of the original data of indicators. In this study, the deviation

normalization method was used to standardize the original data, and it is expressed in the following formula:

$$I_{ij} = b \times \frac{a_{ij} - \min_{ij}}{\max_{ij} - \min_{ij}} \quad (2)$$

where I_{ij} represents the normalized value of the i th indicator in the j th pixel and a_{ij} represents the value of i th indicator in the j th pixel. When the i th indicator is positively correlated with the suitability of fallow, the indicator is positive, and $b = 1$; when the i th indicator is negatively correlated with the suitability of fallow, the indicator is negative, and $b = -1$. The less water is available in the cultivated land, the more urgent the need is to fallow the cultivated land. Therefore, the precipitation indicator was regarded as a negative indicator.

The key challenge in performing spatial suitability evaluations of cultivated land fallow is how to integrate these indicators into the framework of a multidimensional system. Due to the complexity of the evaluation system and the uncertainties caused by the subjectivity of the weights of the factors [72], this study mainly adopted a geometric average method to evaluate the cultivated areas suitable for fallow, and it is expressed in the following formula:

$$\text{ILF}_{ij} = \sqrt[n]{\prod_{m=1}^n (I_{ij} + 1)} \quad (3)$$

where ILF_{ij} represents the comprehensive index in the j th pixel of the i th index, with the value from 1 to 2. The i th index includes the comprehensive index of natural factors (NAT), comprehensive index of social factors (SOC), comprehensive index of location factors (LOC), and comprehensive ILF. Moreover, NAT, SOC, and LOC were also calculated based on Formula 3.

According to the “land evaluation guideline” issued by the Food and Agriculture Organization (the FAO) in 1976, the Jenks method (natural split point method) was adopted to minimize the difference within a class; thus, the differences among classes were the largest. To diagnose and recognize areas for fallowing, cultivated land was classified into four categories: (1) highly appropriate fallow (HAF), under the current socioeconomic conditions, the ecological environment of such cultivated land is very poor, and the level of farming and utilization is low. In such areas, it is urgent to implement long-term fallow to improve the cultivated land fertility, and part of the cultivated land needs to be converted to cropland. (2) Moderately appropriate fallow (MAF), the ecological stress of cultivated land is high and the land is barely suitable for farming. However, due to the low level of farming and utilization, the quality of cultivated land is relatively low, and improper use is likely to cause soil degradation. (3) Lowly appropriate fallow (LAF), the quality of cultivated land is improved and the utilization of cultivated land is moderately suitable. The factors of the suitability evaluation of the natural, social, and location attributes of cultivated land are in an improved state. However, due to the decline of long-term tillage, it is necessary to implement moderate annual rest or seasonal fallowing. (4) Generally appropriate fallow (IAF), the quality of cultivated land is the best, and cultivated land is highly suitable. All the factors of cultivated land are in the best or improved condition. The sustainability of cultivated land is improved, and cultivated land can exhibit high productivity and location advantages and requires only intermittent annual fallow.

3.3. Validating the ILF

The accuracy verification of the ILF is an important step to evaluate the results of the ILF. Because China’s cultivated land fallow is still in the pilot stage, detailed large-scale fallow data are not available, and the simulation results cannot be evaluated at pixel resolution. Therefore, the accuracy of the ILF would be verified using Google Earth imagery and ecological environmental zoning control data. High-resolution remote sensing images can be used to clearly estimate or extract results [73]. These results can be effectively verified through Google Earth images. This study compares the cultivated areas

suitable for fallow by comparing Google Earth images of different ILF values in typical areas. In addition, according to the relevant documents of the CPC Central Committee and the State Council on *Strengthening the Protection of Ecological Environment and Resolutely Fighting Pollution Prevention and Control* and the opinions of the Chongqing Municipal People's Government on the implementation of the ecological protection red line and the bottom line of environmental quality, the establishment of ecological environmental access on the line and the implementation of ecological environmental zoning control are discussed. This process also meets the general requirements of implementing the ecological protection red line, the environmental quality bottom line, and the resource utilization line.

4. Results

4.1. Spatial Differentiation of the NAT Index in Chongqing

4.1.1. Spatial Differentiation of Natural Indicators

Figure 4 shows the spatial distribution of natural indicators of cultivated land in 2015. The values of natural indicators in NE and SE are significantly higher than those in UC and MC (Table 2). This difference is due to the Qinba Mountains to the north of the Yangtze River and the hilly area of the Wuling Mountains to the south of the Yangtze River. The elevation gradually decreases from the south to north in the Yangtze River Valley. Visually, pixels with high values are found in NE, and the elevation in the parallel ridge valley area of UC is the lowest, where the value is only 279 m (Figure 4a). NE has a higher relief amplitude, which reaches 383 m, and WC has the lowest relief amplitude, at 46.7 m (Figure 4b).

