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Suitability Evaluation and Engineering Matching for Agricultural Development of Barren Grassland in Mountainous Area: A Case Study of County Scale

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Abstract: Barren grasslands are an important reserve resource of cultivated land in mountainous areas. The exploitation of barren grassland for agricultural use has played a role in ensuring food security and people's livelihood in many countries and regions. The suitability evaluation of agricultural-use development, based on the conditions of barren grassland itself and the engineering matching, can not only ensure the sustainable development of agriculture but also avoid the ecological negative effects caused by excessive engineering. According to the research, the agricultural development of barren grassland needs to be evaluated from the two angles of natural suitability and engineering suitability, and an innovative "index level serial number summation method" is proposed. The suitability of barren grassland for agricultural use development was divided into three categories: barren grassland suitable for cultivation, barren grassland suitable for forestry, and barren grassland suitable for prataculture. The barren grassland suitable for cultivation was selected for type division and engineering-accurate matching. Taking Tang County as a research area, an example was provided through a combination of theoretical research. According to the characteristics of barren grassland in Tang County, the evaluation indexes of natural suitability and engineering suitability were selected, and the suitability of barren grassland for agricultural development was evaluated and graded. A classification system for the utilization of barren grassland suitable for cultivation is constructed, the required engineering types are explored to eliminate the main limiting factors, and the utilization types are matched with the engineering combination types. The barren grassland suitable for cultivation in the study area can be divided into 37 types, which can match eight engineering combinations. This study proposes a systematic method for the identification, classification, rating, and engineering matching for arable land reserve resources. The study can provide the basis for the effective utilization and accurate development of land resources.

Keywords: barren grassland; suitability evaluation; type division; engineering matching; Tang County

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1. Introduction

Barren grassland is a valuable and widely distributed arable land reserve resource in mountain area. Barren grassland refers to barren and semi-barren land resources that are covered by herbaceous and stunted brushwood and non-utilized or underutilized due to the current economic and technological level. According to China's land use classification system, barren grassland refers to non-grazed grassland with surface soil and herbaceous plants as well as a canopy density of less than 10% [1]. The scientific development of barren grassland is conducive to national food security. China and many developing countries and regions are in a critical development stage, and the demand for construction land is increasing, thus leading to a growing contradiction between food production and development [2–4]. Developing barren grassland is an important way to alleviate the contradiction.

The rational development of barren grassland can reduce ecological risks. Barren grassland generally has a thin soil layer and significant differences in terms of the weathering degree of the bedrock, the thickness of the weathered layer, the nutrient content of weathered products, and the vegetation coverage. The extensive development of barren grassland is prone to lead to ecological risks, such as soil erosion, drought, and loss of biodiversity [5–7]. Accurate engineering matching based on the suitability of barren grassland development is helpful to reduce ecological risks and promote the sustainable use of land resources. The efficient utilization of barren grassland can promote poverty alleviation and rural revitalization. Mountain areas generally have abundant barren grassland resources and are characterized by relatively concentrated poverty. For example, there are 25 poverty-stricken counties in the Yanshan-Taihang Mountain in Hebei Province, China. After the release of Opinions of the Central Committee of the Communist Party of China and the State Council on Strengthening the Protection of Arable lands and Improving the Balance of Land Occupation and Compensation (2017) [8], the task of balancing the occupation of arable lands with compensation can be completed across different regions, thus giving the priority to poverty-stricken areas. The implementation of a rural revitalization strategy requires huge investment, and arable lands transformed from barren grassland can bring huge benefits to the local community and rural revitalization [9,10]. In 2019, the IPCC released the “Special Report on Climate Change and Land”, which elucidated the complex relationship between climate change and land. Climate change has put additional pressure on land, exacerbating existing risks to livelihoods, biodiversity, human and ecosystem health, infrastructure, and food systems [11]. In the context of enhancing human well-being and addressing the challenges of climate change, higher demands have been placed on changing land use patterns. Overexploitation of land resources is one of the key driving factors of climate change [11,12]. The development of barren grassland into farmland is a strong interference and change to the original ecosystem and its utilization methods, and this activity process is also accompanied by a large amount of engineering investment. Evaluating the suitability of development based on the natural endowment of barren grassland resources and matching differentiated development projects can avoid ecological problems caused by blind development and reduce project investment, which is a positive response to sustainable land use and management.

The classification system of barren grassland is not available globally [13,14], yet similar classification systems of mountains and slopes have been proposed in developed countries. In the middle and late twentieth century, countries with limited land resources, including Italy, the Netherlands, Switzerland, South Korea, and Japan, conducted an in-depth study on the feasibility and sustainability of mountain resource development from the perspective of ecological environment [15–17]. Some countries have formed a fixed theoretical system for the development and utilization of land resources in mountain area and mountain ecological protection and accumulated some successful experiences [18]. Funded by the United Nations Educational, Scientific and Cultural Organization, the International Mountain Society was established in 1980 to guide the research and development of mountainous regions. In 1983, the International Mountain Comprehensive Development Center was established to provide services and assistance for the comprehensive development and sustainable utilization of mountainous regions [19]. The comprehensive studies on mountain area in China were mainly performed from two aspects. Firstly, the ecological and environmental problems related to the development and utilization of these areas [20,21]. Secondly, there was an exploration of development suitability and sustainability based on the theory of landscape ecology as well as the experiences in mountain area development and construction [22,23]. While many countries have conducted beneficial explorations on mountain areas, the constituent elements of the classification system remain obscure. Most studies [17,24–30] on barren grassland were included in the overall study on mountainous areas, and the related results are not applicable to barren grassland.

In this study, through field investigation and data collection, a simple and objective evaluation system of mountainous barren grassland was proposed. The classification system of utilization types of barren grassland was established, the method for matching utilization types of barren grassland with development engineering was preliminarily clarified, and Tang County is taken as an example. This study can provide a systematic method of investigation, evaluation, and accurate development of arable land reserve resources for the precise development and utilization.

2. Materials and Methods

2.1. Study Design

The development of barren grassland is a systematic project involves natural factors and engineering factors and can be expressed as:

$$K = F(Z, G) \tag{1}$$

where K is the land development system; Z is the natural factor influencing land development; and G is the engineering factor influencing land development.

The natural suitability of agricultural use refers to the degree of land suitability for agricultural uses under various conditions. The natural suitability to agricultural use is the basis for ensuring the safety and effectiveness of resource utilization. The higher the suitability degree is, the lower the probability of reclaimed lands to be degraded is [31,32]. Agricultural engineering suitability refers to the suitability of environmental conditions, which includes land conditions and water source distance to agricultural engineering. The suitability of agricultural engineering is a prerequisite for ensuring the availability of resources. The higher the level of the suitability of agricultural engineering, the less difficult the engineering operation is [33].

Therefore, the evaluation of the suitability of barren grassland development needs to be measured from the two aspects of natural suitability and engineering suitability. The evaluation indexes and grades are selected. The natural suitability evaluation, engineering suitability evaluation, and agricultural development suitability evaluation are carried out in combination with the "index grade sequence number addition method". The barren grassland is categorized into three types based on their suitability: for cultivation, for forestry, and for prataculture. The barren grassland suitable for cultivation is selected, and the barren grassland is classified for development and utilization according to the main factors of engineering transformation. Following this classification, the development project combinations and matchings are carried out according to the development and utilization classification (Figure 1).

2.2. Study Area

Tang County (38°37′~39°09′ N, 114°27′~115°03′ E), located in the Yanshan-Taihang Mountain with concentrated contiguous poverty areas, is a poverty-stricken county (Figure 2). It is one of the representative counties in the mountain area in Taihang Mountain. With a total land of area 1417 km^2, barren grassland resources are abundant in the study area and account for 31.7% of the total area of the county. The climate type is warm temperate continental monsoon climate, and the altitude difference is significant in the study area. There are four soil types in the study area: brown soil, cinnamon soil, paddy soil, and meadow soil. Influenced by parameters such as topography, climate, hydrology, soil, and other conditions, the vegetation in the territory decreases from northwest to southeast and from high altitude to low altitude, mainly comprising shrubs and herbaceous plants. Tang County is a traditional agricultural county. The agricultural sectors are mainly devoted to the planting industry, and the agricultural products mainly include wheat and corn, which are the key crops in the northern mountainous areas.

