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RESEARCH ARTICLE

Regionalization of Human Settlement Suitability in the Natural Environment of the Tibetan Plateau

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The natural environment provides the geographical foundation for human survival and development; however, its suitability for human settlement in high-altitude regions remains insufficiently addressed. This study focuses on the Tibetan Plateau and proposes a Natural Environment Suitability Index of the Plateau (NESP), designed specifically for high-altitude areas. Using the natural location quotient, we assessed the influence of 9 key environmental factors on settlement suitability. To determine indicator weights objectively and comprehensively, we applied 3 methods: the random forest method, the consulting graded method, and the correlation coefficient method. The results indicate a clear spatial gradient: environmental suitability decreases from east to west as altitude increases. Only about 31% of the plateau is categorized as suitable or very suitable, primarily in low-altitude river valleys, while over 69% is classified as unsuitable or very unsuitable, concentrated in central and western regions. Suitable or very suitable areas are deemed appropriate for regulated human activities under strict environmental protection, while unsuitable or very unsuitable regions should be prioritized for ecological conservation. Based on the NESP, we delineated 11 distinct natural suitability zones across the plateau. This study offers a high-altitude-specific framework for assessing the quality of the natural environment for human settlement, providing a scientific foundation for regional planning, environmental management, and the promotion of Sustainable Development Goals in fragile plateau ecosystems.

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Introduction

The natural environment is the geographical basis of human production and life. The quality of a region's natural environment directly determines if the region could become a human settlement. The suitability of the natural environment is directly related to the people's physical and mental health and affects the development of the human economy, society, and civilization [1]. With the improvement in economic and living standards, humans have started to pay more attention to their quality of life and the demand for good natural environments has increased. Suitable natural environments have become foci of social attention [2]. Understanding the spatial distribution pattern of the suitability of the natural environment and identifying a suitable natural environment for human settlement is the basic work of regional protection and development. Studying the suitability of natural environments is of great importance to global development.

Based on the 2030 Agenda for Sustainable Development proposed at the 70th session of the United Nations General Assembly, "no one will be left behind" [3]. More than 10% of the people in the world live at an altitude above 1,000 m. The sustainable development of high-altitude areas is as important as that of other areas [4,5]. The natural environment of high-altitude areas differs from that of low-altitude areas; the temperature is low and not suitable for life, radiation is strong, and the oxygen content is low [6]. High-altitude regions face a range of harsh environmental conditions—such as hypoxia, temperature extremes, limited land resources, and fragile ecosystems—that pose substantial challenges to achieving the United Nations Sustainable Development Goals (SDGs). Assessment of natural environment suitability for human settlement will provide a scientific foundation to address these challenges, which will directly support the achievement of multiple SDGs. For example, delineation suitability zones for human settlement enables evidence-based decision-making for equitable urban and rural development (SDG 11). The framework also aids in climate adaptation by mapping vulnerability to environmental stressors (SDG 13) and contributes to biodiversity protection by helping avoid human encroachment into ecologically fragile areas (SDG 15).

The Tibetan Plateau is one of the most unique natural environments worldwide. Its high altitude, thin air, and strong solar radiation make it inhospitable [6]. People's lives on the plateau have improved due to the implementation of China's aid program in Xizang and the demand for a suitable natural environment is increasing [5,7]. However, the distribution of the suitability of the natural environment in the Tibetan Plateau remains unclear, which restricts the local economic development and construction. Assessing the natural environment suitability in the Tibetan Plateau plays an important role in ecological protection and infrastructure construction. In 2017, China launched the Second Tibetan Plateau Scientific Expedition Program, which aims to make new contributions to safeguarding "the last pure land in the world", building a beautiful Tibetan Plateau, and bringing more happiness and well-being to people of all ethnic groups on the plateau. In this context, it is of great importance to study the suitability of human settlement environment on the Tibetan Plateau to promote local development.

Despite the growing number of studies on natural environment suitability assessment methods [8–11], the following problems remain: First, in the assessment of natural environment suitability, different factors may have different weights in different regions. Elevation, slope, and water resources carry greater weight in mountainous and hilly regions [12,13], while in plains, plateaus, and basins, water resources and climate are more heavily weighted [14]. As a result, the selection and weighting of indicators vary across different regions. Therefore, natural environment suitability assessment method may not be universal in different regions. Second, natural environment factors have complex interrelationships and many of the factors are collinear, which makes it difficult to assign weights. Different weight definition methods may lead to different results. Feng et al. [15] investigated the natural environment suitability of China's human settlement environment based on Chinese population development strategy research entrusted by the National Population and Family Planning Commission in 2006. However, their study focuses primarily on the national scale, with the Tibetan Plateau comprising only a small portion of the analysis. As a result, it lacks a detailed depiction of natural environment suitability specific to the Tibetan Plateau, particularly in terms of its internal spatial differentiation. Wang et al. [16] evaluated human settlement environment suitability in Zhejiang Province, but due to its low elevation and gentle terrain, natural factors that vary greatly with altitude were overlooked. In summary, all those researches have improved our understanding of the suitability of the natural environment. However, plateaus have distinct characteristics, such as low oxygen levels and high radiation [17]. Previous studies have either overlooked these high-altitude features or given them minimal consideration, and no assessment method specifically tailored to the suitability of the natural environment in high-altitude regions has been proposed.

The determination method of indicator weights can profoundly influence the outcomes of natural environment suitability assessments. A wide range of techniques are currently employed, including the analytic hierarchy process, the entropy weight method, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) model, the Delphi method, and the random forest (RF) method. Each method assigns weights to suitability indicators from a different perspective, often producing divergent results [18]. Yet, this methodological fragmentation is frequently overlooked. Therefore, systematically evaluating how methodological choices shape zoning outcomes carries urgent scientific and practical importance for researchers, policymakers, and planners. To ensure robustness and accuracy, multiple weighting methods should be applied and compared.

In summary, although extensive research has been conducted on natural environment suitability, the unique conditions of high-altitude regions require a more focused investigation. In such areas, it is necessary to incorporate plateau-specific indicators and weighting methods when evaluating environmental suitability. Therefore, this study aims to assess the natural environment suitability for human settlement on the Tibetan Plateau, analyze the differences in results obtained from various weighting methods, and ultimately carry out regionalization based on human settlement quality in the natural environment. The findings are intended to provide a theoretical foundation to support human settlement planning in the region.

Methods

Study area

The Tibetan Plateau, which is located southwestern China (26°00′12″N to 39°46′50″N, 73°18′52″E to 104°46′59″E), is the highest physical geographic unit in the world. The Tibetan Plateau covers an area of 258.24×10^4 km^2, accounting for 26.8% of the total land area of China including Xizang, Qinghai, and parts of the Xinjiang, Gansu, Sichuan, and Yunnan provinces (Fig. S1). The average altitude of the Tibetan Plateau is >4,000 m above sea level. It is the origin of many large rivers in East, Southeast, and South Asia and an important ecological security barrier in China and Asia. The high altitude of the Tibetan Plateau, that is, the third pole of the world, has caused regional isolation, which led to the formation of a special natural and geographical environment and a unique national culture. The Tibetan Plateau is vast and sparsely populated, the level of urbanization is low, and human activities greatly differ from those at low altitudes. In recent years, the intensity of human activity in the Tibetan Plateau has increased [12]. Rapid urbanization and population agglomeration drive local economic development but put pressure on the natural environment in high-altitude areas. Therefore, the Tibetan Plateau is a particularly ideal area for the study of high-altitude natural environment suitability assessment methods, and it is vital to carry out suitability assessment in the Tibetan Plateau.

