

Glacier tourism suitability on the Qinghai-Tibet Plateau: Future projections in response to climate change

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Abstract: Against the backdrop of climate change, glacier tourism has become an increasingly visible form of nature-based tourism, and its future development is closely connected to plateau ecosystem protection and local livelihoods. This study develops scenario-based projections of glacier tourism suitability on the Qinghai-Tibet Plateau (QTP). The PLUS model was used to generate scenario-conditioned glacier-extent projections, and an XGBoost model with SHAP interpretation was used to assess tourism suitability. The projections indicate that: (1) by 2035, the high-suitability zone is projected to contract by up to 16.00×10^4 km², while the low-suitability zone is projected to expand by 25.13×10^4 km²; (2) the modeled retention rate of high-suitability areas is 66.7% under SSP1-2.6 and 59.4% under SSP5-8.5, a difference of 7.3 percentage points; (3) glacier viewing accessibility represents 37.21% of the summed mean absolute SHAP importance, with the strongest modeled relationship occurring within 20 km of glaciers; and (4) multi-scenario overlay identifies continuously suitable zones (9.68%), temporarily suitable zones (9.49%), future suitable zones (0.85%), and unsuitable zones (79.98%). These results extend dynamic, scenario-based assessments of glacier tourism suitability, offering practical references for the sustainable development of global glacier tourism in response to climate change.

Keywords: Climate change; Glacier tourism; Suitability evaluation; Multi-scenario simulation; Sustainable development; Qinghai-Tibet Plateau

Introduction

Under the background of climate change, glaciers, as a key component of the cryosphere, are drawing multidimensional and global attention (Dussaillant et al., 2025). Apart from its significant impact on sea levels and water resources, glaciers, as unique, spectacular and increasingly scarce natural landscapes, play an irreplaceable role in global natural heritage protection, ecological tourism development, and regional cultural identity (Van et al., 2025). Over the past few decades, many glaciers around the world have become popular tourist attractions, giving rise to glacier tourism (Welling et al., 2015).

Glacier tourism refers to tourism activities that utilize modern glaciers or glacier relics as tourist attractions. Essentially, it is a form of tourism based on nature (Purdie, 2013). Its development has significant economic, political and symbolic impacts (Salim et al., 2026). In recent years, glacier tourism has received increasing attention (Wang et al., 2020a; Yang et al., 2023), but it is also facing threats from climate change (Wang, 2024; Duglio et al., 2025). How to balance the relationship between the development of glacier tourism and ecological environment protection while responding to climate change is a key scientific issue for achieving sustainable development in the regions where glaciers are located (Wang et al., 2019).

Relevant research has progressively expanded from conceptual definition (Furunes and Mykletun, 2012) to the construction of sustainable resource development models (Bollati et al., 2013), regional development potential assessment (Wang et al., 2020a), and adaptive management of glacier tourism (Salim et al., 2021a). Moreover, the declining stability and aesthetic appeal of glacial landscapes under climate change exert significant impacts on economic and social systems (Wang and Zhou, 2019), further complicating spatial governance (Lv et al., 2023) and compelling the transformation of glacier tourism destination positioning (Mayer et al., 2024; Salim, 2023).

Tourism suitability evaluation refers to determining the weights of different landscape factors based on their importance relative to tourism activities, and their spatial combinations, in order to assess the suitability of different areas for conducting tourism activities (Zhong et al., 2002). By systematically evaluating the resource endowment, environmental constraints and development potential of a specific area, it can achieve spatial optimization allocation, avoid development conflicts, and promote sustainable utilization (Yu et al., 2022; Wang et al., 2022; An et al., 2021), and thus becomes one of the tools for coordinating the relationship between protection and

development. For glacier tourism, this is particularly important and urgent. The glacial ecosystem is extremely fragile and highly sensitive to climate change. The balance threshold between tourism activities and environmental protection is very low. Any improper development could lead to ecological degradation and irreversible loss of resources (Geschke et al., 2025), and also affect the economic development of communities that rely on glacial tourism.