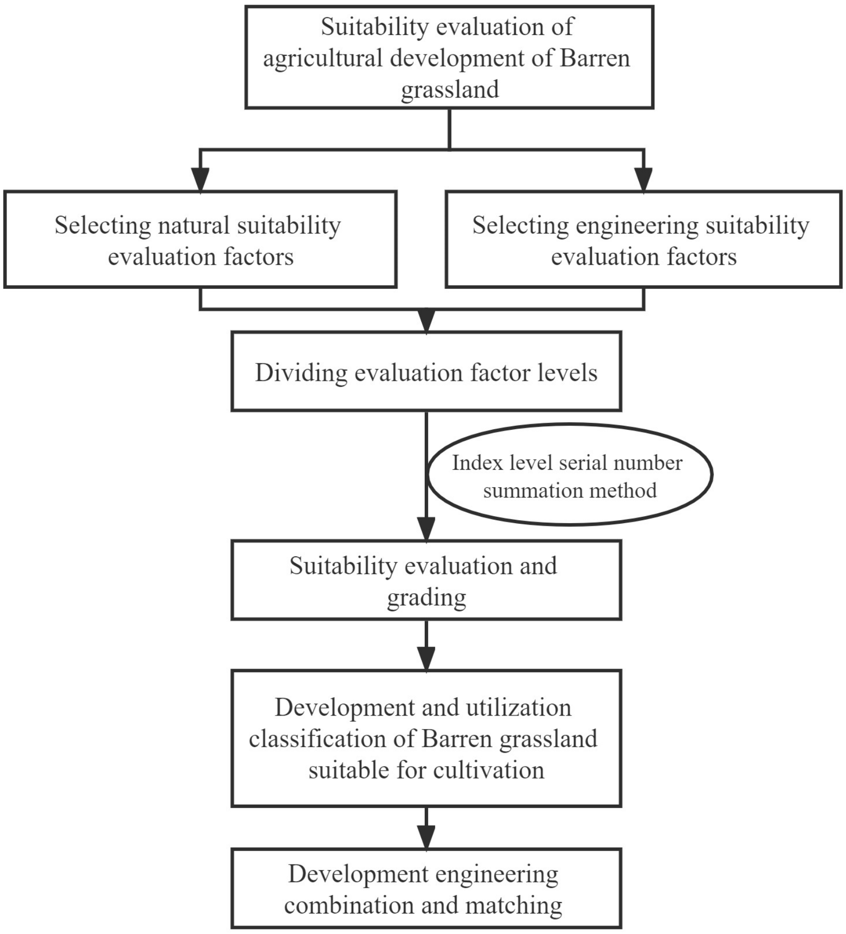


Figure 1. Technology roadmap.

Figure 2. Location of the study area. The red star represents the location of the Chinese government; The arrow indicates an enlarged display of the research area.

Tang County is a large county in Taihang Mountain. It is located in the green uplift belt of the western Taihang Mountain. The elevation is between 52–1869.8 m. The mountainous area comprises 82% of the total area of the county. The terrain is high in the northwest and low in the southeast. The proportion of mountainous areas, waters, and fields is 7:1:2. Variety in terrain is apparent with the presence of hills, plains, and rivers throughout the county. In the ecological function division of Hebei Province, Tang County primarily resides in the water conservation area and soil conservation area. The South-to-North Water Transfer Engineering crosses through the county. Xidayang Reservoir is both the water source of Baoding City and the emergency water source of Beijing.

2.3. Data Source

Research data could be divided into three types: documents, remote sensing data, and survey data. The ArcGIS10.2 geographic information platform and ENVI 4.7 remote sensing image processing platform was used for data processing and analysis.

Firstly, documents were provided by the Tang County Land and Resources Bureau and mainly include Tang County Land Use Master Plan (2010~2020), Administrative Division Map, Tang County Land Survey Update Data (2013), Tang County Forestry Plan (2010~2020), and soil map of Tang County (1:250,000).

Secondly, GDEMDEM 30M DEM remote sensing images were downloaded from Geospatial Data Cloud (http://www.gscloud.cn/, accessed on 16 July 2021) and included elevation, slope, and aspect data. The data identifications are, respectively, ASTGTM_N38E114, ASTGTM_N38E115, and ASTGTM_N39E114.

Thirdly, survey data included soil thickness, topsoil texture, bedrock type, soil organic matter content, and other data from 149 sampling site and indoor analysis. Through the scale conversion by the spatial interpolation, the index status of barren grassland in the whole region was obtained.

A reasonable layout of sampling sites is crucial for the representativeness of survey data [34]. The 3S technology has gradually replaced the traditional cumbersome indoor interpretation survey method [35] and can acquire different kinds of data, including slope and altitude through remote sensing interpretation and conveniently realizing the spatial interpolation of survey data [36]. The distribution of the sampling sites should be relatively uniform throughout the whole area, covering all soil types and topographic types. More sampling sites should be arranged in the areas with evident changes in remote sensing images and the transition zones in order to improve the accuracy of the survey indexes. A total of 149 sampling sites were arranged in this study. Their spatial distribution is shown in Figure 3.

2.4. Unit of Evaluation

The suitability to agricultural development is a comprehensive feedback of land elements of each evaluation unit. Currently, the division methods of evaluation units mainly include the superposition method, the polygon method, and the grid method. While the superposition method requires sufficient data inventory, the selection method of the superposition factors is not clear. The grid method is prone to cause inconsistency between the total area of the evaluation unit and the actual area, so it is difficult to accurately obtain the evaluation index. In the polygon method, the polygon in the land use is used as the evaluation unit. The polygon method can be combined with the actual situation and conveniently distinguish various resources, but it cannot reflect partial important information such as bedrock type, groundwater depth, and soil quality. In order to achieve the accuracy and rationality of the evaluation results, in this study, the polygon method was adopted, and the field survey was performed to supplement the information that could not be reflected by the map method.

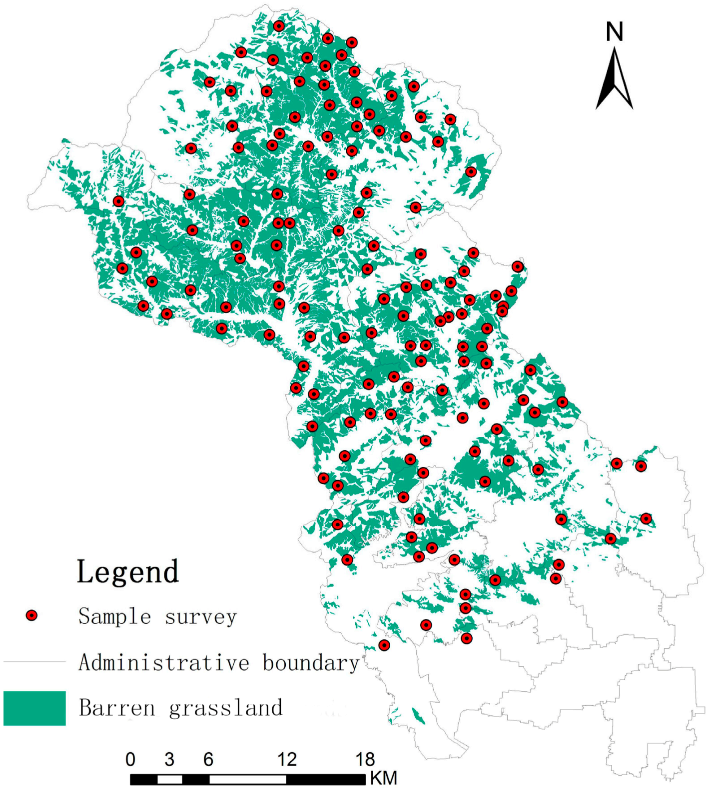


Figure 3. Distribution of sampling sites of barren grassland resources in Tang County.

2.5. Suitability Evaluation

2.5.1. Natural Suitability Evaluation of Agricultural Uses

(1) Evaluation index system

Evaluation indexes were the focal point for suitability evaluation research. In the selection process of evaluation indexes, the factors to be considered included the dominant type, comprehensiveness, difference, and accessibility. Moreover, the selected evaluation indexes should reliably represent the normal states of certain properties of barren grassland [37–39]. The complexity of mountainous regions added another dimension to the research. The altitude has different effects on the changes in the ecological environment, the layout of agricultural production, and crop growth. The topographic conditions such as slope and aspect have an important impact on the surface erosion [40]. There are certain shortcomings in the agricultural production conditions of barren grassland. The temperature and solar radiation conditions in mountainous areas change evidently with altitude and aspect. Generally, the soil thickness of barren grassland is thin and has relatively large slope, and the weathering degrees of different types of bedrock, the thickness of regolith, and the nutrient content of barren grassland soil have great differences, and the agricultural production convenience has evident differences.