Dataset used in research

Slope, aspect, altitude, temperature [19], solar radiation, and precipitation data [20] are obtained from the National Tibetan Plateau/Third Pole Environment Data Center. Active accumulated temperature (AAT) data are obtained from the Resources and Environmental Sciences and Data Center [21]. The population data used in the study are obtained from ORNL LandScan [22]. The main river data are obtained from the National Geomatics Center of China, and the distance to the main river is obtained using the ArcGIS Euclidean distance. The Normalized Difference Vegetation Index (NDVI) data for the period of 2000 to 2019 is obtained from the National Aeronautics and Space Administration (NASA) Earth Observing System Data and Information System (https://ladsweb.modaps.eosdis.nasa.gov/). All data are converted to 1,000 m and all maps in this study have a resolution of 1,000 m. All data sources in this paper are shown in Table 1.

Natural environment suitability index of the plateau

To assess the natural environment suitability of the Tibetan Plateau, 9 natural factors were selected as evaluation indicators, and the influence of each factor on human settlement quality was analyzed, with their thresholds determined using the

Table 1. Data sources

Indicator	Variable	Unit	Producer	Time	Data sources
Terrain	Slope	°	Tang Guo'an	–	The National Tibetan Plateau/Third Pole Environment Data Center (http://data.tpdc.ac.cn)
	Aspect	°	Tang Guo'an	–	The National Tibetan Plateau/Third Pole Environment Data Center (http://data.tpdc.ac.cn)
	Altitude	m	Tang Guo'an	–	The National Tibetan Plateau/Third Pole Environment Data Center (http://data.tpdc.ac.cn)
Climate	Temperature	°C	Yang Kun	1980–2019	The National Tibetan Plateau/Third Pole Environment Data Center (http://data.tpdc.ac.cn)
	Solar radiation	$W/(m^2 \cdot a)$	Yang Kun	1980–2019	The National Tibetan Plateau/Third Pole Environment Data Center (http://data.tpdc.ac.cn)
Hydrology	Precipitation	mm	Yang Kun	1980–2019	The National Tibetan Plateau/Third Pole Environment Data Center (http://data.tpdc.ac.cn)
	Main rivers	–	Government	1980–2019	National Geomatics Center of China (https://www.ngcc.cn/)
Vegetation	AAT	°C	Xu Xinliang	-	Resources and Environmental Sciences and Data Center (http://www.resdc.cn)
	NDVI	–	NASA	2000–2019	MODIS (https://ladsweb.modaps.eosdis.nasa.gov/search/)
Population density		cap/km^2	Rose	2019	ORNL's LandScan (https://landscan.ornl.gov/)

natural location quotient. Factor weights were then assigned through a combination of methods, including the RF method, the consulting graded method, and the correlation coefficient method. Based on these results, a spatial distribution map of natural environment suitability was produced. Finally, spatial analysis and regionalization of environmental suitability were conducted using the natural breaks classification method combined with restrictive factor thresholds (Fig. 1).

Characteristic indicators

When developing the natural environment suitability assessment method, we take population density as a characteristic indicator to represent the natural environment suitability, which is widely used to assess the suitability of the natural environment [15,23,24]. It suggests that people tend to migrate to places with a suitable natural environment for human settlement, and with thousands of years of migration, the higher the population density, the better the natural environment suitability. However, population density is affected not only by the natural environment but also by social and other factors such as transportation, urban planning policy, religion, and historical origins. By analyzing the relationship between population and land on the Tibetan Plateau, we found that 70% of the population lives on 2% of the land on the Tibetan Plateau, which is obviously not caused by natural environmental factors but caused by the agglomeration effect of cities (Fig. 2). Moreover, 100% of the population on the Tibetan Plateau is distributed across only 32% of the land, with large areas remaining sparsely populated. If these vast unpopulated areas are used to determine the weights for each indicator, the natural environment suitability assessment would be inaccurate. Therefore, the population density of the Tibetan Plateau after excluding the area that covers the top 2% of the population density and the unpopulated areas (68%) is used to determine the weights for each indicator.

Indicator system

Based on previous studies, 9 natural environmental factors, that is, the slope, aspect, altitude, temperature, solar radiation, distance to the main rivers, precipitation, AAT, and NDVI, are used to develop the method for the assessment of the suitability of the natural plateau environment [10,11,15]. Precipitation and temperature are the key climatic factors shaping the suitability of human settlements. The distance to major rivers determines the ease of accessing water resources, while slope, aspect, and altitude influence the challenges of production and daily life. NDVI, in turn, reflects the state of vegetation. Notably, these factors include high-altitude characteristics such as solar radiation and AAT [6]. Compared to low-altitude areas, high-altitude regions experience intense solar radiation, which poses serious risks to human survival [25]. AAT, an ecological factor crucial for vegetation growth and development, is typically used for vegetation zoning at low altitudes and has minimal impact on human activities in those regions. However, at high altitudes, the extremely low effective accumulated temperature severely restricts food availability, thereby limiting human habitation [26]. Additionally, oxygen partial pressure is a critical factor affecting human survival on high-altitude areas, which is determined by both the oxygen volume fraction and atmospheric pressure. We use extensive measured data from the Tibetan Plateau to explore the relationship between oxygen partial pressure and altitude [27,28]. The oxygen partial pressure (oxygen volume fraction × atmospheric pressure) was calculated and found that it is linearly correlated with altitude (Fig. S2). Therefore, this study uses altitude as a proxy for oxygen partial pressure.