Therefore, a spatially explicit suitability assessment can support the sustainable management of glacier tourism and its host regions. However, research focusing on glacier tourism suitability remains limited. First, compared with other forms of nature-based tourism, relatively few studies have evaluated glaciers as a distinctive tourism resource. Second, most existing assessments focus on current resources and infrastructure and therefore provide limited evidence about how suitability may change under future climate scenarios (Yu et al., 2022; Wang et al., 2022). Although machine-learning methods can represent nonlinear relationships among multiple predictors (Kavzoglu and Teke, 2022; Wu et al., 2025), their outputs remain conditional on the data, sampling design, and scenario assumptions used. Integrating future climate scenarios with suitability assessment may therefore provide additional, rather than definitive, evidence for long-term adaptation planning.

The QTP contains one of the world's largest concentrations of mountain glaciers and provides a large, environmentally heterogeneous case for examining glacier-tourism suitability. This study investigates the influencing factors and projected spatial patterns of glacier tourism suitability under climate change. Specifically, it aims to: (1) characterize the modeled spatial pattern of glacier tourism suitability in 2020 and its associations with selected predictors; (2) compare projected suitability in 2035 under three emission scenarios; and (3) identify differentiated development zones from the multi-scenario overlay and discuss possible adaptation implications. The results may inform spatial planning, ecological-risk screening, and community-transition discussions on the QTP; their relevance to other mountain regions requires context-specific validation.

Materials and methods

Study area. The QTP (within China) is located in the west of China, with an average altitude exceeding 4000 m, and its total area is 2.54×10^6 km² (Fig. 1). As one of the regions with the most concentrated glaciers in the world, the QTP boasts extremely rich and unique glacier tourism resources. Among them, the Midui glacier, the Mushitage glacier, the Laigu glacier, and the Hailuoguo glacier, with their magnificent landscape resources, unique geological features and scientific value, have now been developed into famous tourist attractions. They attract numerous tourists every year and have become an important growth point for the economic development of the local community. Furthermore, there are still a large number of unique landscapes and valuable resources with both aesthetic and scientific value on the QTP that have not been properly developed, and it has great potential for glacier tourism. In the context of global climate change, scientific prediction and the establishment of a suitable pattern for glacier tourism can help promote the sustainable development of regional glacier tourism.