Temperature, solar radiation, soil conditions, and field slope are factors that affect agricultural production. Referring to relevant studies [41–48] and combined with the actual situation of the study area, the altitude, slope, and aspect indexes were chosen to characterize temperature, solar radiation, and field slope, and soil thickness, organic matter content, soil texture, bedrock type, and gravel content were selected to characterize soil conditions and formulated the index classification (Table 1).

Table 1. Evaluation index system for agricultural natural suitability of barren grassland in mountain area.

Evaluation Factor	Evaluation Factor	Grading Standard			
		S1	S2	S3	S4
Geomorphological conditions	Altitude (m)	>800	500–800	300–500	≤300
	slope (°)	>25	15–25	6–15	≤6
	Aspect	North slope and northwest	Northeast and west slopes	East slope, southeast, and southwest	South slope
Soil conditions	Soil thickness (cm)	≤10	10–30	30–50	>50
	Organic matter content (%)	≤0.6	0.6–1.2	1.2–1.8	>1.8
	Soil texture	Gravel soil	Sandy soil	Middle soil, clay	Light loam
	Bedrock type	Limestone	Sandstone, basic rock	Shale	Gneiss
	Gravel content (%)	>50	30–50	15–30	≤15

(2) Evaluation method

In this study, the index level number summation method was used to determine the suitability level. The index level serial number summation method is a new land suitability evaluation method with the dual characteristics of objectivity and simplicity. Its core idea is to divide the order of each evaluation factor into several index levels, which are then numbered in the ascending or descending order. The serial numbers of the index levels corresponding to each evaluation factor in a specific evaluation unit are added as the suitability level serial number summation index of the unit (hereinafter referred to as "the index"). The range of the index value is divided into several intervals based on real conditions, and each interval is considered as a suitability grade. Through the above steps, an index-based suitability evaluation method, called the index level serial number summation method, is obtained.

The method can be broadly divided into two steps. The first step is to establish a series of indexes, sort the indexes according to the influencing degrees of the evaluation factors on the suitability, assign the serial number to the corresponding index, and calculate the index through summing the serial number of each element of the evaluation unit. The second step is to divide the index into intervals and generate a serial of suitability ratings. The method is illustrated though a case as follows.

Elevation, slope, and aspect are the factors reflecting the topographical features. According to their effects on suitability, they are divided into four index levels: S1, S2, S3, and S4. The corresponding grade numbers are 1, 2, 3, and 4. Supposing that the suitability indexes of elevation, slope, and aspect of a unit are, respectively, S3, S2, and S3, the corresponding index levels are 3, 2, and 3, and the index of the unit is calculated as 8.

According to the permutations and combinations, all the index level numbers of the three factors (elevation, slope, and aspect) are correspondingly added, and then 10 index values of 3 to 12 are obtained. Based on the index results and the average method, the index values of 3, 4, and 5 are determined as the D1 class; the index values of 6, 7, 8, and 9 are determined as the D2 class; the index values of 10, 11, and 12 are determined as the D3 class. In this case, the three factors of elevation, slope, and aspect indicate the comprehensive suitability of the geomorphological conditions, and the index level of the three factors shows the consistent tendency with the degree of suitability.

According to the above methods and steps, all the index level serial numbers of the 5 factors of soil conditions are summed to obtain a total of 16 index values from 5 to 20. The index values of 5 to 9 are determined as the T1 class; the index values of 10 to 15 are determined as the T2 class; and the index values of 16 to 20 are determined as the T3 class.

On the basis of the evaluation results of geomorphological conditions and soil conditions, according to the above methods and steps, the natural suitability index values of barren grassland to agricultural uses are obtained, and the natural suitability of barren grassland to agricultural uses is graded. The calculation process is described as follows:

The indexes of the geomorphological condition evaluation results are divided into D1, D2, and D3. The indexes of soil condition evaluation results are divided into T1, T2, and T3, and the corresponding numbers of the two evaluation results are summed to obtain 5 index values of 2, 3, 4, 5, and 6. Based on the serial number summation index result and the actual situation, the fixed index value of 2 is determined as the Z1 class; the index values of 3 and 4 are determined as the Z2 class; the index values of 5 and 6 are determined as the Z3 class.

2.5.2. Engineering Suitability Evaluation of Agricultural Uses

(1) Evaluation index system

The selected agricultural engineering suitability evaluation indexes should reflect regional factors [49–51]. According to the relevant results [42,44,45,51–53] and the actual situation of the research area, the evaluation index of engineering suitability is selected, and the index classification is carried out. Water source condition, soil source condition, and locational condition determine the difficulty and cost of development, as well as the convenience of agricultural production. Therefore, surface water distance and groundwater depth were selected to represent water source condition, soil source distance was selected to represent soil source condition, and road conditions and village conditions were selected to represent locational condition (Table 2).

Table 2. Suitability evaluation index system for barren grassland agricultural engineering in mountain area.

Evaluation Factors	**Evaluation Factors**	**Grading Standards**			
		S1	**S2**	**S3**	**S4**
Water source condition	Surface water distance (m)	>2500	1500–2500	500–1500	≤500
	Groundwater depth (m)	>150	100–150	50–100	≤50
Locational condition	Road conditions (m)	>1500	1000–1500	500–1000	≤500
	Village conditions (m)	>3000	2000–3000	1000–2000	≤1000
Soil source condition	Soil source distance (km)	>10	5–10	2–5	≤2

(2) Evaluation method

The engineering suitability was determined with the above five factors and evaluated by the index level serial number summation method.

According to permutations and combinations, all the index levels of the five factors were summed to get a total of 16 index values from 5 to 20. The index values of 5 to 9 were determined as the G1 class; the index values of 10 to 15 were determined as the G2 class; and the index values of 16 to 20 were determined as the G3 class.

2.5.3. Agricultural Development Suitability Evaluation

(1) Evaluation method

The suitability of agricultural development was determined by the 13 indexes included in the above five influencing factors. Based on the evaluation results of natural suitability and engineering suitability, the index level serial number summation index of the development suitability was obtained, and the development suitability was graded. The calculation process is described as follows:

The indexes of natural suitability evaluation results were determined as Z1, Z2, and Z3. The indexes of engineering suitability evaluation results were, respectively, determined as G1, G2, and G3, and the corresponding serial numbers were summed to obtain total 5 serial number index values of 2, 3, 4, 5, and 6. The index value of 2 was determined as K1; the index values of 3 and 4 were determined as K2; and the index values of 5 and 6 were determined as K3.

(2) Classification of suitability level

According to China's current land policy, the comprehensive quality of barren grassland suitable for cultivation is the best and that of barren grassland suitable for prataculture is the worst. Therefore, the suitability level of agricultural use development is divided into three categories from high to low as suitable for cultivation, suitable for forestry, and suitable for prataculture. The grades in the evaluation results are divided into three categories: suitable for cultivation barren grassland (K3), suitable for forestry barren grassland (K2), and suitable for grass (K1).

Lands with the slope $>25^{\circ}$ are highly likely to cause soil erosion, which can easily cause serious soil loss and high ecological risks [54]. The development cost is high, and the engineering measures are complex. Considering ecological risks and development benefit, the one-vote veto system is adopted for barren grassland with an optimum slope $>25^{\circ}$, which is included in suitable forestry lands of barren grassland according to the above principles.

2.6. Development and Utilization Classification of Barren Grassland Suitable for Cultivation

2.6.1. Development and Utilization Classification System

The current classification system of land use status fails to reflect the conditions of climate, topography, bedrock, hydrology, and soil. Moreover, it does not adequately represent the development conditions of specific attributes. Therefore, barren grassland development projects cannot be classified according to the status of land. It is necessary to divide the types of development and utilization according to the natural conditions and the nature of barren grassland, combined with the development direction and engineering transformation factors. Land leveling and water conservancy are the core projects for the development of barren grassland into cultivated land in mountainous areas. Through the land leveling project, the size of the field, the thickness of the soil, and the slope can comply with the requirements of irrigation and production. Through water conservancy projects, regulate and increase the water condition of farmland and regional water conservancy conditions. The investment of these two types of projects mainly depends on the bedrock type, slope, soil thickness, and water source condition. According to the relevant results [12,45,52,53] and the actual situation of the research area, four factors, including bedrock type, slope, soil thickness, and water source, were selected as the classification indexes, and the index classification was carried out (Table 3).

Table 3. Classification index system for development and utilization of barren grassland in mountain area.