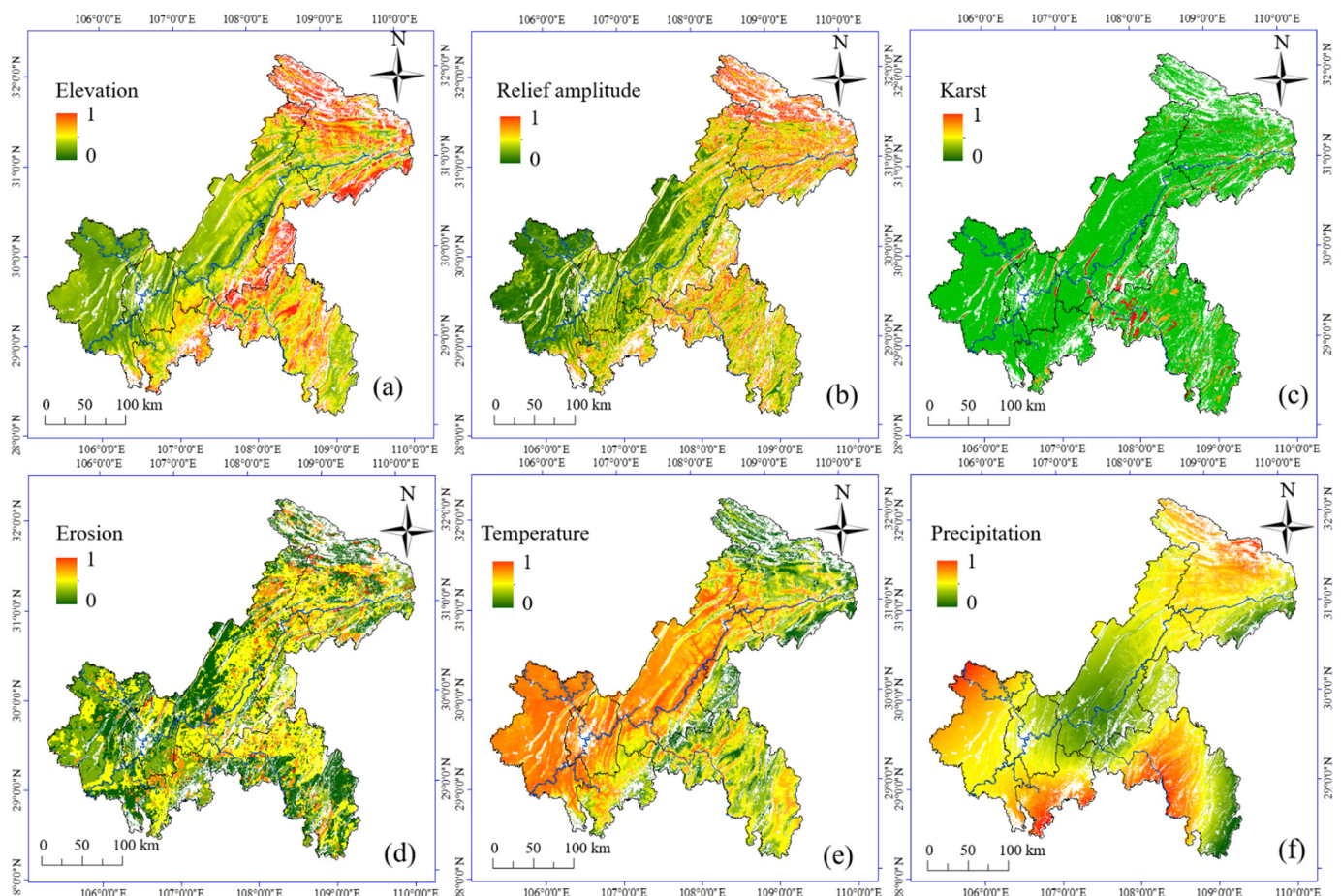


Figure 4. Spatial distribution of the indicators of the NAT index —(a) Elevation; (b) Relief amplitude; (c) Karst; (d) Erosion; (e) Temperature; (f) Precipitation. Note: Value = 1 express the most suitability to fallow.

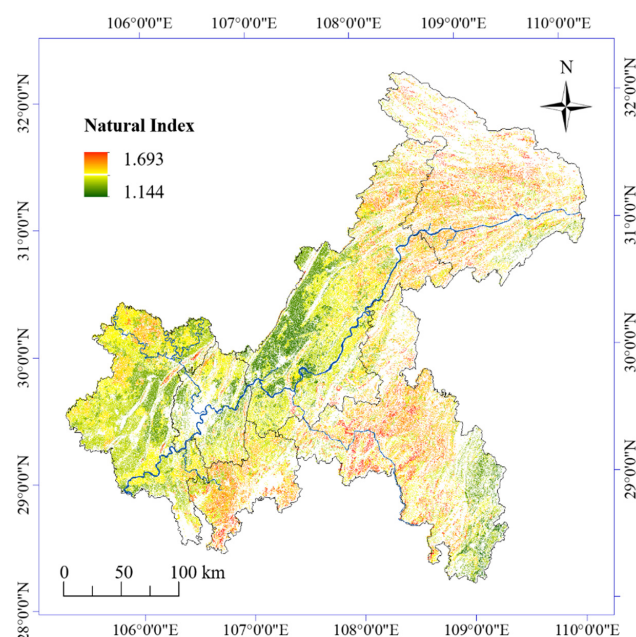
Table 2. Statistical table of the natural indicators. Note: the table shows the average statistical results of data in Chongqing.

No	Region	Elevation (m)	Relief Amplitude (m)	Karst Reclassify	Soil Erosion	Temperature (°C)	Precipitation (mm)
1	Urban area (UC)	399.16	130.06	0.04	2.02	18.23	1195.91
2	Northeastern area (NE)	847.18	286.23	0.08	2.28	14.14	1167.87
3	South—eastern area (SE)	753.70	218.85	0.14	2.25	15.50	1181.24
4	Southern area (SC)	683.97	187.40	0.04	2.28	16.06	1140.46
5	Western area (WC)	333.70	77.17	0.02	1.94	18.38	1150.42
6	Metropolitan area (MC)	517.83	153.05	0.06	2.36	17.23	1213.71

The present area of rocky desertification is 1.42×10^4 km² and is mainly distributed in SE and NE, where the values are 0.37 and 0.24, respectively (Figure 4c). The soil erosion of NE is the most serious, and the value reaches 2.81. The area of moderate soil erosion in Chongqing is distributed to different degrees and is concentrated along the Yangtze River. The values in SE and NE both reach 2.55. The area of slight soil erosion is mainly distributed in UC, where the value is only 1.28 (Figure 4d). Under the influence of topography and urban heat island effects, the temperatures of UC and WC are obviously higher than those of NE and SE. The temperature of UC is the highest and reaches 18.8 °C, while that of NE is the lowest at only 12.9 °C (Figure 4e). The precipitation in SE is obviously higher than that in UC, MC, and NE. The highest value of precipitation in SE reaches 1254 mm (Figure 4f).