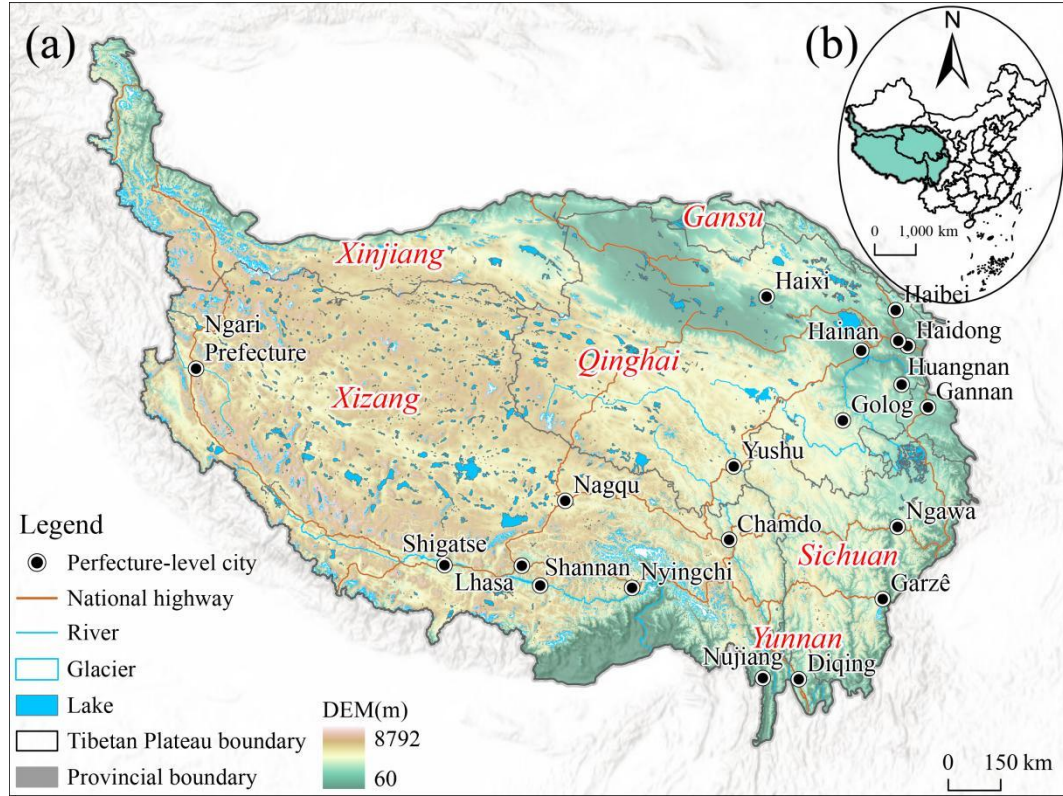


Fig. 1. Study area.(a) The range of the QTP; (b) A geographical map of the QTP in China.

Data sources and preprocessing. The data used in this study include raster, vector, and point datasets. To improve spatial comparability, the datasets were transformed to the CGCS2000 coordinate reference system and processed to a 1 km×1 km analysis grid for 2010–2020 and 2035 (Table 1). The source resolution, temporal coverage, processing method, and intended analytical role of each dataset are reported below and in Appendix C.

First, raster data. Land use (LU), temperature (Tem), precipitation (Pre), population density (PD), and GDP from 2010 to 2020 are all sourced from the National Earth System Science Data Center (NESSDC). DEM is from the Geospatial Data Cloud (GDC). Tem, Pre, wind speed (WS), and relative humidity (RH) for 2035 (under SSP123, SSP245, and SSP585 scenarios) are from the NEX-GDDP-CMIP6 dataset. Solar radiation (SR) is from the National Qinghai-Tibet Plateau Science Data Center (NQTPSDC). Normalized Difference Vegetation Index (NDVI) is from the National Ecological Science Data Center (NESDC).

Second, vector data. The boundary of the QTP is sourced from the NESSDC. Administrative boundaries and locations (ABL) are derived from the Resource and Environment Science Data Platform (RESDP). Tourist reception facilities (TRF) and transportation road networks (TRN) are sourced from OpenStreetMap.

Third, other data. The data of glacier tourist attractions (GTA) is sourced from the cultural and tourism departments (CTD) of each administrative region. It has been compiled into a database containing information such as names, coordinates, and administrative locations.

Table 1 Basic information of multi-source data

Format	Name	Resolution	Year	Source
Raster	LU	TIFF, 30m	2010-2020	NESSDC (www.geodata.cn)
	Tem	TIFF, 1 km	2010-2020	
	Pre	TIFF, 1 km	2010-2020	
	PD	TIFF, 100m	2010-2020	
	GDP	TIFF, 1 km	2010-2020	
	DEM	TIFF, 90 m	2020	GDC (www.gscloud.cn)

	Tem	TIFF, 25 km	2035	
	Pre	TIFF, 25 km	2035	NEX-GDDP-CMIP6 dataset
	WS	TIFF, 25 km	2035	(https://doi.org/10.1038/s41597-022-01393-4)
	RH	TIFF, 25 km	2035	
	SR	TIFF, 10 km	2020,2035	NQTPSDC (https://data.tpsc.ac.cn/)
	NDVI	TIFF, 30 m	2020,2035	NESDC (https://www.nesdc.org.cn/)
	Boundary of the QTP	Shp, -	2020	NESDC (www.geodata.cn)
Vector	ABL	Shp,-	2020	RESDC (https://www.resdc.cn/)
	TRN	Shp, -	2020	
	TRF	Shp, -	2020	OpenStreetMap(openmaptiles.org)
Other	GTA	CSV, -	2020	CTD of each administrative region