Development Limiting Factors	**Factor Types**	**Classification Levels**
Bedrock type	Gneiss, shale	Strong weathering
	Sandstone, limestone, granite, basic rock	Weak weathering
Slope (°)	Slope $\leq$ 6	Gentle slope
	6 < slope $\leq$ 15	Moderate gentle slope
	15 < slope $\leq$ 25	Middle steep slope
Soil thickness (cm)	Soil thickness $\leq$ 30	Thin layer
	30 < layer thickness $\leq$ 50	Middle layer
	Soil thickness > 50	Thick layer
Water source condition (m)	Surface water distance $\leq$ 500 or groundwater depth $\leq$ 100	Rich water
	500 < surface water distance $\leq$ 1500 or 100 < groundwater depth $\leq$ 150	Less water
	Surface water distance > 1500 and groundwater depth > 150	Water shortage

2.6.2. Classification and Nomenclature

Internationally, land classification methods can be roughly divided into the landscape method, parameter method, and process method. The parameter method has typical quantitative characteristics, high objectivity, and is convenient for quantitative comparison. If it is combined with the landscape method, it can make up for the shortcomings of the complicated process and improve the accuracy of the classification results. Therefore, in this study, the parameter method was combined with the landscape to construct a comprehensive method for classify the development and utilization types of barren grassland.

There is no common nomenclature of land types. In this study, the landscape parameter method was used for classification, and the continuous nomenclature was used for naming land types [55,56]. The four fields, in turn, indicated bedrock type, slope, soil thickness, and water source conditions. For example, in some barren grassland, the bedrock type was gneiss; the slope was 12°; the soil thickness was 10 cm; the groundwater depth was 180 m; and the surface water distance was 2100 m. This land type was named by strong-weathering, gentle-slope, thin-layer, and water-shortage type. Based on this method, the mountain barren grass area could be divided into 54 types theoretically.

2.7. Development Engineering Combination and Matching

The mountain barren grassland development project mainly solves the slope, irrigation, and soil problems. Based on the analysis of the required engineering combination characteristics of each type of barren grassland, the engineering combination was carried out according to the characteristics of engineering measures and matched with the types of development and utilization. In this study, the types were classified according to the main limiting factors that needed to be overcome in the development of suitable cultivated land, and the continuous naming method was adopted to name them, so the engineering types were matched according to the names of each type. For example, the weak-weathering, moderate-steep slope, thin-layer, and water-rich type barren grasslands had the weak bedrock weathering phenomenon and thin weathered layers. The thickness of the soil layer itself was relatively thin. Therefore, in matching engineering, it was necessary to adopt the soil replacement and the application of organic fertilizer. The moderate steep slope indicated that the slope was relatively large, and the steep slope terraces needed to be built during development. At the same time, the protection slope was required, and land leveling should be performed in the terraces. The water-rich type indicated that there was a surface water source within the distance of 500 m or groundwater buried less than 100 m, and a well and diversion irrigation system could be constructed. According to the method, the mountain barren grassland development engineering combination could be integrated into 12 types theoretically.

2.8. Structural Feature Analysis

The concept of land type structure is introduced in the study to reflect the distribution of lands and the difficulty in development and utilization. The land type structure includes the spatial structure and quantitative structure of the land type [57]. The quantitative structure is to characterize the quantitative feature of the individual or group by studying the relationship between them [58]. The area ratio and the regional average distance serve as indicators to depict these quantitative attributes. The spatial structure can clearly reflect whether barren grasslands of the same engineering type are spatially ordered [59].

2.8.1. Quantitative Structure

The quantitative structure reflects the quantitative relationship of barren grassland of an engineering combination. The quantitative indexes of the land structure are mainly expressed as:

(1) Area ratio

Area ratio is expressed as [58]:

$$K = \frac{a_i}{A} \times 100\% \tag{2}$$

where K is the area ratio of barren grassland suitable for cultivation of a certain engineering combination; a_i is the area of barren grassland suitable for cultivation of a certain engineering combination; and A is the area of barren grassland suitable for cultivation.

The greater value of K indicates the greater influencing area of the engineering combination type on the study area and the stronger dominance.

(2) Regional average nearest distance

Regional average nearest distance is expressed as [60]:

$$Menn = \frac{\sum_{i=1}^{n} d_i}{N} (i = 1, 2, \ldots n) \tag{3}$$

where $Menn$ is the average nearest neighbor distance in barren grassland of a certain engineering combination; d_i represents the distance from an barren grassland suitable for a certain use corresponding to the i-th engineering combination type to its nearest barren grassland of the same combination type; and N is the number of barren grassland suitable for cultivation of the same engineering combination.

$Menn$ is a pattern indicator that measures the relationship among the landscape elements in the same engineering combination. The smaller value of $Menn$ indicates the closer distance among the patches of the same types, the better connectivity, the agglomeration landscape distribution pattern, and the low difficulty in centralized development.

2.8.2. Spatial Structure

The spatial structure can effectively reflect whether barren grasslands suitable for cultivation corresponding to different engineering combinations are spatially ordered [60]. Common spatial structures include repetitive combination structures, stepped combination structures, symmetric combination structures, and mosaic combination structures.

3. Results

3.1. Evaluation Index

3.1.1. Natural Suitability Evaluation Index

According to the characteristics of natural conditions in the study area, eight indexes, including altitude, organic matter content, and soil thickness, were selected from landform and soil conditions as indicators for the evaluation of natural suitability for agricultural use after field investigation and expert discussion. The classification was carried out according to Table 1, with the results visually represented in Figure 4. Among them, altitude, slope, and aspect indexes are all derived from the interpretation and extraction of DEM images in Tang County. Soil thickness, organic matter content, soil texture, bedrock type, and other indicators were obtained through field investigation, and the obtained survey data were obtained through spatial interpolation to obtain the county information.

3.1.2. Engineering Suitability Evaluation Index

The classification was carried out according to Table 2, and the results are shown in Figure 5. The groundwater depth was obtained through field survey. The scale conversion was carried out by spatial interpolation. The surface water distance and the indexes of location conditions passing through roads, villages, towns, rivers, and other elements were obtained in the land map. The soil source distance was obtained through investigation, and distance buffering was performed through ArcGIS10.0. The results of each indicator are provided as follows.