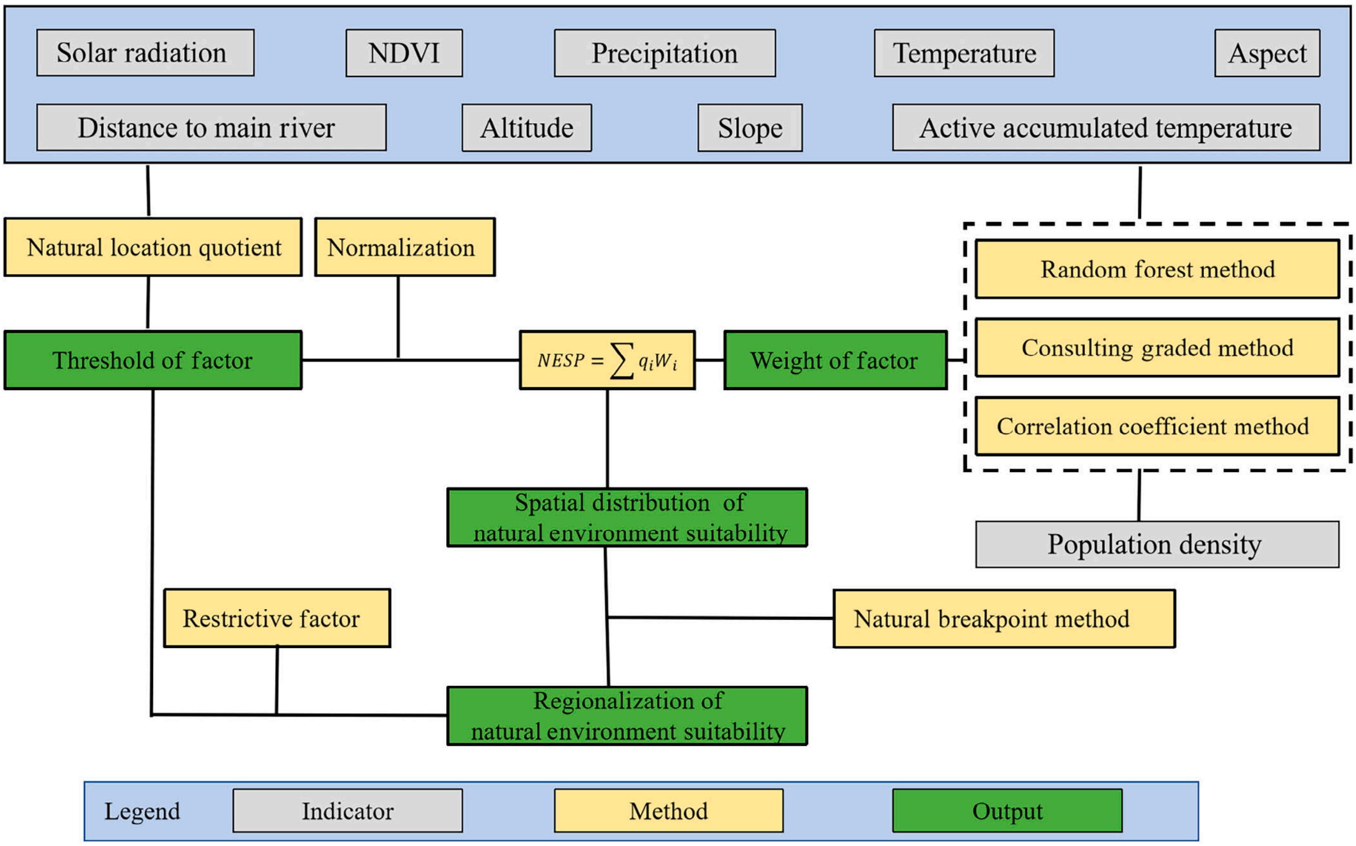

Fig. 1. Theoretical framework for assessing natural environment suitability for human settlements in this study.

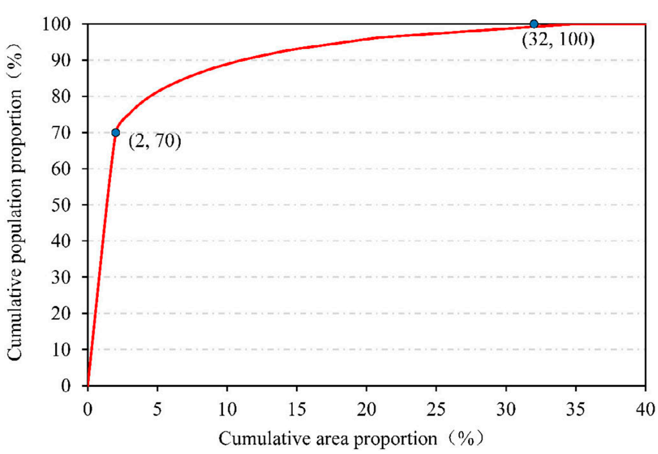

Fig. 2. The relationship between population and land density on the Tibetan Plateau.

To assess the effect of individual natural factors on human settlement quality, we employed the natural location quotient, which is based on the concept of location entropy in economics [29,30]. It depicts the relative relationship between population distribution and natural conditions, essentially reflecting the types of natural environments that are preferred for human settlement. The equation is:

$$Q_{ij} = \frac{\frac{P_{ij}}{Ai}}{\frac{P}{A}} \tag{1}$$

where Q_{ij} is the natural location quotient of natural environment factor j in the ith analysis unit, P_{ij} is the population in the ith analysis unit, Ai is the area of the ith analysis unit, P is the total population of the research area, and A is the total area of the research area. The higher the $\mathbf{Q_{ij}}$ value is, the higher is the population concentration and the better is the suitability of the natural environment. When $Q_{ij} < 1$, the natural environment factor j in this region is severe and is the restrictive factor in this area; the smaller the Q_{ij} value is, the more unsuitable is the environment.

The natural location quotient represents the relative relationship between population distribution and natural environmental conditions. It is obtained by extracting the grid values of natural factors across the Tibetan Plateau using ArcGIS and ranking the grids from high to low according to each natural factor. The grids are then divided into 100 units for analysis, and the natural location quotient is calculated for each unit.

To eliminate the dimensional effects of indexes, data normalization is required. Different normalization methods are used to ensure that the higher the index is, the more suitable is the natural environment.

The higher the index is, the more suitable is the natural environment. The normalization equation is as follows:

$$x^* = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \tag{2}$$

The lower the index is, the more unsuitable is the natural environment. The normalization formula is as follows:

$$x^* = \frac{x_{\max} - x}{x_{\max} - x_{\min}} \tag{3}$$

If the index has a special value that makes the natural environment more suitable, the normalization equation is as follows:

$$x^* = 1 - \frac{\left|x_{\mathrm{sp}} - x_i\right|}{\max\left|x_{\mathrm{sp}} - x_i\right|} \tag{4}$$

where x^* is the value after normalization; $x_{\max}$ is the maximum value of the factor in the Tibetan Plateau; $x_{\min}$ is the minimum value of the factor in the Tibetan Plateau; and x_{sp} is the value of the factor in the Tibetan Plateau, which is the most suitable for human settlement.

Weight definition methods

We use 3 methods to determine the weight of evaluating the suitability of natural environment, among which the RF method is a new method based on machine learning and big data operation, the consulting graded method represents people's subjective feelings on the suitability of natural environment, and the correlation coefficient method represents the correlation between various natural factors and suitability, which is an objective method.

RF method

The rapid development of geospatial big data and machine learning has provided a new method for the development of a natural environment suitability assessment method. RF has emerged as a machine learning method in recent years [31]. It is a nonlinear model that could be used to simulate the complex relationships between multiple influencing factors and avoid the effect of collinearity on the result. Determining the weight of each natural factor is the key to build the plateau natural environment suitability assessment method. It is difficult to objectively assign weights because of the complex interrelations among various natural environmental factors, which may be collinear. The RF method could be used to optimize the results and avoid the collinearity problem. Therefore, we used the importance values determined by the RF as the weights of each index to develop the assessment method of the suitability of the natural plateau environment. The RF importance value is determined using the Gini coefficient, which is widely used as a weight in different models [32,33].

The main parameters that affect the RF accuracy are the number of trees and maximum depth. ArcGIS is used to randomly generate 10% of total grid points and extract information about each element associated with the points. The RF model is trained using the population as the goal orientation. The optimal RF parameters are selected using a cross-validation method. The results show that the RF model is the best when the number of trees is 631 and the maximum depth is 57. Subsequently, the importance values of each factor are obtained (Fig. S3).