Methodology

Research framework. This study used a five-step analytical framework (Fig. 2). First, multi-source data were cleaned, projected, resampled, and standardized to construct a 1 km×1 km feature matrix. Second, based on historical glacier change data and multidimensional driving factors, this study used multiple regression models and the PLUS model to predict the spatiotemporal evolution of glaciers under three SSP climate scenarios by 2035. Third, indicators of glacier-resource endowment, environmental constraints, and service support were combined in an XGBoost model to estimate scenario-specific tourism suitability. Fourth, SHAP values were used to describe the direction and relative magnitude of associations between model predictors and predicted suitability. Fifth, the scenario outputs were overlaid to identify differentiated development zones.

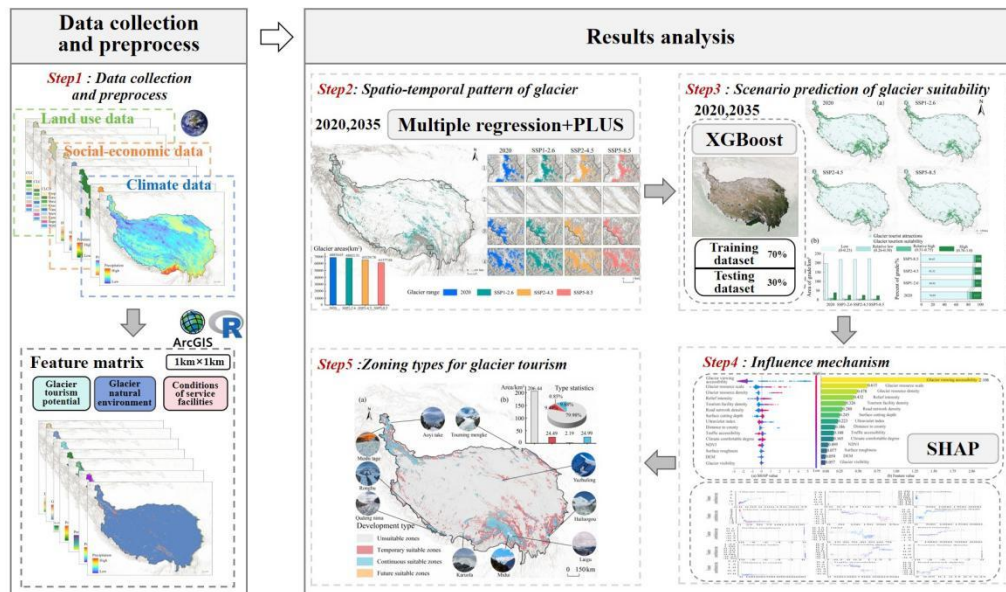


Fig. 2 Research framework

Multi-scenario simulation of glacier extent. To balance the prediction of total glacier area changes with the characterization of spatial heterogeneity in glacial retreat, this study establishes a multi-scenario simulation framework for glaciers that combines regression-based forecasting and PLUS spatial modeling. First, based on the “glaciers and permanent snow” land cover class in the GlobeLand30 dataset (2010–2020), the total glacier area for different years was calculated. A multiple regression model was then established using temperature and precipitation data from the same period as explanatory variables to characterize the relationship between glacier area and climate change. This model was used to determine the future land demand for glaciers under different scenarios. Building on this, the PLUS model was used to further simulate the spatial

patterns of glacial retreat. The PLUS model consists of a rule-mining framework based on the Land Use Expansion Analysis Strategy (LEAS) and a cellular automaton model (CARS) based on multi-type random patch seeds (Tan et al., 2025).

Glacier change is associated with heat and mass balance and varies across the QTP (Zhao et al., 2024; Kumar et al., 2015; Robbins et al., 2023; Xu et al., 2024; McCarthy et al., 2022). The PLUS predictor set included mean temperature and total precipitation, elevation and slope, and GDP and population density. The model was calibrated using glacier-change data and corresponding predictors for 2010–2020 and then applied to the scenario-specific predictor layers. These predictors are spatial proxies and do not explicitly represent glacier thickness, ice flow, accumulation, ablation, or refreezing.