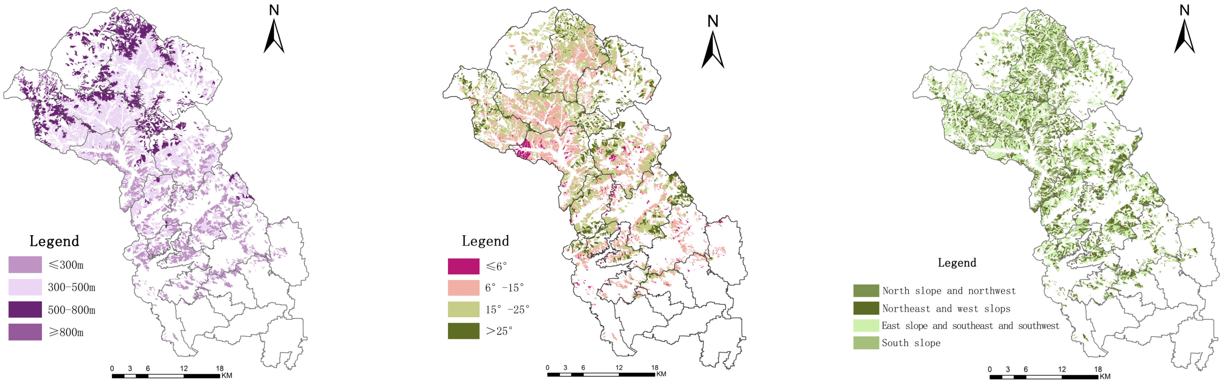
3.2. Suitability Evaluation Results

3.2.1. Natural Suitability Evaluation Results

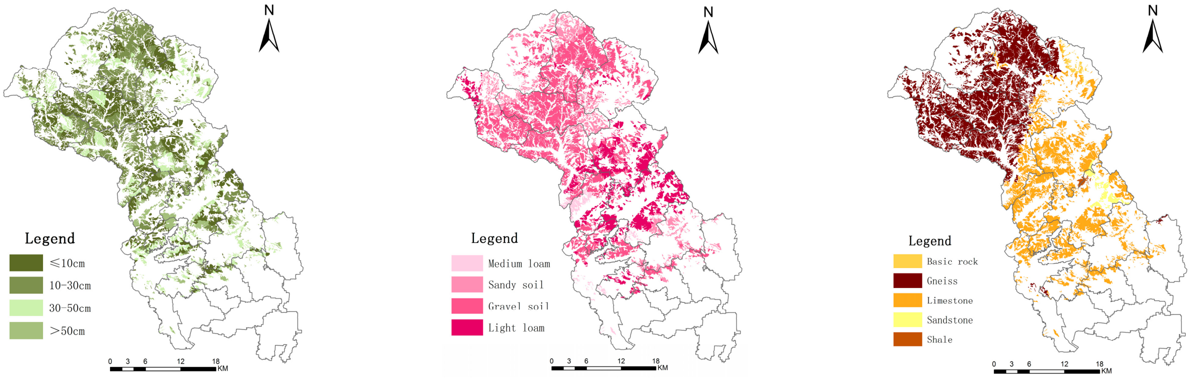
The evaluation results of natural suitability of barren grassland to agricultural uses showed that the area of the Z2 class in the study area was the largest (30,424.20 hm^2) and accounted for 69.48% of the total area of the study area. The Z2 class was mainly distributed in the northern part of the county. The area of the Z3 class was the second largest (7139.21 hm^2) and accounted for 16.31% of the total area of the study area. The Z3 class was mainly distributed in the middle of the county. The area of the Z1 class was the least (6221.90 hm^2) and accounted for only 14.21% of the total area of the study area. The area of the Z1 class was mainly distributed in the northern part of the county (Figure 6).

3.2.2. Engineering Suitability Evaluation Results

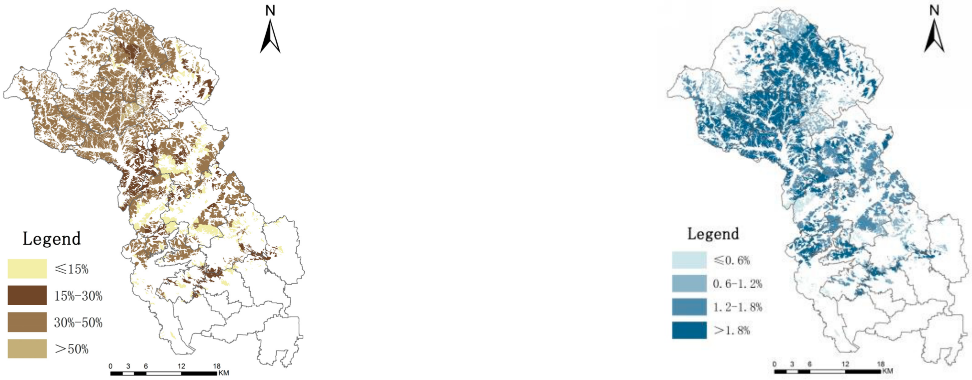
In the engineering suitability evaluation of barren grasslands (Figure 7), the area of the G2 class was the largest (23,051.92 hm^2) and accounted for 52.64% of the total area. The area of G3 class was the second largest (16,317.82 hm^2) and accounted for 37.27% of the total area. The area of G1 class was the least and accounted for 10.85% of the total area. Based on the comprehensive analysis of the above research results, barren grasslands in the study area have the ideal engineering construction conditions in terms of road, groundwater depth, and soil source.



(**a**) altitude (**b**) slope (**c**) aspect

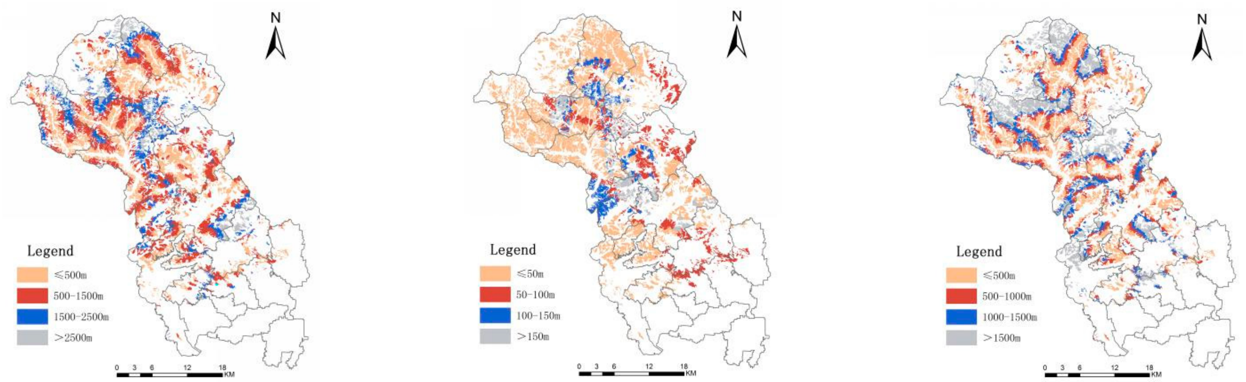


(**d**) soil thickness (**e**) soil texture (**f**) bedrock type

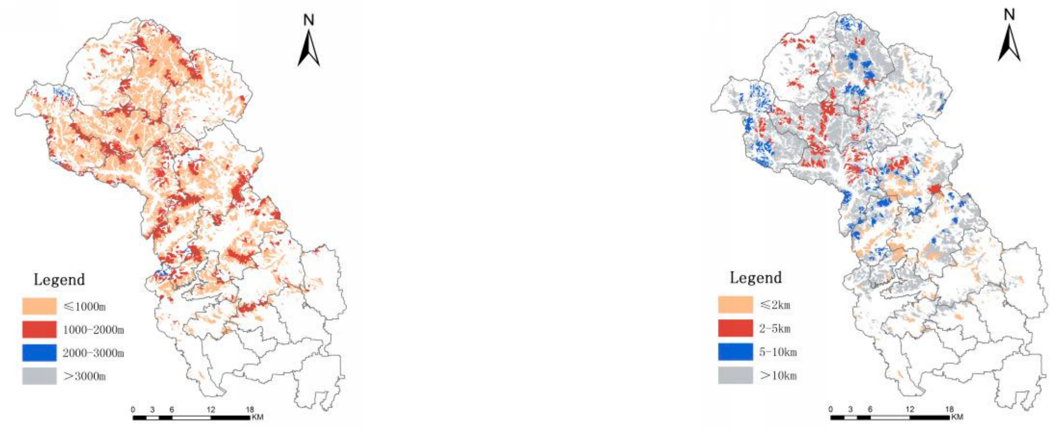


(**g**) gravel content (**h**) organic matter content

Figure 4. Evaluation indexes of natural suitability of agricultural uses.



(**a**) surface water distance (**b**) groundwater depth (**c**) road conditions



(**d**) village condition (**e**) soil source distance

Figure 5. Agricultural engineering suitability evaluation factors.

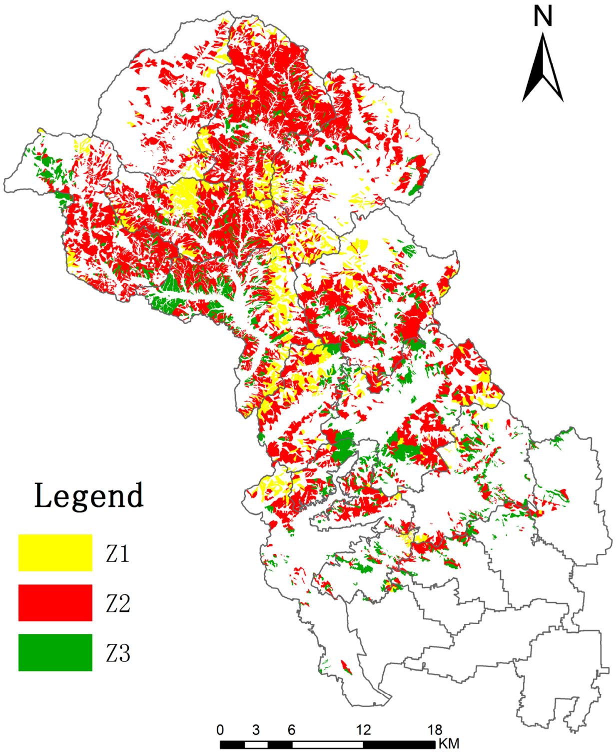


Figure 6. Spatial distribution of natural suitability of barren grassland to agricultural uses in Tang County.