Consulting graded method

The consulting graded method determines the weight by taking into account the accumulated experience of experts who work on the Tibetan Plateau for a long time. This method combined the opinions of 10 scholars who have studied the Tibetan Plateau for more than 1 year to obtain the weights of every index in plateau natural environment suitability index.

Table 2. Weight obtained by different methods

Variable	CCM	CGM	RFM
Solar radiation	0.120	0.144	0.106
Precipitation	0.104	0.132	0.141
Altitude	0.121	0.123	0.114
Distance to the main river	0.107	0.121	0.124
Temperature	0.120	0.120	0.102
NDVI	0.130	0.110	0.168
AAT	0.065	0.102	0.037
Slope	0.110	0.094	0.114
Aspect	0.121	0.054	0.094

CCM, correlation coefficient method; CGM, consulting graded method; RFM, random forest method

Correlation coefficient method

This method uses the correlation coefficient between index factors and population density as the weight of the index. The correlation of every natural environment factor with population density is analyzed. On this basis, the weight of each individual index was determined according to the proportion of the correlation coefficient between the environment factors and population density in the total sum of the correlation coefficient.

Model construction

Then, the method to assess the natural environment suitability of plateau is developed. The equation is as follows:

$$\mathrm{NESP} = \Sigma q_i W_i \tag{5}$$

where q_i is the weight obtained by the RF method, consulting graded method, and consulting graded method. The weights determined by the 3 methods can be found in Table 2. W_i is the natural factor after normalization. The natural factor and normalization used in this study can be found in the "Indicator system" section.

NESP is the Natural Environment Suitability Index of the Plateau and it is a dimensionless number ranging from 0 to 1. The larger the value is, the more suitable is the natural environment.

Regionalization of natural environment suitability

To provide guidance for regional development, this study is based on the assessment results and actual investigation. The characteristics of geographical factors are considered and the natural environment suitability is regionalized to provide a basis for regional economic development and infrastructure construction. The main regionalization method is as follows:

Step 1: Primary zoning based on natural breaks

In the first step, we assessed the natural environment suitability across the Tibetan Plateau and applied the natural breaks classification method to delineate the primary zones (Level I). This method determines break points by maximizing interclass differences and minimizing intraclass variance, making it particularly suitable for data with nonuniform distribution. Based on the natural environment suitability contours, the plateau was classified into 4 categories: very suitable, suitable, unsuitable, and very unsuitable. This classification reflects the spatial heterogeneity of the natural environment and provides a foundation for more detailed subzoning.

Step 2: Secondary zoning based on restrictive factors

Building upon the primary zones, we conducted a secondary zoning (Level II) using restrictive factors identified through the natural location quotient method. A range of environmental indicators, such as temperature, precipitation, soil properties, and vegetation coverage, were evaluated to determine which factors limited suitability in each area. Thresholds for each restrictive factor are detailed in the "Indicator system" section and Table 3. The number of limiting factors was used to define secondary region types: Very unsuitable secondary zones possess 5 or 6 restrictive factors; unsuitable zones have 3 or 4 restrictive factors; suitable zones have 1 or 2 restrictive factors; and very suitable zones have no limiting factors or only one restrictive factor. This stratified classification ensures that each secondary zone maintains a high degree of internal consistency and ecological relevance.

Step 3: Regional adjustment and naming

To further refine the zoning results, we incorporated geographical characteristics, spatial patterns, and regional coherence. Manual adjustments were made based on known landscape boundaries, administrative divisions, and expert knowledge. Each final zone was then named using a standard format: [Geographical name] - [Suitability category] (e.g., "Qinghai Basin -Suitable"). For each zone, the dominant restrictive factors were identified and recorded, providing a clear ecological profile for future management and planning applications.

Results

Effect of individual nature factors on environmental suitability

We used the natural location quotient to evaluate the influence of each natural environmental factor on suitability. According to the natural location quotient, the relationship between natural environmental factors and suitability could be classified into 3 groups (Fig. 3). The first group is altitude, slope, solar radiation, and distance according to the river. The lower the value of the natural location quotient, the more unsuitable for human settlement, while the second group is AAT, temperature, rainfall, and NDVI. The higher the value of the natural location quotient, the more suitable for human settlement. The third group is the aspect; there is an optimal threshold (120°) of the natural location quotient; the farther away from this threshold, the less suitable for human settlement. At the same time, the first group and second group have a range (from minimum threshold to maximum threshold) of influence on natural environmental suitability. Within this range, there is a good linear relationship between natural environment factors and natural location quotient, indicating that natural effects have a marked impact on suitability, and beyond the range, the restricting effect of natural environmental factors will not be obvious. To further determine the threshold effects of natural environmental factors, we employed an optimal fitting approach. Specifically, the thresholds were identified by selecting the range that produced the highest R^2 value during the fitting process. The threshold can be found in Table 2. Besides, in order to accurately express the influence of natural factors on suitability, we decided to use the normalized formula within the range (see details in the "Indicator system" section), and directly setting the normalization value as 0 or 1 if the value is outside the range of minimum threshold to maximum threshold. We determined the minimum and maximum thresholds based on the results of the natural location quotient and normalized the data accordingly. In addition, we take natural position entropy = 1 as the judgment condition and determine the threshold value of each factor as the restrictive factor (Table 3). It lays a foundation for determining the restrictive factors of each area in the next step of natural environment suitability regionalization.

Spatial pattern of natural environment suitability

We applied 3 weighting methods to obtain 3 different spatial distributions of natural environmental suitability on the Tibetan Plateau. The spatial patterns derived from these methods are generally similar, exhibiting comparable density distribution curves, while also assessing natural environmental suitability from different subjective and objective perspectives (Fig. 4A to C). Besides, we assessed the variability of the natural environmental suitability obtained using 3 different weighting methods. The results indicate that the variability among the outcomes is

Table 3. Thresholds of natural environment factors

Indicator	Variable	Minimum threshold	Maximum threshold	Restrictive threshold
Terrain	Slope (°)	3	15	9
	Aspect (°)	0	360	<45 or >270
	Altitude (m)	3,000	6,000	4,500
Vegetation	NDVI	0	0.9	0.3
	Active accumulated temperature (°C)	0	2,000	0
Climate	Solar radiation (W/m^2)	220	280	250
	Temperature (°C)	−10	5	0
Hydrology	Precipitation (mm)	0	1,000	400
	Distance to main river (km)	0	400	100