To quantify the impact of different climate change pathways on glacier persistence, this study adopts the Shared Socioeconomic Pathways (SSPs) proposed by the IPCC as a framework for future scenarios (Riahi et al., 2017), selecting three representative scenarios: SSP1-2.6 (sustainable development pathway), SSP2-4.5 (intermediate development pathway), and SSP5-8.5 (fossil fuel-dependent pathway). First, the 2035 temperature and precipitation data for each scenario were input into a regression model to predict the total glacier area in 2035, which was then converted into land demand constraints for the PLUS model; Subsequently, by combining climate and socioeconomic drivers with relatively stable topographic factors for each scenario, the PLUS model was used to simulate the spatial distribution of glacier retreat under the three scenarios, ultimately yielding data on glacier extent in 2035, which served as the basis for subsequent predictions of glacier tourism suitability. The PLUS model parameter settings, training process, and accuracy validation results are presented in Appendix A.

Glacier tourism suitability evaluation. The QTP presents strong spatial heterogeneity and potentially nonlinear relationships among tourism-resource, environmental, and infrastructure predictors. XGBoost was therefore used to estimate suitability from the selected feature matrix (Chen and Guestrin, 2016). The algorithm can represent nonlinear associations and interactions, but its projections remain conditional on the training sample, predictor definitions, hyperparameters, and the assumption that learned relationships remain informative in 2035. The objective function is given below:

$$Obj = -\frac{1}{2} \sum_T^{j=1} \frac{G_j^2}{H_j + \theta} + \gamma T \quad (\text{Equation 1})$$

where: θ denotes the fixed coefficient; γ denotes the complexity coefficient; T denotes the number of leaf nodes in the tree; G_j denotes the sum of first-order partial derivatives for samples in leaf node j ; H_j denotes the sum of second-order partial derivatives for samples in leaf node j .

The XGBoost workflow comprised five steps. First, the predictor layers were harmonized to the 1 km×1 km analysis grid and assembled into a feature matrix. Second, predictor values were extracted for 185 positive samples representing existing or documented glacier-tourism sites and 1,850 negative samples sampled from areas subject to strong ecological, hazard, accessibility, or glacier-absence constraints. The 2,035 samples were divided into training and test sets at a 7:3 ratio. Third, model performance was assessed using probability-threshold comparisons, 10-fold cross-validation, the receiver operating characteristic curve and area under the curve (ROC-AUC), and Bayesian hyperparameter optimization (Sun et al., 2020). Fourth, the trained model was applied to the scenario-specific feature matrices. Fifth, SHAP values were calculated to summarize predictor contributions to the model outputs (Yuan et al., 2024). The sample rules and validation statistics are reported in Appendix B.

Research on the suitability of glacier tourism has predominantly focused on analyzing resource endowments while overlooking the combined impact of ecological fragility and tourism safety in high-altitude environments. Other studies, though addressing service facility conditions, insufficiently consider visitors' comfort perceptions in extreme natural settings, making it difficult to comprehensively reflect the actual suitability of glacier tourism destinations. Therefore, the suitability framework developed in this paper encompasses glacier tourism potential, the natural glacial environment, and the conditions of tourism facilities. Seven criterion-level dimensions and 15 indicators were selected to characterize resource endowment, scenic conditions, ecological constraints, tourism safety, climatic comfort, and service support (Table 2). The specific calculation process of each indicator can be found in Appendix C.