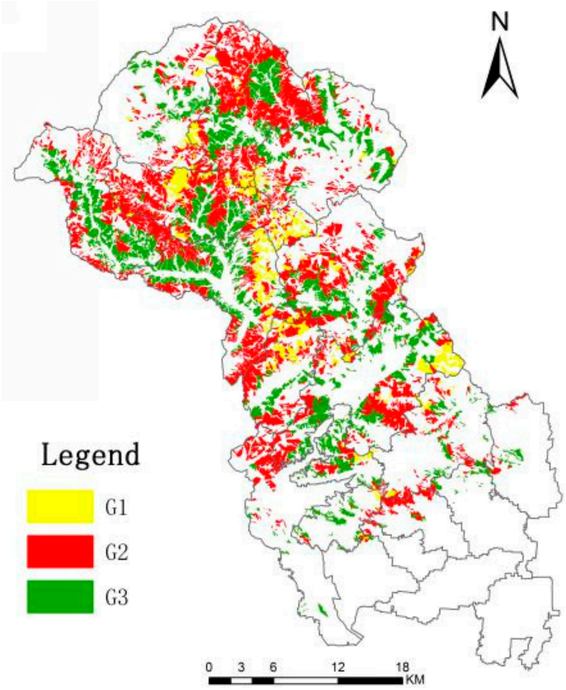


Figure 7. Spatial distribution of suitability of barren grassland to agricultural engineering in Tang County.

3.2.3. Development Suitability Evaluation Results

As shown in Figure 8, the proportion of barren grassland areas suitable for forestry was the largest (25,231.18 hm^2) and accounted for 57.62% of the total area, followed by barren grassland suitable for cultivation accounting for 33.73%, and barren grassland suitable for prataculture (3783.30 hm^2) accounting for 8.64%.

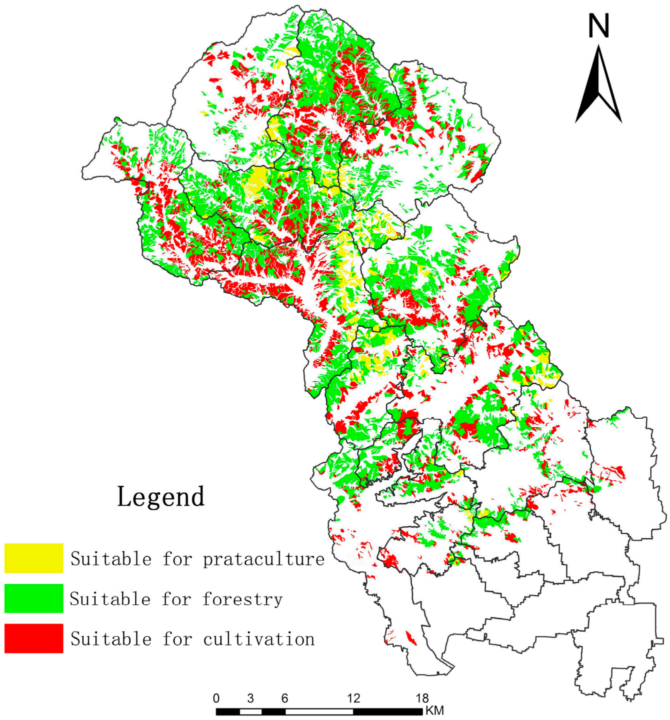


Figure 8. Spatial distribution of the suitability of barren grassland agricultural development in Tang County.

Barren grasslands suitable for forestry have the largest areas and are widely distributed throughout the whole study area, showing an increasing trend from the south to the north. Barren grasslands suitable for forestry are mainly distributed in the northern part of the county. The elevation is high, and the bedrocks are mostly gneiss. Both surface water and groundwater resources are abundant, and the organic matter contents are relatively high. However, the soil layer in these barren grasslands, suitable for forestry, are relatively thin, the terrains feature quite steep slopes, and the soils have poor textures. Furthermore, these grasslands are notably distant from villages, roads, and soil sources.

Barren grasslands suitable for cultivation are concentrated in the northern and central parts of the county and characterized by an evident distribution trend along the banks. The elevation is high. The bedrocks are mostly gneiss, and the textures are soft. The organic matter contents are high, and the surface water and groundwater resources are abundant. Barren grasslands suitable for cultivation are relatively close to villages, roads, and soil sources. However, they are characterized by thin soil layers and extensive slopes.

Barren grassland suitable for prataculture are concentrated in the central and northern parts of the county and are generally distant from villages, roads, and soil sources. Moreover, surface water and groundwater resources are scarce. Steep terrains and poor soil textures characterize these areas, compounded by notably thin layers of soil.

3.3. Classification of Barren Grassland Suitable for Cultivation and Engineering Matching

Theoretically, the suitable barren areas can be divided into 54 types of development and utilization and 12 engineering combinations (Tables A1 and A2 in Appendix A).

There are 37 development and utilization types in the barren grassland suitable for cultivation in the study area (Table A2 in Appendix A). The barren grassland type with the largest area (2728.20 hm^2) is the strong-weathering, moderate-slope, thin-soil, and less-water-barren grassland and accounts for 18.47% of the total area of the study area. The barren grassland type is distributed in Juncheng Town, Yangjiao Town, and Chuanli Town in the northern part of the county. The secondary types are the strong-weathering, steep-slope, thin-soil, and less-water type; the strong-weathering, moderate-slope, thin-soil, and water-rich type; and the weak-weathering, moderate-slope, and less-water type, which, respectively, account for 10.72%, 8.81%, and 6.18% of the area of barren grassland suitable for cultivation.

There are eight engineering combinations in the study area (Table A1 in Appendix A). The soil-replacement, slope-to-terrace, and water-drainage-lift type; the slope-to-terrace and water-drainage-lift type; and the deep-ploughing, slope-to-terrace, and water-drainage-lift type are the dominant types, with a total area of 13,525.02 hm^2, accounting for 91.56% of the study area. The soil-replacement, slope-to-terrace, and water-drainage-lift type includes the most types of barren grassland suitable for cultivation (12 types). The second is the slope-to-terrace and water-drainage-lift type, which includes six types of barren grassland suitable for cultivation. The deep-ploughing, slope-to-terrace, and water-drainage-lift type includes four types of barren grassland suitable for cultivation. There are no barren grasslands suitable for cultivation corresponding to the soil-replacement and rainwater-collection-storage type; the deep-ploughing, slope-to-terrace, and rainwater-collection-storage type; the deep-ploughing and rainwater-collection-storage type; and the slope-to-terrace and rainwater-collection-storage type in the study area.

3.4. Distribution Structure

There are eight engineering combinations of barren grassland suitable for cultivation in the study area (Table 4 and Figure 9). An analysis of area ratios reveals that the largest section of barren grassland corresponding to the soil-replacement, slope-to-terrace, and water-drainage-lift type is the largest (9394.19 hm^2) and accounts for 63.60% of the total area of the study area, followed by the slope-to-terrace and rainwater-collection-storage type and the deep-ploughing, slope-to-terrace, and water-drainage-lift type, respectively, accounting for 15.82% and 12.14% of the total area of the study area. Most of the barren grasslands suitable for cultivation in the study area are thinner and have larger slopes. However, they benefit from favorable water source conditions. Among these, the area characterized by the longest average nearest distance (0.58 km) is the deep-ploughing, slope-to-terrace, and water-drainage-lift type, indicating that the barren grasslands suitable for cultivation in this area are characterized by poor connectivity, scattered distribution, high difficulty in development and utilization, and short, regional-average nearest distance. For example, the patches of barren grassland landscape elements corresponding to the soil-replacement, slope-to-terrace, and water-drainage-lift type are characterized by close distance, good connectivity, agglomerated landscape, and relatively low development difficulty.

Table 4. Quantitative structure of the engineering combinations of barren grassland in Tang County.