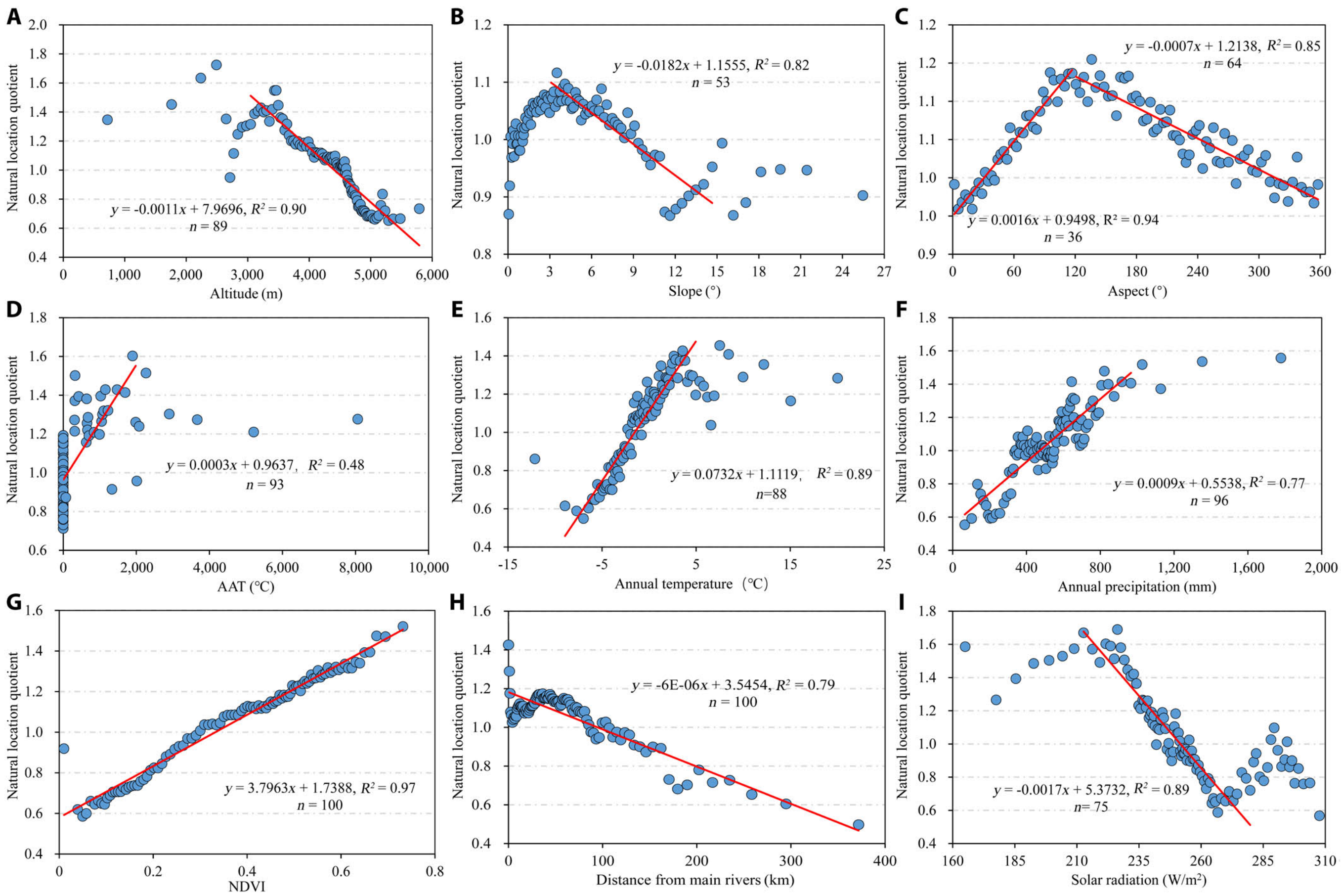

Fig. 3. Natural location quotient of each natural environmental factor. Higher values of the natural location quotient indicate better suitability of the environmental factor. (A) Altitude, (B) slope, (C) aspect, (D) annual accumulated temperature (AAT), (E) annual temperature, (F) annual precipitation, (G) NDVI, (H) distance to main rivers, and (I) solar radiation.

very low, with the maximum value not exceeding 15%, primarily occurring in the northwestern region of the Tibetan Plateau (Fig. 4E and F). To comprehensively account for these aspects, we constructed the NESP by averaging the results of the 3 methods (Fig. 4D). NESP represents the overall evaluation of natural environmental suitability, calculated as the mean of the 3 approaches.

NESP shows decreases from east to west (Fig. 4A), indicating that the natural environment of the Tibetan Plateau becomes increasingly unsuitable from east to west with an increase in altitude, precipitation, and a decrease in oxygen levels. The eastern and southeastern parts of the plateau and river valleys represent the best natural environment of the Tibetan Plateau. Areas with a poor natural environment are mainly distributed in the western part of the Tibetan Plateau (Fig. 5).

The Tibetan Plateau could be divided into 4 natural environment suitability areas based on the natural break point method: very suitable, suitable, unsuitable, and very unsuitable areas (Fig. 5). The most suitable area is 24.93×10^4 km^2 (9.7%) in size, mainly distributed on the eastern edge of the Tibetan Plateau. The adjacent area to the west is a suitable area with an area of 55.4×10^4 km^2 (21.4%). In addition, the valley area is also a more suitable area. The inland area is an unsuitable area with a size of 67.7×10^4 km^2 (26.2%) and the farthest inland area is a very unsuitable area, covering an area of 110.2×10^4 km^2 (42.7%), which is almost uninhabited. More than 69% of the area is classified as very unsuitable or unsuitable with severe natural conditions and less than 31% is classified as suitable or very suitable area.

Natural environment suitability regionalization

To better support regional economic development and spatial planning, we conducted a comprehensive regionalization of the natural environment suitability across the Tibetan Plateau. This process was based on the spatial distribution patterns and limiting factors identified through our research and was further refined by incorporating local administrative boundaries and cultural characteristics. As a result, the plateau has been divided into 11 distinct suitability zones, each named following the format of "geographical name - suitability region type" (Fig. 6).

The environmental suitability of the Tibetan Plateau is categorized into 4 hierarchical levels: very suitable (A), suitable (B), unsuitable (C), and very unsuitable (D). Each category is further subdivided into representative subregions, reflecting both natural characteristics and human–environment interactions.

Very suitable regions include Nyingchi (AI) and Xining–Ruoergai (AII), which benefit from favorable climatic conditions, relatively moderate elevations, and abundant ecological resources, making them highly conducive to human habitation and economic activity.

Suitable regions encompass the Three-River Source Region (BI), the Southeastern Alpine Valley (BII), and the Kangding-to-Gaize