4.1.2. Spatial Differentiation of the NAT Index

As a comprehensive indicator of the six natural indicators, the spatial distribution of the NAT in 2015 was obtained. The value was between 1.144 and 1.693, and the average value was 1.304. The cultivated land area above the average value accounted for 50.30% of the total cultivated land (Figure 5). The value of the NAT increased from UC to WC, MC, NE, and SE. The average value was 1.23, and the value in UC was 1.24. The lowest values appeared in the SE and NE, and their values reached 1.37 and 1.36, respectively. High values of the natural indicators appeared in the Daba Mountain and Wuling Mountain areas. This result is due to the poor natural environment of the cultivated land in the NE and SE mountain areas; therefore, the average values in those areas were 1.27 and 1.28, respectively. The internal dams, hills, and medium and low mountains are interlaced and affected by the central basin in SE. The cultivated land condition is relatively good, and the average value in SE is 1.22.

**Figure 5.** Spatial distribution of the NAT in Chongqing in 2015.

4.2. Spatial Differentiation of the SOC Index

4.2.1. Spatial Differentiation of Social Indicators

In 2015, the spatial distribution of the social indicators of Chongqing showed that the spatial difference of each indicator was obvious. The value of the social indicators in UC and WC was large, and in NE, the values in SE and MC were small and showed a decreasing circular pattern from the main city to the districts and counties and from the urban areas to the non—urban areas. Chongqing showed the same level of structure as the administrative level (Table 3 and Figure 6).

Table 3. Statistical table of the social indicators. Note: the table shows the average statistical results of the data in Chongqing.

No.	Region	Population	GDP (USD)	NPP-VIIRS
1	UC	1.09	0.22	1.40
2	NE	0.19	0.03	0.14
3	SE	0.17	0.04	0.19
4	SC	0.27	0.13	0.31
5	WC	0.66	0.16	0.49
6	MC	0.45	0.11	0.29

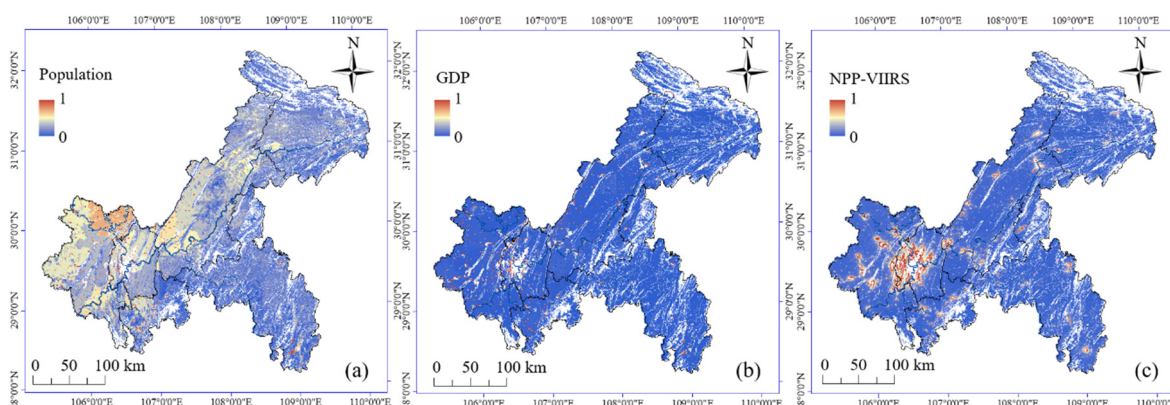


Figure 6. Spatial distribution of the social indicators in 2015—(a) Population; (b) GDP; (c) NPP-VIIRS.

The influence of the DEM indicators is the highest in UC, with a value of 0.99. However, SC and NE have the lowest values of only 0.13 and 0.10, respectively (Figure 6a). The same trend is observed for the influence of the GDP indicator, where the highest value is 0.48 in UC and the lowest values of 0.01 are observed both in NE and SE (Figure 6b). The nighttime light indicator is lowest in NE and SE at only 0.13 and 0.12, respectively (Figure 6c).

4.2.2. Spatial Differentiation of the SOC Index

Synthesizing the above three social indicators, Figure 7 shows the spatial distribution of the SOC in Chongqing in 2015. This figure shows that the value of the SOC ranges between 1.000 and 3.460, with an average value of only 1.031. In terms of the spatial distribution, 37.71% of the cultivated land area has an average value above the total cultivated land area. The value of UC is the highest, reaching 1.13. The values of SE and NE are the lowest at only 1.01. UC and WC are obviously superior to NE and SE. From the main urban ecological zone to the main new city area, NE and SE exhibit a descending pattern of SOC. At the same time, the value in each district—level city is obviously higher than that in the county—level cities, while the values in county—level cities are obviously higher than those in rural areas. There is a clear hierarchy of administrative levels. The spatial distribution of the night light index is greatly affected by the spatial layout of towns.