Engineering Types	Area (hm^2)	K (%)	Menn (km)
Soil-replacement, slope-to-terrace, and water-drainage-lift type	9394.19	63.6	0.32
Soil-replacement, slope-to-terrace, and rainwater-collection-storage type	36.06	0.24	0.43
Deep-ploughing, slope-to-terrace, and rainwater-collection-storage type	1793.84	12.14	0.58
Deep-ploughing and water-drainage-lift type	231.62	1.57	0.41
Soil-replacement and water-drainage-lift type	694.98	4.71	0.52
Slope-to-terrace and water-drainage-lift type	2336.99	15.82	0.37
Land-leveling and rainwater-collection-storage type	12.90	0.09%	0.34
Land-leveling and water-drainage-lift type	270.25	1.83	0.45

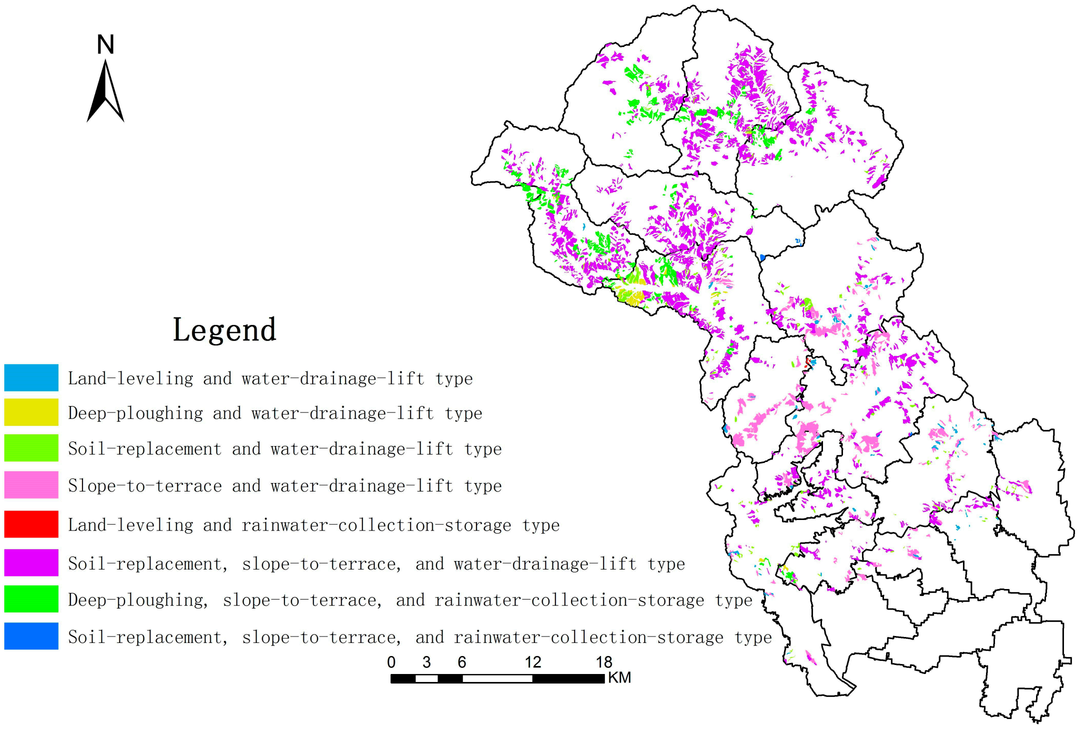


Figure 9. Spatial distribution of engineering combinations of barren grassland suitable for cultivation in Tang County.

The barren grasslands suitable for cultivation corresponding to the eight engineering combinations show significant step-like combination structures, which are composed of the slope-to-terrace and water-drainage-lift type; soil-replacement, slope-to-terrace, and water-drainage-lift type; and deep-ploughing, slope-to-terrace, and water drainage-lift type from the south to the north. The structures are consistent with the study area, including the relatively thick layer in the south–central part, the thin thick layer in the northern part, the weak bedrock weathering intensity in the south–central part, the strong bedrock weathering intensity in the north, and the better water source conditions. Furthermore, the study area also showed the typical mosaic combination structures. For example, the deep-ploughing and water-drainage-lift type and the soil-replacement and water-drainage-lift type in the northwestern part of the county are embedded in the soil-replacement, slope-to-terrace, and water-drainage-lift type. The land-leveling and water-drainage-lift type and land-leveling and rainwater-collection-storage type are embedded in the slope-to-terrace and water-drainage-lift type. The above-mentioned mosaic combinations indicate that the properties of the combinations of landform, water, and soil in the study area are complicated. The complex properties are more unfavorable for the building-block engineering in the study area.

4. Discussion

The evaluation of barren grassland in mountain area is affected by many factors, and the evaluation indexes and methods are still in the exploratory stage. This study puts forward the "index level serial number summation method" for suitability evaluation, which enriches and expands the theory and methods for suitability evaluation of barren grassland in mountain area. However, during the evaluation process, due to the limitations of the evaluation methods, extreme phenomena may exist in the evaluation results. For example, barren grassland with better evaluation results may have evident disadvantages. Therefore, further improvements to the method are necessary to avoid such phenomenon in the suitability evaluation.

In the evaluation of agricultural development suitability of barren grassland, both natural factors and engineering elements were incorporated, leading to an enhancement in the accuracy of evaluation. However, affected by national policies and the continuous deterioration of the regional environment, ecological factors have gradually become an essential option in the process of land evaluation and utilization. In the future, more ecological elements may be added and integrated with the social and natural attributes of the land in order to further improve the evaluation accuracy.

This study aimed to propose an initiative for the scientific utilization of mountainous barren grassland; propose a work approach for investigation, evaluation, classification, and engineering matching; and selected Tang County for a case study. Owing to differences in terrain, climate, soil and other conditions, there are different complex and diverse combinations of limiting factors in different regions. The application of research results requires necessary adjustments based on the actual situation of the project area, in order to better improve land use. In addition, saline and alkaline land, bare land, sandy land, inland mudflat, coastal mudflat, and other land types are also valuable reserve resources of cultivated land. As there are several limiting factors for agriculture, they can be converted into agricultural land only after engineering renovation. The evaluation, classification, and engineering-matching methods adopted by the research can be applied to the development of other types of land. This approach has certain reference and guiding significance for improving the land development engineering models in different land type areas.

The research on land remediation technology in China is relatively late, and the gap between China and the advanced world level is still quite evident. The contradiction between man and land in mountainous areas is more prominent, and the complexity of development problems in mountainous areas is also more evident. In the macro-management of land development and utilization in mountainous areas, there is a lack of a perfect legal system, and blindness and disorder in the local area are serious. Therefore, actively promoting the legislative work of land development and utilization in mountain areas and strengthening systematic top-level design will help to improve the stability, orderliness, and long-term development of mountain areas. Only by issuing corresponding standards for land survey, evaluation, development, and utilization in mountain areas, guiding and restricting related behaviors of land development in mountain areas, can we form the governance foundation for scientific development, coordinated development, and sustainable development in mountain areas and then fundamentally reverse the chaotic situation of land development in mountain areas.

There are evident geographical environment differences in mountainous areas. The state should fully consider the particularity of mountainous areas and respect their geographical environmental characteristics when formulating and implementing land policies in mountainous areas. At present, at the national level, there is no specific policy for land use in mountain areas, and the existing policy lacks sufficient pertinent in mountain areas, which is difficult to meet the special needs of land development and utilization in mountain areas, thus affecting the implementation effect of the policy in mountain areas to a certain extent. Therefore, it is of great significance to establish a multi-level policy system for land development and utilization in mountainous areas and formulate and implement special policies in line with the actual situation of the region to improve the quality and efficiency of mountain development and promote the comprehensive, coordinated, and sustainable development of mountain areas.

Engineering technology plays an important role in the process of land development and is also the forerunner of land improvement. In addition to the engineering technology mentioned in this paper, land development activities also include ecological engineering technology, information technology, environmental impact assessment technology, mapping technology, and so on. Therefore, land development is a systematic and interdisciplinary project, strengthening the integration and research of land development engineering technology; exploring the establishment of a land development engineering database and a land development management integrated information system as a future development direction to improve the land development system; and promoting sustainable land use.

5. Conclusions

On the basis of the analysis of the influencing factors of agricultural development suitability, in this study, the evaluation index system of natural suitability of agricultural uses and the agricultural engineering suitability evaluation index system were, respectively, established, and the index level serial number summation method was proposed. Additionally, the index level serial number summation method could combine the characteristics of objectivity and convenience when dealing with the comprehensive classification problems under multi-level and multi-factor intervention. According to the comprehensive results of natural evaluation and engineering evaluation, barren grasslands are divided into three categories: barren grassland suitable for cultivation, barren grassland suitable for forestry, and barren grassland suitable for prataculture, according to the comprehensive conditions.

Taking the barren grassland as the research object, the development and utilization classification system of barren grassland suitable for cultivation in mountainous area was constructed. The landscape parameter method and continuous nomenclature were used to divide the barren grasslands in a mountainous area into 54 types of development and utilization. Furthermore, based on the classification results, corresponding engineering explorations and 12 types of development engineering in barren grasslands suitable for cultivation in a mountainous area were determined.