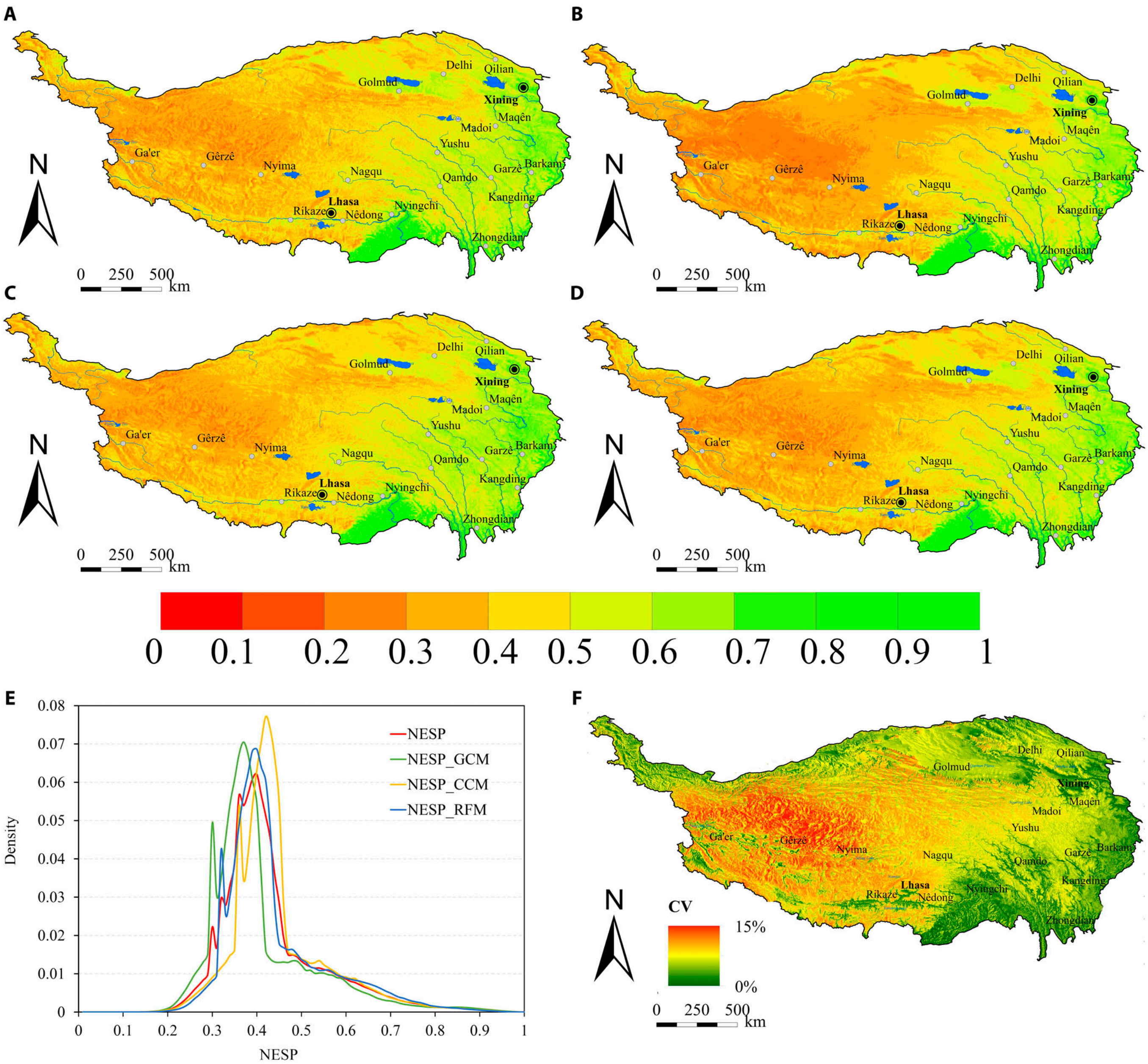

Fig. 4. Suitability of natural environment on the Tibetan Plateau. (A) Spatial distribution of the suitability index of the natural plateau environment on the Tibetan Plateau obtained by the random forest method. (B) Spatial distribution of the suitability index of the natural plateau environment on the Tibetan Plateau obtained by the consulting graded method. (C) Spatial distribution of the suitability index of the natural plateau environment on the Tibetan Plateau obtained by the correlation coefficient method. (D) Spatial distribution of the suitability index of the natural plateau environment on the Tibetan Plateau obtained by the average of 3 methods. (E) Density distributions of the 4 methods. (F) Coefficient of variation (CV) of the 3 weight determination methods.

Corridor (BIII). These areas possess moderate environmental advantages but may still face certain constraints such as rugged terrain.

Unsuitable regions, such as the Qaidam Basin (CI), the broad valley and lake basin of the Yellow River Source (CII), and the Lhasa-to-Nagqu belt (CIII), are primarily limited by aridity, high altitude, and ecological vulnerability, which collectively reduce their capacity to support sustained human development.

Very unsuitable regions include the North Kunlun Mountains (DI), the Northern Tibetan Plateau (DII), and the upper reaches of the Yarlung Zangbo River (DIII). These regions are marked by extreme environmental conditions, such as severe cold and hypoxia, which greatly hinder human settlement and infrastructure development.

Furthermore, each suitability region is associated with specific environmental constraints, which serve as key limiting factors in their development potential. These restrictive factors are illustrated in Fig. S6, and detailed descriptions of each region's characteristics and constraints are provided in Table S1. In summary, we mapped the spatial distribution of natural environment suitability for human settlement and, based on our findings, conducted a regionalization of the Tibetan Plateau, identifying the limiting factors specific to each zone.

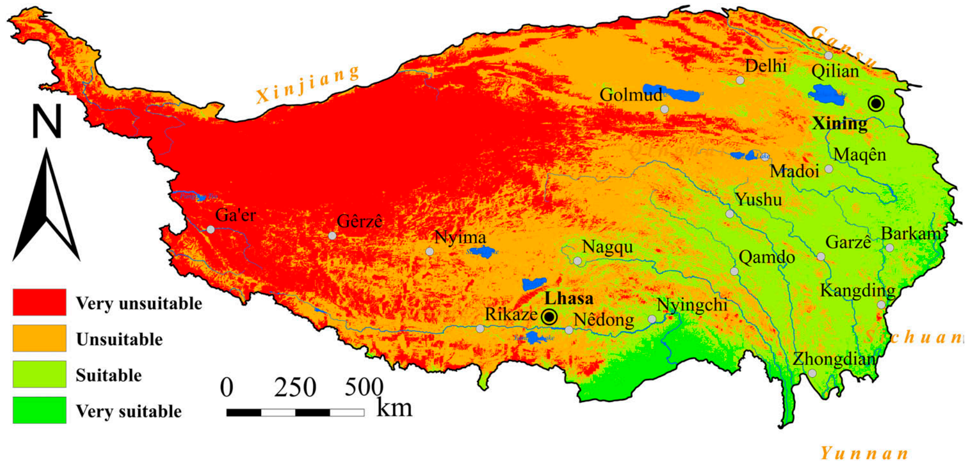

Fig. 5. The suitability zones of the natural environment on the Tibetan Plateau, divided into 4 categories (very unsuitable, unsuitable, suitable, and very suitable) using the natural break point method based on NESP.

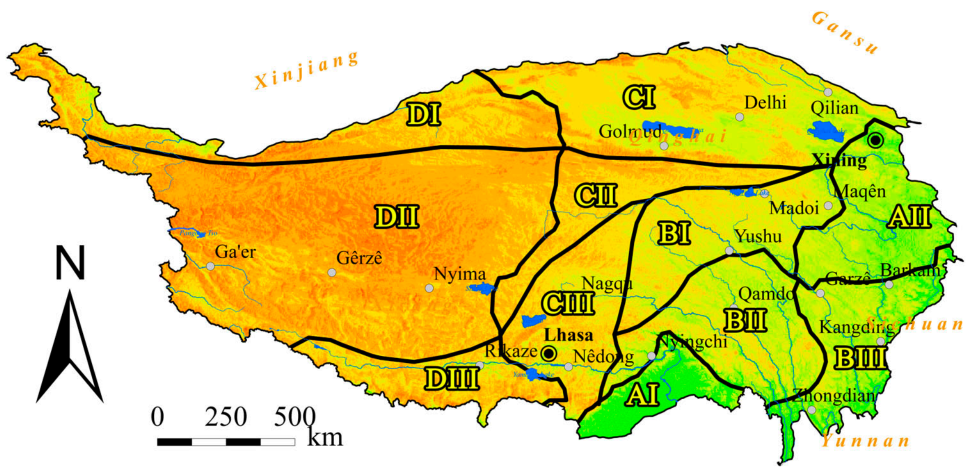

Fig. 6. Regionalization of the natural environment suitability on the Tibetan Plateau. The Tibetan Plateau is classified into 4 main categories of environmental suitability: very suitable regions include Nyingchi (AI) and Xining to Ruoergai (AII); suitable regions include the Three River Source (BI), Xizang Southeast Alpine Valley (BII), and Kangding to Gaize (BIII); unsuitable regions include the Qaidam Basin (CI), Yellow River Source Wide Valley Lake Basin (CII), and Lhasa to Nagqu (CIII); very unsuitable regions include North Kunlun Mountains (DI), Northern Tibetan Plateau (DII), and the Upper Reaches of the Yarlung Zangbo River (DIII).