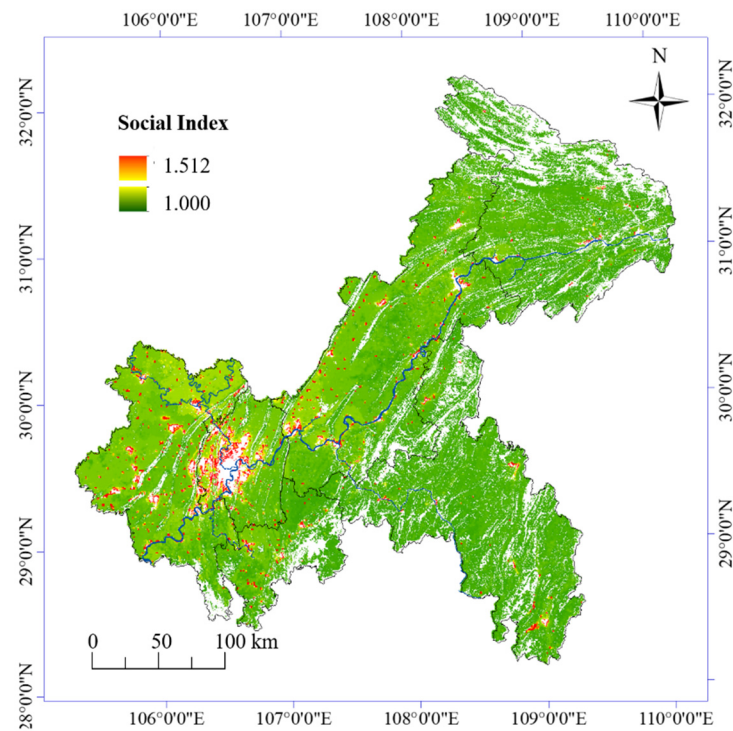


Figure 7. Spatial distribution of the SOC in Chongqing in 2015.

4.3. Spatial Differentiation of the LOC Index

4.3.1. Spatial Differentiation of Location Indicators

In 2015, the spatial distribution of the location indicators of Chongqing showed obvious spatial differences among each indicator (Figure 8 and Table 4). In addition to the core area of the main city, Chongqing has six major regions, namely, Wanzhou, Fuling, Jiangjin, Hechuan, Yongchuan, and Changshou. In 2015, the maximal value of Distance_{city} appeared in NE, which was 8.88 km, and the lowest value of 6.35 km appeared in another area (Figure 8a). The maximum value of the Distance_{town} indicator appeared in SE, which was 4.23 km, and the minimal value of 1.63 km appeared in UC (Figure 8b). The highest Distance_{Rural} value in Chongqing was also in SE, and the value was 177 m (Figure 8c). The distances of the cultivated land grids from the highway were also the highest in NE, where the value of the Distance_{Highway} indicator was 1.67 km (Figure 8d). The distance of each cultivated land pixel from water was highest in SE, where the value of the Distance_{Water} indicator was 1.05 km (Figure 8e).

Table 4. Statistical table of the location indicators. Note: the table shows the average statistical results of data in Chongqing.

No.	Region	City (m)	Town (m)	Rural Settlement (m)	Highway (m)	Water (m)
1	UC	6350.97	1625.24	86.40	933.55	311.26
2	NE	88,817.47	3893.24	113.48	1670.71	832.00
3	SE	51,756.42	4231.29	177.25	1545.64	1054.60
4	SC	18,990.47	2048.83	110.05	1074.26	484.89
5	WC	18,366.36	2095.95	79.48	1002.02	235.18
6	MC	29,614.67	2284.04	100.60	1039.88	354.12

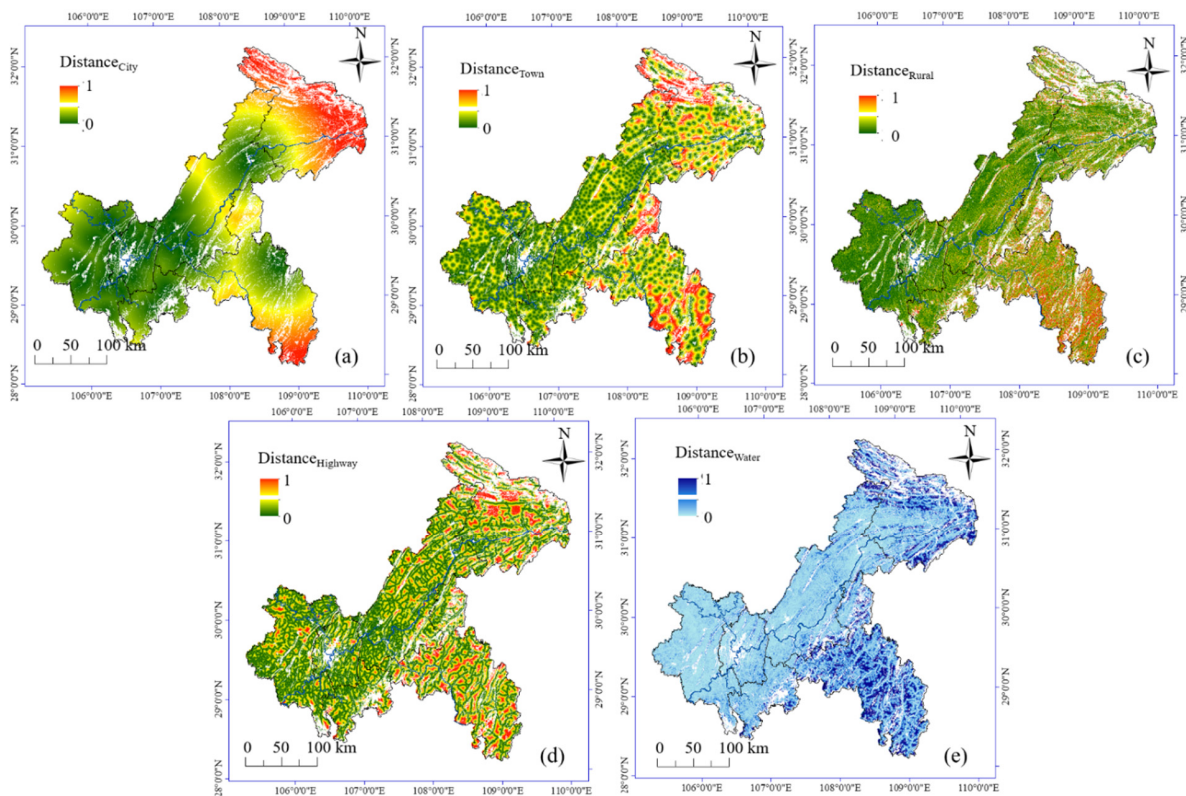


Figure 8. Spatial distribution of the location indicators in 2015—(a) Distance_{City}; (b) Distance_{Town}; (c) Distance_{Rural}; (d) Distance_{Highway}; (e) Distance_{Water}.