Taking Tang County, Hebei Province, as an example, an empirical study was performed. The area of barren grassland suitable for cultivation in the study area was 14770.83 hm^2, accounting for 33.73% of the total area. There were 37 development and utilization types and 8 development engineering combinations in the barren grasslands in the study area. The combinations with the larger area were, respectively, the soil-replacement, slope-to-terrace, and water-drainage-lift type; the slope-to-terrace and water-drainage-lift type; and the deep-ploughing, slope-to-terrace, and water-drainage-lift type with a total area of 13525.02 hm^2 and accounting for 91.56% of the study area.

Author Contributions: Z.C., N.G. and Y.C. conceptualized the project and investigated, collected, and analyzed the original draft of data; Z.C. and N.G. administrated and supervised; N.G. edited the graphs; Z.C. and Y.C. reviewed and edited; Z.C. and N.G. assisted with field and lab work. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Engineering types of barren grassland suitable for cultivation in mountain area in Tang County.

Engineering Combination Types	Basic Engineering Combination Characteristics						
	Water Source Type	**Water Intake Engineering**	**Bedrock Type**	**Soil Thickness (cm)**	**Soil Thickening Engineering**	**Slope (°)**	**Leveling Engineering**
Soil-replacement, slope-to-terrace, and water-drainage-lift type	River water, groundwater	Water diversion irrigation and water lifting irrigation	Strong weathering/weak weathering	0–30/0–50	Soil replacement	>6	Slope-to- terrace
Soil-replacement, slope-to-terrace, and rainwater-collection-storage type	Rainwater	Water storage engineering	Strong weathering/weak weathering	0–30/0–50	Soil replacement	>6	Slope-to- terrace
Deep-ploughing, slope-to-terrace, and water-drainage-lift type	River water, groundwater	Water diversion irrigation and water lifting irrigation	Strong weathering	30–50	Deep plowing	>6	Slope-to- terrace
Deep-ploughing, slope-to-terrace, and rainwater-collection storage type	Rainwater	Water storage engineering	Strong weathering	30–50	Deep plowing	>6	Slope-to- terrace
Deep-ploughing drainage water lifts type	River water, groundwater	Water diversion irrigation and water lifting irrigation	Strong weathering	30–50	Deep plowing	<6	Land leveling
Deep-ploughing and rainwater-collection storage type	rainwater	Water storage engineering	Strong weathering	30–50	Deep plowing	<6	Land leveling
Soil-replacement and water-drainage-lift type	River water, groundwater	Water diversion irrigation and water lifting irrigation	Strong weathering/weak weathering	0–30/0–50	Soil replacement	<6	Land leveling
Soil-replacement and rainwater-collection-storage type	rainwater	Water storage engineering	Strong weathering/weak weathering	0–30/0–50	Soil replacement	<6	Land leveling
Slope-to-terrace and water-drainage-lift type	River water, groundwater	Water diversion irrigation and water lifting irrigation	Strong weathering, weak weathering	>50	-	>6	Slope-to- terrace
Slope-to-terrace and rainwater-collection-storage type	rainwater	Water storage engineering	Strong weathering, weak weathering	>50	-	>6	S Slope-to- terrace
Land-leveling and rainwater-collection-storage type	rainwater	Water storage engineering	Strong weathering, weak weathering	>50	-	<6	Land leveling
Land-leveling and water-drainage-lift type	River water, groundwater	Water diversion irrigation and water lifting irrigation	Strong weathering, weak weathering	>50	-	<6	Land leveling

Table A2. Barren grassland suitable for cultivation types and engineering assembly matching.

Engineering Combinations	Barren Grassland Types	Area (hm^2)
Soil-replacement, slope-to-terrace, and water-drainage-lift type	Strong-weathering, medium/steep slope, thin-layer, and water-rich type	633.15
	Strong-weathering, medium/steep-slope, thin-layer, and less-water type	1583.62
	Strong-weathering, gentle-slope, thin-layer, and water-rich type	1301.61
	Strong-weathering, medium/gentle-slope, thin-layer, and less-water type	2728.20
	Weak-weathering, medium/steep-slope, thin-layer, and water-rich type	166.19
	Weak-weathering, medium/steep slope, thin-layer, and less-water type	317.43
	Weak-weathering medium/steep slope, and water-rich type	285.37
	Weak-weathering, medium/steep-slope, medium-layer, and less-water type	349.56
	Weak-weathering, medium/gentle-slope, thin-layer, and water-rich type	137.93
	Weak-weathering, medium/gentle-slope, thin-layer, and less-water type	290.31
	Weak-weathering, medium/gentle slope, and water-rich type	687.40
	Weak-weathering, gentle-slope, medium-layer, and less-water type	913.42
Slope-to-terrace and water-drainage-lift type	Strong-weathering, medium/gentle-slope, thick-layer, and water-rich type	56.96
	Strong-weathering, medium/gentle-slope, thick-layer, and less-water type	29.14
	Weak-weathering medium/steep-slope thick-layer, and water-rich	469.06
	Weak-weathering, medium/steep-slope, thick-layer, and less-water type	523.81
	Weak-weathering, medium/gentle-slope, thick-layer, and water-rich	538.90
	Weak weathering, medium gentle slope, thick layer, less water type	719.12
	Strong weathering, medium/steep slope, thick layer, and water-rich type	-
	Strong-weathering, medium/steep-slope, thick-layer, and less-water type	-
Soil-replacement, slope-to-terrace, and rainwater-collection-storage type	Weak-weathering, steep-slope, thin-layer, and water-shortage type	34.72
	Weak-weathering, medium gentle slope, thin layer, water shortage type	1.34
	Strong-weathering, medium steep slope, thin layer, water shortage type	-
	Strong-weathering, medium gentle slope, thin layer, water shortage	-
	Weak-weathering, medium/steep-slope, medium-layer, and water-shortage type	-
	Weak-weathering, moderate-slope, and water-shortage type	-
Land-leveling and water-drainage-lift type	Strong-weathering, medium/gentle-slope, thick-layer, and water-rich type	13.03
	Strong-weathering, medium/gentle-slope, thick-layer, and less-water type	10.09
	Weak-weathering, medium/gentle-slope, thick-layer, and water-rich type	122.85
	Weak-weathering, medium/gentle-slope, thick-layer, and less-water type	124.28
Deep-ploughing, slope-to-terrace, and water-drainage-lift type	Strong-weathering medium-layer, and water-rich type	314.46
	Strong-weathering, steep-slope, middle-layer, and less water type	673.25
	Gentle weathering moderate-slope, and water-rich type	319.11
	Strong-weathering, medium/gentle-slope, medium-layer, and less-water type	487.02
Soil-replacement and rainwater-collection-storage type	Strong-weathering medium/gentle-slope thin-layer, and water-rich type	117.96
	Strong-weathering, medium/gentle-slope, thin-layer, and less-water type	235.07
	Weak-weathering medium/gentle-slope thin-layer, and water-rich type	13.15
	Weak-weathering medium/gentle-slope thin-layer, and less-water type	61.88
	Weak-weathering medium/gentle-slope medium-layer, and water-rich type	137.50
	Weak-weathering medium/gentle-slope medium-layer, and less-water type	129.42
Slope-to-terrace and rainwater-collection-storage type	Strong-weathering, medium/steep-slope, thick-layer, and water-shortage type	-
	Strong-weathering, medium/gentle-slope, thick-layer, and water-shortage type	-
	Weak-weathering, medium/steep-slope, thick-layer, and water-shortage type	-
	Weak-weathering, medium/gentle-slope, thick-layer, and water shortage	-
Soil-replacement and rainwater-collection-storage type	Strong-weathering, medium/gentle-slope, thin-layer, and water-shortage type	-
	Weak-weathering, medium/gentle-slope, medium-layer, and water-shortage type	-
	Weak-weathering, medium/gentle-slope, thin-layer, and water-shortage type	-
Deep-ploughing, slope-to-terrace, and water-drainage-lift type	Strong-weathering, medium/gentle-slope medium-layer, and water-rich type	126.76
	Strong-weathering, medium/gentle-slope, medium-layer, and less-water type	104.86
Land-leveling and rainwater-collection-storage type	Weak-weathering, medium/gentle-slope, thick-layer, and water-shortage type	12.90
	Strong-weathering, medium/gentle-slope, thick-layer, and water-shortage type	-
Deep-ploughing, slope-to-terrace, and rainwater-collection-storage type	Deep-weathering, medium/steep-slope, middle-layer, and water-shortage type	-
	Moderate-weathering, medium-slope, and water-shortage type	-
Deep-ploughing and rainwater-collection-storage type	Strong-weathering gentle-slope, medium-layer, and water-shortage type	-

Note: “-” indicates that there is no corresponding grassland type in this study area.

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