Discussion

The robustness of natural environment suitability results

Firstly, the determination of indicator weights has long been a critical aspect in natural environment suitability assessments, as the weighting process strongly affects influences the accuracy and credibility of the final evaluation results. To enhance the robustness and representativeness of our assessment, we adopted a comprehensive approach that integrates subjective, objective, and data-driven methods to determine the weights of the factors involved in evaluating natural environment suitability. First, we applied the consulting graded method, a widely used subjective approach that captures expert knowledge and human perception regarding the relative importance of environmental factors in influencing settlement suitability. This method reflects the experiential understanding of environmental constraints and advantages accumulated over time, making it valuable for incorporating local knowledge and contextual sensitivity [34]. Second, we utilized the correlation coefficient method, an objective statistical approach that determines the weights based on the strength of the relationship between each environmental factor and population density—a proxy for human settlement preference [26]. This method minimizes human bias and allows the weight assignment to be driven by empirical evidence. Third, we employed the RF algorithm, a machine learning technique known for its robustness, flexibility, and ability to handle complex nonlinear relationships among variables. As a data-driven method, RF provides a more comprehensive and technologically advanced means of weight determination, offering a new avenue for enhancing the scientific rigor of regional planning and environmental assessments [35]. The natural environment suitability maps generated using the 3 weighting strategies demonstrated a consistent spatial pattern across the Tibetan Plateau, suggesting a high degree of agreement in the understanding of environmental suitability regardless of the method employed (Fig. 4). This consistency not only validates the reliability of our methodological framework but also reinforces the robustness of the spatial trends observed. To synthesize the strengths of each method and reduce the influence of any single methodological bias, we calculated the final NESP by averaging the results derived from the 3 approaches.

Secondly, we classified the Tibetan Plateau into 4 suitability categories—very unsuitable, unsuitable, suitable, and very suitable—based on the calculated NESP. The classification was performed using the natural break (Jenks) method, which is widely employed in spatial analysis to identify inherent patterns in the data by minimizing variance within groups and maximizing variance between groups [36]. To further enhance the reliability and objectivity of the classification results, and to ensure that the delineated suitability zones were not unduly influenced by a single classification scheme, we additionally applied 3 alternative grading methods: the quantile method, the geometrical interval method, and the standard deviation method. A comparative analysis of the spatial distribution patterns resulting from these 4 classification techniques revealed a high degree of consistency (Fig. S4), with all methods producing similar regional patterns of suitability. This convergence across multiple classification frameworks underscores the robustness and internal consistency of our evaluation results. The similarity in spatial zoning outcomes suggests that the underlying suitability patterns identified by our assessment are stable and largely unaffected by the specific method of classification.

Besides, we divided the Tibetan Plateau into 11 regions. The regionalization of the suitability of the natural environment in the Tibetan Plateau has not been studied in the past. Therefore, we compare our results with the widely used ecogeographic regional system of the Tibetan Plateau by Zheng et al. [37,38] (Fig. S5). Our regionalization yields similar results in most areas of the Tibetan Plateau compared with the ecogeographic regional system because we all take into account natural factors. The main difference is in the southeastern part of the Tibetan Plateau, and our regionalization in this area is more complex than that of the ecogeographic regional system of the Tibetan Plateau. The reason for this difference is that ecogeographic regional systems mainly focus on the natural environment, whereas the focus of our zoning is placed on the effect of natural environment suitability on human development. The southeastern part of the Tibetan Plateau belongs to the plateau hilly area and has a complex terrain. Although this area belongs to a unified geographical unit, the suitability of adjacent areas varies markedly because of the mountain barrier [39]. Thus, we need a more complex division to describe the impact of different natural environments on human settlement.

The correlation between natural environment suitability and population distribution serves as an important means of validating the accuracy and practical relevance of the NESP. In our study, a statistically significant positive correlation was observed between NESP and population density ($P < 0.01$) (Fig. 7). Nevertheless, certain regions exhibit notable deviations from this overall trend. For example, the Nyingchi area demonstrates a relatively high environmental suitability score but maintains a low population density. This discrepancy may be attributed to its geopolitical location along the China–India border, where historical and ongoing territorial tensions could have constrained large-scale population settlement despite favorable natural conditions [40]. Similarly, the Xining region also shows a marked deviation from the fitted regression line, indicating that factors beyond natural environmental suitability—such as administrative status, economic development policies, infrastructure availability, and regional governance—play a critical role in shaping population distribution. These spatial mismatches highlight the complex interplay between environmental and socio-political factors in determining settlement patterns on the Tibetan Plateau [41].

In summary, the robustness of our results is validated through multiple lines of evidence, including the consistency across different weight determination methods, the reliability of the regional classification approaches, comparisons with previous studies, and the significant correlation between NESP and population density ($P < 0.01$). These cross-validations collectively demonstrate the stability and credibility of our assessment framework.

Human activities on the Tibetan Plateau based on regionalization

In total, we identified 2 regions as very suitable, 3 regions as suitable, 3 regions as unsuitable, and 3 regions as very unsuitable for human settlement. Given the distinct environmental characteristics and suitability levels of these zones, differentiated strategies for human activity and ecological conservation should be adopted to ensure both sustainable development and effective environmental protection.

In the very suitable regions, natural constraints are minimal, with environmental conditions such as topography, climate, water resources, and soil quality offering optimal support for human settlement and development. These areas provide favorable conditions for infrastructure construction, economic development, and population agglomeration [42]. Therefore, they hold potential for large-scale, planned regional development. However, such development must be implemented under the framework of ecological sustainability, ensuring that growth does not come at the expense of environmental degradation.

In the suitable regions, while natural conditions are generally favorable, several limiting factors, such as undulating terrain and natural disasters, still exist [43]. Historically, these areas have been key zones for human habitation and cultural development, as seen in cities like Yushu and Qamdo. Despite their long-standing settlement history, the environmental fragility of these regions necessitates cautious and informed development [44]. Any future regional planning should strike a balance between population demands and ecosystem integrity. For instance, policies should emphasize low-impact development, restoration of degraded land, and the implementation of environmental thresholds for construction activities [45].