4.3.2. Spatial Differentiation of the LOC Index

Based on the above five location indicators, the spatial distribution of the LOC index in Chongqing in 2015 was obtained (Figure 9). The quantified value was between 1.000 and 1.667, and the average value was 1.098. The cultivated land area above the average value accounted for 39.51% of the total cultivated land. The spatial distribution indicated that the location conditions of the NE and SE ecological zones were the weakest, with a value of 1.22. The location indicators of cultivated land in UC were the best, with a value of 1.02.

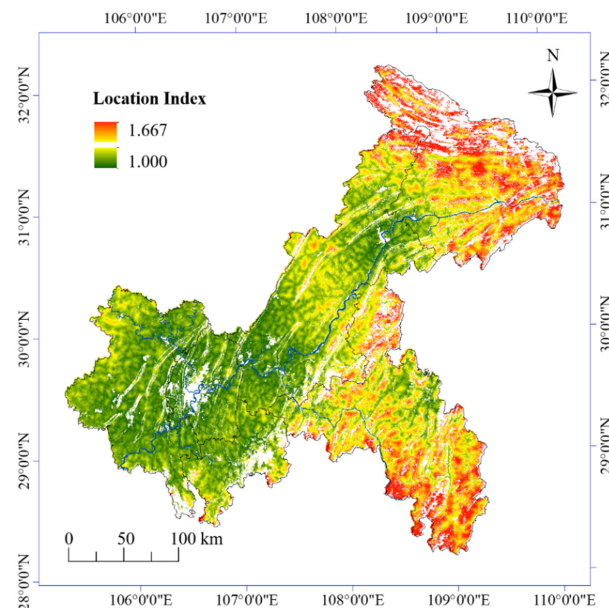


Figure 9. Spatial distribution of the LOC index in Chongqing in 2015.

4.4. Spatial Differentiation of the ILF

Based on the results of the three comprehensive indexes of the NAT, SOC, and LOC, Figure 10 reflects the spatial distribution of the ILF in Chongqing in 2015. Cultivated land with values above and below the average value accounts for 34.38% and 65.62% of the total cultivated land, respectively. The results showed that the comprehensive quality of cultivated land was generally high, although the difference in the local spatial distribution was large.

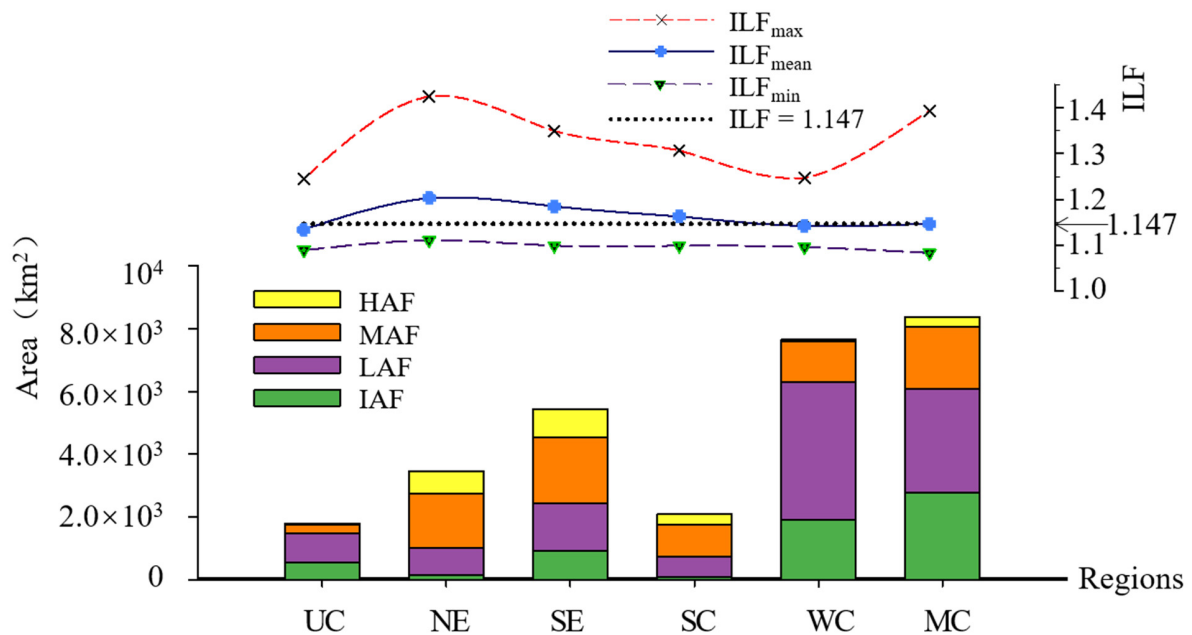


Figure 10. Distribution of the index of cultivated land fallow (ILF) in different regions in Chongqing in 2015. Note: UC represents the metropolitan region of Chongqing, MC represents the central region, WC represents the western region, SC represents the southern region, NE represents the northeastern region, and SE represents the southeastern region. The average value is 1.147, and values above the average value account for 34.38%. The comprehensive quality of cultivated land was generally high, although the difference in the local spatial distribution was large.

At the regional scale, the IAF was concentrated in MC and WC, whereas the HAF was mainly located in SE, SC, and NE. Theoretically, a large amount of cultivated land should be prioritized for fallowing (Figure 10). Specifically, a large part of cultivated land related to HAF (2375 km²) accounted for 8.24% of the total cultivated land (28,802 km²) in Chongqing in 2015. The cultivated land exhibiting IAF accounted for 22.34% (6434 km²) of the total cultivated land, and that exhibiting LAF accounted for 40.32% (11,614 km²). Moreover, the MAF and HAF represented 29.09% (8379 km²) and 8.24% (2375 km²) of the total cultivated land, respectively (Figure 10 and Table 5).

An obvious gradient in cultivated land fallow was identified at the regional scale (Figure 8b). HAF and MAF were the dominant types in NE, SE, and SC, whereas IAF and LAF were the dominant types in UC, WC, and MC. In NE, the sum of HAF and MAF generally covered 70.24% (2430 km²) of the total cultivated land (3459 km²) in 2015, with the sum of IAF and LAF accounting for 29.75% (1029 km²) of the total cultivated land. The HAF accounted for 20.84% (721 km²) of the total cultivated land. In SE, more than 912 km² was related to the HAF, which accounted for 16.78% of the total cultivated land (5434 km²). Correspondingly, the percentage of MAF was 38.23% (1509 km²) in 2015. By comparison, the cultivated land showing LAF and IAF covered 27.77% (936 km²) and less than 17.22% (936 km²) of the total cultivated land, respectively. In SC, HAF and MAF account for 15.84% (331 km²) and 49.32% (1029 km²) of the total cultivated land (2087 km²), respectively. In addition, the LAF and IAF accounted for 30.86% (644 km²) and only 3.98% (83 km²) of the total cultivated land, respectively.

Table 5. Statistics of the index of cultivated land fallow (ILF) in Chongqing in 2015. Note: UC represents the metropolitan region of Chongqing, MC represents the central region, WC represents the western region, SC represents the southern region, NE represents the northeastern region, and SE represents the southeastern region. HAF and MAF were the dominant types in NE, SE, and SC, whereas IAF and LAF were the dominant types in UC, WC, and MC.

County	IAF		LAF		MAF		HAF		Total (km ²)
	Area (km ²)	Percent (%)	Area (km ²)	Percent (%)	Area (km ²)	Percent (%)	Area (km ²)	Percent (%)	
UC	568.23	31.66	909.82	50.69	290.54	16.19	26.15	1.46	1794.74
NE	157.90	4.56	871.24	25.19	1708.96	49.40	721.02	20.84	3459.13
SE	935.80	17.22	1509.23	27.77	2077.30	38.23	911.67	16.78	5434.00
SC	83.18	3.98	644.18	30.86	1029.42	49.32	330.64	15.84	2087.41
WC	1907.23	24.93	4379.16	57.24	1297.08	16.95	66.87	0.87	7650.34
MC	2781.20	33.20	3300.80	39.41	1976.18	23.59	318.36	3.80	8376.54
Total	6433.54	22.34	11,614.42	40.32	8379.48	29.09	2374.73	8.24	28,802.17

In WC, more than 4379 km² was related to the MAF, which accounted for 57.24% of the total cultivated land (7650 km²). However, the MAF and HAF accounted for only 0.87% (67 km²) and 16.95% (1297 km²), respectively. We found that MC had a relatively high percentage of IAF (33.2%, 2781 km²). Moreover, in MC, the LAF, MAF, and HAF accounted for more than 39.41% (3301 km²), 23.59% (1976 km²), and 3.8% (318 km²) of the total cultivated land (8377 km²), respectively. In UC, the total area of cultivated land was only 1795 km², and the dominant types were the IAF and LAF, accounting for 31.66 (568 km²) and 50.69% (910 km²), respectively. In contrast, the HAF and MAF accounted for only 1.46% (26 km²) and 16.19% (291 km²), respectively (Table 5).

5. Discussion

5.1. Validation of Results

To verify the accuracy of the results, a stratified random sampling method was adopted in this study [28]. Figure 11 shows the spatial distribution of the ILF and a comparison of the results of 8 random points. A visual comparison showed that the IAF was mainly located near rural settlements or water bodies. The LAF was located near cultivated land that is suitable for mechanized farming, near rural settlements, and far away from the highway or a city. The MAF was distributed at high elevations and in areas with high relief. The HAF of cultivated land is more severe than rocky desertification, the peripheral 500 m has few settlements, and the terrain is undulating. Moreover, the distance from cities, water bodies, and highways is long; thus, cultivation is difficult for residents. Therefore, cultivated land is not suitable for long-term farming, and years of laying fallow or conversion of cultivated land to forests is required.

Figure 11 shows that high ILF values are mostly distributed in steep terrain or in areas with severe rocky desertification, inconvenient transportation, low population, and poor productivity. Low ILF values are in areas that are relatively flat and with generally developed road infrastructure. The above analysis results are basically consistent with previous studies [19,20,74]. The corresponding cultivated land in areas with very complex terrain should be prioritized for fallowing. In contrast, low ILF values are mainly distributed in plains areas, where there are convenient transportation and water resources. Therefore, if these areas adopt reasonable farming practices, sustainable agricultural production can be carried out. These comparative results show the effectiveness of ILF in simulating cultivated land fallow. The ILF can reflect the spatial distribution of the suitability of cultivated land for fallowing to a certain extent.

In addition, by comparing the distribution map of environmental management and control units in Chongqing, this study compares the results of the spatial suitability evaluation of cultivated land fallow in Chongqing with the ecological control units, as shown in Figure 12. The priority protection units are mainly in the main urban area, the Three Gorges Reservoir Area in NE, and the Wuling mountainous town group in SE. In these areas, the ILF value is high, and the total HAF and MAF share is 55.54%. Thus, these areas are the key areas for fallowing. This result is consistent with the implementation of the red line of ecological protection, the bottom line of environmental quality, and the hard constraints on

the utilization of resources. The IAF and LAF in the key control areas accounted for 48.56% and 41.52%, respectively, and the ILF value of the general control was generally low. These areas require the conservation of resources and protection of the ecological environment, which can be accomplished by adjusting the industrial structure and changing the mode of production. Moreover, the main farming approach should be green development, which is consistent with the evaluation results of the ILF.