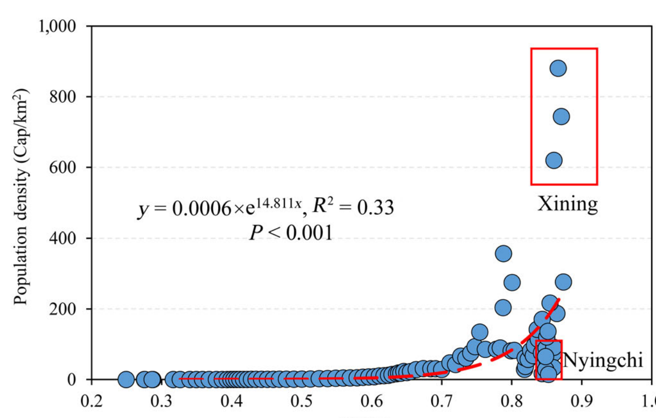

Fig. 7. Correlation between the population density and NESP. We divided the Tibetan Plateau into 100 areas as labels using the Slice (Spatial Analyst) tool in ArcGIS 10.2 and calculated the actual correspondence of each area to NESP and population density. It shows that the relationship between population density and NESP is exponential.

The unsuitable regions are characterized by harsh environmental conditions, including steep terrain, frequent geological hazards, extreme cold, or aridity, which limit their capacity to support large-scale human activity. Development in such areas typically requires a disproportionately high economic cost and is likely to exacerbate ecological risks. Therefore, in these zones, policy efforts should prioritize ecological conservation and the reduction of human-induced pressures. Nonetheless, due to historical or culture considerations, some urban centers—such as Rikaze, located along river valleys—have emerged in these zones [46]. In such cases, targeted ecological compensation policies, stringent environmental regulations, and the possible implementation of ecological relocation or resettlement programs should be considered when necessary, particularly in vulnerable or disaster-prone area [47].

Finally, the very unsuitable regions encompass the vast uninhabited or sparsely populated zones of the Plateau, including areas such as the Changtang in northern Xizang. These areas are marked by extreme environmental conditions—low oxygen levels, severe cold, minimal vegetation, and poor accessibility—rendering them fundamentally unfit for permanent human settlement [48]. Accordingly, these regions should be designated as ecological protection zones with minimal to no human disturbance. Conservation strategies should focus on preserving native biodiversity, maintaining ecosystem functions, and possibly designating large-scale nature reserves or protected areas, such as extensions of the existing national park [49].

It is important to note that our regionalization reflects only the overall conditions of a region. “Unsuitable regions” does not mean that every part of the area is uninhabitable; there may still be suitable areas for human habitation, such as in river valleys. Conversely, even in “very suitable regions”, unforeseen natural disasters, such as earthquakes, could make certain areas unsuitable for human life.

Limitations and prospects

Firstly, the Tibetan Plateau’s unique geographical characteristics pose substantial challenges for comprehensive environmental monitoring. As the world’s highest and most extensive plateau, its extreme altitude, complex terrain, and harsh climatic conditions have resulted in substantial gaps in the monitoring of key natural environmental factors. This limitation underscores the critical need for future research to incorporate more advanced remote sensing technologies and denser observational networks that can provide higher spatial and temporal resolution data, particularly for understanding fine-scale environmental variations across this vast region. Secondly, our methodological approach represents a pioneering effort in high-altitude environmental assessment. The indicator system and weighting scheme were carefully calibrated to account for the distinctive ecological processes and environmental constraints characteristic of such extreme environments. However, the generalizability of this methodology requires further empirical validation across other major high-altitude regions worldwide to determine whether similar parameterizations and thresholds are universally applicable or require regional-specific adjustments. Finally, the Tibetan Plateau’s exceptional sensitivity to climate change adds both urgency and importance to our research. As one of Earth’s most rapidly warming regions and a critical driver of hemispheric climate patterns, the plateau serves as a vital natural laboratory for studying environmental suitability under changing climatic conditions. Our findings not only provide baseline assessments for current conditions but also establish a crucial framework for projecting future scenarios. This work thus contributes valuable insights to the broader scientific understanding of how high-altitude ecosystems may respond to and be managed under anticipated climate change trajectories, with important implications for biodiversity conservation, sustainable development, and climate adaptation strategies across mountainous regions globally.

Conclusion

The aim of this study is to develop a system specifically tailored for high altitudes and determine the appropriate weights for each indicator to assess the suitability of the natural environment on the Tibetan Plateau, providing a theoretical foundation for regional planning in the area. The main conclusions are as follows:

1. We select 9 natural environment factors to build the index system and use 3 weight determination methods (RF method, consulting graded method, and correlation coefficient method) to develop the plateau natural environment suitability assessment method. The natural environment suitability obtained by 3 weight methods show the same trend. We finally use the comprehensive weight of the 3 methods to develop the natural environment suitability assessment method.
2. The suitability index of the natural plateau environment indicates that the natural environment of the Tibetan Plateau becomes more unsuitable from east to west with an increase in altitude, precipitation, and a decrease in oxygen levels. The Tibetan Plateau is divided into 4 areas by using the natural break point method. The most suitable mainly distributes on the eastern edge of the Tibetan Plateau with an area of 24.9×10^4 km^2 (9.7%) in size. The suitable area is mainly in the river valley and on the western side of the very suitable area, with a size of 55.4×10^4 km^2 (21.4%). The unsuitable area lies in the middle of the Tibetan Plateau, which covers 67.7×10^4 km^2 (26.2%). The farthest inland area with a size of 110.18×10^4 km^2 (42.7%) is very unsuitable, sparsely populated, and almost uninhabited, which is the most unsuitable for human settlement.
3. To provide guidance for regional development, we regionalize the suitability of the natural environment in the Tibetan Plateau based on the assessment results and field investigation into 11 regions. The unsuitable region and the very unsuitable region should focus on environmental protection and avoid human activities. The suitable area should be the most important area for human development planning in the future.

Our results may provide a basis for regional economic development and infrastructure construction in the Tibetan Plateau. It also provides basic theoretical support for the evaluation of natural environment suitability in the world’s high-altitude areas.

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Data Availability

Data will be made available on request.

Supplementary Materials

Figs. S1 to S6
Table S1

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Regionalization of Human Settlement Suitability in the Natural Environment of the Tibetan Plateau

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The natural environment provides the geographical foundation for human survival and development; however, its suitability for human settlement in high-altitude regions remains insufficiently addressed. This study focuses on the Tibetan Plateau and proposes a Natural Environment Suitability Index of the Plateau (NESP), designed specifically for high-altitude areas. Using the natural location quotient, we assessed the influence of 9 key environmental factors on settlement suitability. To determine indicator weights objectively and comprehensively, we applied 3 methods: the random forest method, the consulting graded method, and the correlation coefficient method. The results indicate a clear spatial gradient: environmental suitability decreases from east to west as altitude increases. Only about 31% of the plateau is categorized as suitable or very suitable, primarily in low-altitude river valleys, while over 69% is classified as unsuitable or very unsuitable, concentrated in central and western regions. Suitable or very suitable areas are deemed appropriate for regulated human activities under strict environmental protection, while unsuitable or very unsuitable regions should be prioritized for ecological conservation. Based on the NESP, we delineated 11 distinct natural suitability zones across the plateau. This study offers a high-altitude-specific framework for assessing the quality of the natural environment for human settlement, providing a scientific foundation for regional planning, environmental management, and the promotion of Sustainable Development Goals in fragile plateau ecosystems.
Image

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