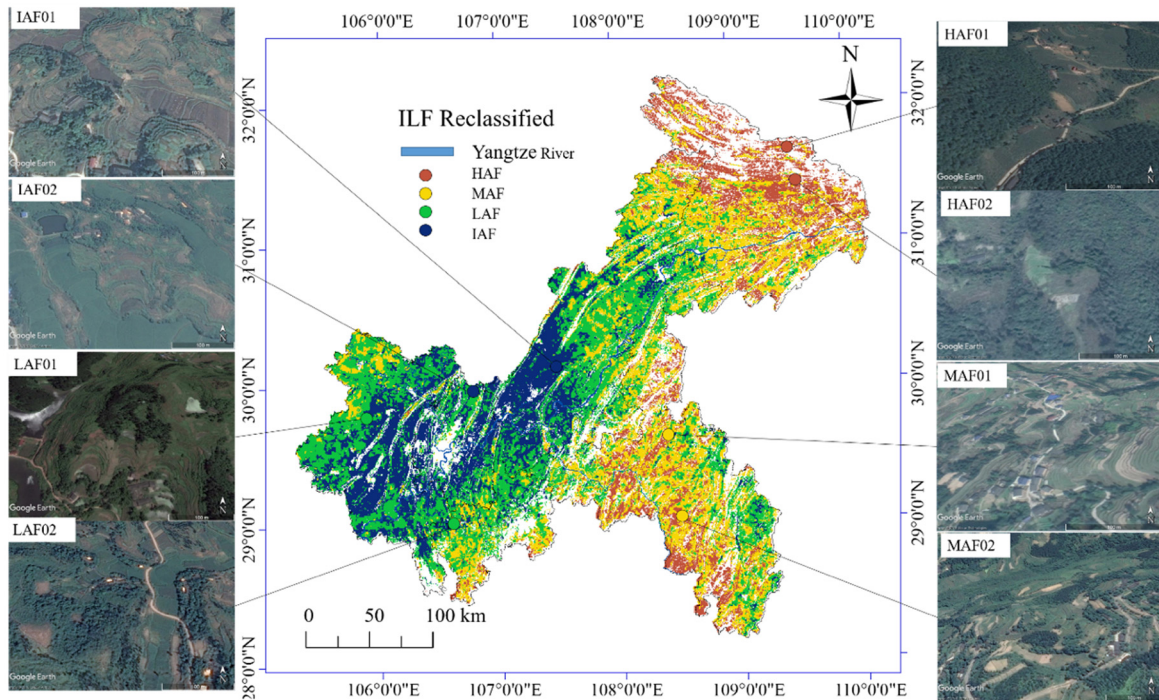


Figure 11. Spatial verification of the ILF using Google Earth imagery in Chongqing. Note: high ILF values are mostly distributed in steep terrain or in areas with severe rocky desertification, inconvenient transportation, low population, and poor productivity. Low ILF values are relatively flat, with generally developed traffic and more villages.

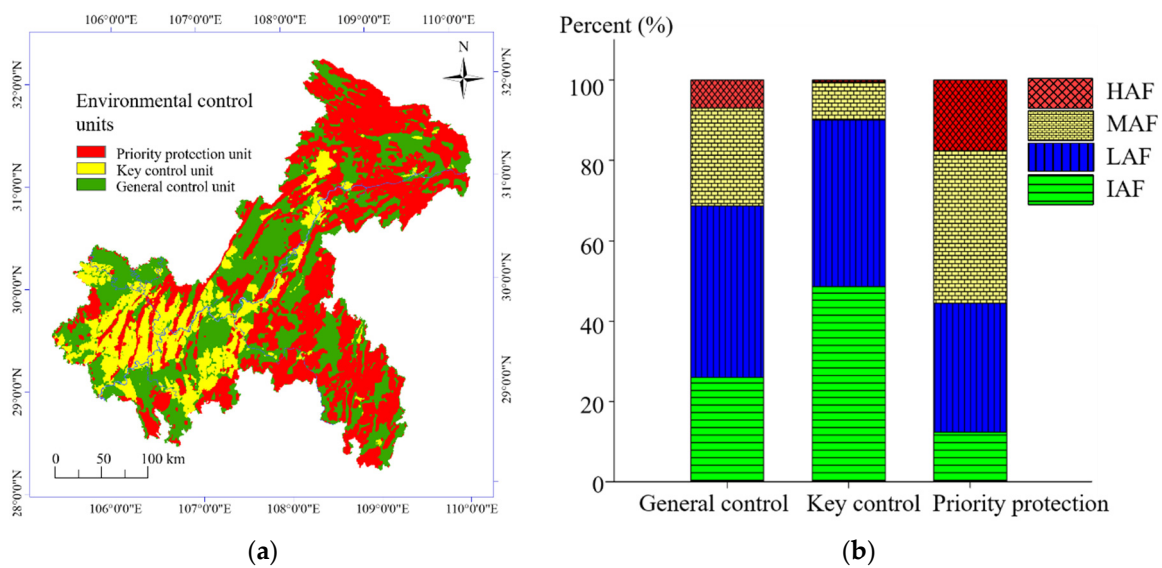


Figure 12. (a) Spatial distribution of environmental control units and (b) ecological management vs. ILF. Note: (a) is from the Chongqing Ecological Environment Bureau. Based on the comparison of the environmental control unit and ILF, the ILF value in the priority protection units is high, and these areas are the key areas for following.

Considering natural factors, social factors, and location factors of cultivated land, this research can provide insights for evaluating the cultivated areas suitable for fallow. However, the scale of cultivated land fallow should not only be analyzed from the perspective of ecological security but also needs to be further explored from the aspect of food security. Appropriate adjustments should be made according to the local composition and geological background data of cultivated land. With the advancement of micro— and macro—scale research, developing a more comprehensive index system for suitability evaluations for fallowing is a key issue for future research.

5.2. Spatial Variation of Cultivated Land Fallow in Chongqing

Yang et al. have identified the spatial characteristics of food security to suggest the suitability of cultivated land for fallow [20], but it is in the provincial and prefecture level. This study, however, used higher—accuracy data to dissect the spatial features of fallow suitability in one provincial level region. To be specific, the NAT was significantly affected by the Dabashan and Wuling Mountains and the parallel ridge valleys of eastern Sichuan. The cultivated land area above the average value accounted for 50.30% (14,487 km²) of the total cultivated land, and there were 16 districts and counties above the average value. The spatial differentiation from the west—central area to the northeast indicates that the terrain indicators and climatic indicators in the main urban ecological area and the main urban area were significantly higher than those in NE and SE. The topography is high in the southwest part and it low in the northeast and central basin; therefore, the cultivated land conditions are relatively good in Xiushan.

The evaluation results of the SOC index showed that the areas above the average value accounted for 37.71% (10,867 km²) of the total cultivated land, and there were 23 districts and counties above the average value. The values in each district level were significantly higher than those in the county—level cities, while the values in the county—level cities were significantly higher than those in the rural areas. The main urban ecological zone was the best in the Dadukou district and the south bank area, followed by the Fuling district in the main urban area, the Wanzhou area in the Three Gorges Reservoir area of NE and the Wuling Mountain Ecological Area in southeastern Chongqing. The value of the night light indicator was highest in UC, MC, and WC, whereas the value was lowest in NE and SE.

The LOC index is greatly affected by the main urban ecological zone and the new urban area. The cultivated land area with above—average values accounts for 39.51% (11,380 km²) of the total cultivated land. The LOC in UC is the highest, followed by WC, MC, SC, SE, and NE. The worst conditions are observed in the Three Gorges Reservoir Area in NE.

The ILF is used for spatial suitability evaluations of cultivated land fallow and integrates natural, social, and location indicators. A higher ILF value corresponds to a greater possibility of fallowing in a given area. From the spatial distribution, the cultivated land areas above the average value account for 34.38% (9902 km²) of the total cultivated land. The cultivated land with high ILF values is mainly concentrated in the ecological area of the Three Gorges Reservoir Area in NE and some parts of the Wuling Mountain Ecological Area in SE. Cultivated land with high ILF values exhibits lagging economic and social development, inconvenient transportation, a limited population, and a large proportion of sloping cultivated land.

5.3. Limitations and Future Perspectives

Although this study provides a scientifically based methodology to spatially locate the cultivated areas most suitable for fallow, a few limitations remain. Firstly, some of the data used in this study were derived from statistical data, and the accuracy of them have a considerable influence on the results of the suitability evaluation of cultivated land fallow. The indicator system for the suitability evaluation of cultivated land is not perfect. At the pixel scale, the grain yield indicators need to be included in subsequent studies. Secondly, the research on the suitability evaluation of cultivated land fallow in China is in the initial

stage, and Chongqing has not yet been included in the pilot area of national fallow. Due to the insufficiency of data for consistency testing, the research results can be verified only by Google Earth images in 2015 and ecological environment zoning data in Chongqing. Thirdly, land erosion causes a decrease in the soil fertility, and they are not able to include soil fertility in the Land capability GIS layer due to the lack of data.

In the future, more attention should be paid to the identification of the interests of fallow land holders and the analysis of the role and function of stakeholders, and their action mechanism. By doing so, we could summarize the factors influencing the implementation of fallow policy and then formulate an evaluation index system for the implementation of fallow policy. Due to the promotion of the construction of the Chengdu—Chongqing Economic Circle and the coordinated development of “one district, two groups”, the problem of cultivated land occupation and land degradation seem to most likely remain, and the amount of cultivated land is bound to decrease. However, this decrease will not have an essential impact on the evaluation results of the cultivated areas suitable for fallow in Chongqing.

6. Conclusions and Policy Implications

This study attempts to quantify and evaluate the cultivated areas suitable for fallow in Chongqing, China. First, we developed the ILF for mapping cultivated land fallow through the integrated use of natural indicators (DEM, slope, relief amplitude, precipitation, temperature, rocky desertification, soil erosion), social indicators (demographic, night light, GDP), and location indicators (water resources, central cities, towns, highways, rural settlements). Second, the spatial suitability degree of fallow land was systematically assessed in Chongqing. With respect to cultivated land, the ILF can reflect the spatial distribution of the degree of cultivated land fallow suitability.

A fallow area consist of small fallow land plots. The technology for the evaluation of the suitability of fallow space is intended to optimize the configuration and form of fallow land by using certain rules and to improve the layout efficiency of fallow space. This process can be optimized through the following aspects. First, according to the physiognomy type and ecological zoning, the applicability of fallow space suitability evaluations for the protection of fragile ecological environments can be improved. Second, the size of a single fallow plot in plains areas should be different from that in hilly and mountainous areas. Moreover, differences should be considered between karst areas and non—karst areas, and the designation of fallow land should be adapted to local conditions. Third, fallow areas should be linked to ecological priority protection areas, such as water source protection areas and forest parks. Compulsory fallowing should be carried out in areas between protected areas, and a certain distance of cultivated land should be maintained from protected areas. Considering that the ILF reflects the urgency of cultivated land fallow at the pixel scale, the ownership of cultivated land at the same level is often variable and lacks regularity. The optimization of fallow area space based on the ILF and actual regional fallow scale can enable a reasonable fallow period and will not bother the local social and economic development.

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Abbreviations

RESDC	Center for Resources and Environmental Sciences of the Chinese Academy of Sciences
NE	Northeastern region of Chongqing
SE	Southeastern region of Chongqing
MC	Midlands region of Chongqing
UC	Metropolitan region of Chongqing
WC	Western region of Chongqing
SC	Southern region of Chongqing
ILF	Comprehensive index of cultivated land fallow
NAT	Comprehensive index of natural factors
SOC	Comprehensive index of social factors
LOC	Comprehensive index of location factors
HAF	Highly appropriate cultivated land fallow
MAF	Moderately appropriate cultivated land fallow
LAF	Lowly appropriate cultivated land fallow
IAF	Inappropriate cultivated land fallow

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