Table 2 Glacier tourism suitability evaluation characteristic matrix

Goal level	Criterion level	Indicator level	Indicator explanation	Indicator source
A1 Glacier tourism potential	B1 Glacier resource endowment	C1 Glacier resource density	Reflects the concentration and enrichment of glacier resources within a unit space.	Welling et al., 2015
		C2 Glacier resource scale	Reflects the grandeur and visual scale of glaciers as a landscape entity.	Salim et al., 2026
		C3 Glacier visibility	Reflects the visual opportunities to observe glaciers from potential tourist activity areas.	Wang et al., 2020a
	B2 Sightseeing and recreational value	C4 Glacier viewing accessibility	Reflecting the accessibility to glaciers and the cost of visiting, the closer the distance, the greater the opportunity for viewing.	Salim and Ravanel, 2023
		C5 NDVI	Reflects vegetation coverage, a direct indicator of ecosystem stability.	Bowen and Stevens, 2020
		C6 Surface cutting depth	Reflects the extent of surface erosion; the deeper the erosion, the more fragile the ecosystem.	Dhami et al., 2017
	B3 Ecological fragility	C7 Surface roughness	Reflects the undulation of the land surface; the rougher the surface, the poorer the ecosystem's recovery capacity.	Yu et al., 2022
		C8 Elevation	Reflects altitude, directly related to low oxygen environments and high-altitude sickness risks.	Yu et al., 2025
		C9 Relief intensity	Reflects the ruggedness of glacier surface terrain, affecting the safety of glacier tourism activities.	Yu et al., 2022
	B4 Tourism safety level	C10 Ultraviolet index	Reflects the intensity of ultraviolet radiation, influencing outdoor tourism experience and health risks.	Amelung and Nicholls, 2014
		C11 Climate comfortable degree	Reflects the overall conditions such as temperature, humidity and wind speed, it indicates the degree of comfort of the climate for the human body.	Prinsloo and Fitchett, 2025
		C12 Tourism facility density	Reflects the spatial concentration and overall bearing capacity of tourism reception facilities.	Hou et al., 2022
	B5 Climatic suitability	C13 Distance to county	Reflects the convenience of obtaining daily life supplies, emergency rescue, and social service support.	Yu et al., 2022
		C14 Traffic accessibility	Reflects the relative convenience of reaching the site from major external tourist sources.	Wang et al., 2020a
		C15 Road network density	Reflects the development of the road network within the area.	Deng et al., 2025

188 Results

189 **Spatiotemporal evolution characteristics of glaciers under different scenarios.** Based on the
190 PLUS model, this study simulated glacier in 2035 under the SSPs (Fig. 3). The analysis of their
191 spatiotemporal evolution patterns reveals three key characteristics.

192 First, glaciers on the QTP are showing a persistent retreat trend, though significant differences
193 exist between scenarios. Under the low-emission SSP1-2.6 pathway, glaciers on the plateau receive
194 relatively effective protection, with their area decreasing by approximately 1.21% by 2035
195 compared to the 2020, maintaining a largely stable glacier system. Under the intermediate SSP2-4.5

pathway, retreat intensifies, with area decreasing by about 5.25%. Under the high-emission SSP5-8.5 pathway, glacier area shrunk dramatically to $6.14 \times 10^4 \text{ km}^2$, representing a loss of 10.86%. This indicated that future socioeconomic development pathways will have a decisive impact on the loss of glacier mass.

Second, the spatial pattern of glaciers on the QTP has evolved from a general retreat to local persistence. Glacier retreat begins first in the lower-altitude marginal areas, foothills, and at the ends of the glaciers. Under SSP2-4.5 and SSP5-8.5 scenarios, previously extensive continuous ice sheets or ice caps gradually fragmented and separated into smaller, spatially isolated glacial bodies, significantly reducing glacial connectivity. This pattern of glacier margin melting, glacier body fragmentation, and glacier front residue will be the main process for the change of the future glacier spatial configuration of the QTP.

Third, under different scenarios, the spatial evolution of QTP glaciers exhibited significant spatial heterogeneity. Temperate glacier distributed in southeastern Tibet and the eastern Himalayas, situated in regions with higher temperatures and abundant precipitation, demonstrate extreme sensitivity in their mass balance response to climate change. Their retreat rates and mass loss were the most pronounced across the entire plateau. In contrast, cold glaciers in the inland regions of the QTP and the western Kunlun Mountains exhibit relatively slow responses to climate warming due to their existence in extremely cold and arid environments, resulting in more moderate retreat rates. This spatial differentiation pattern revealed the internal complexity of glacial systems' responses to climate change.

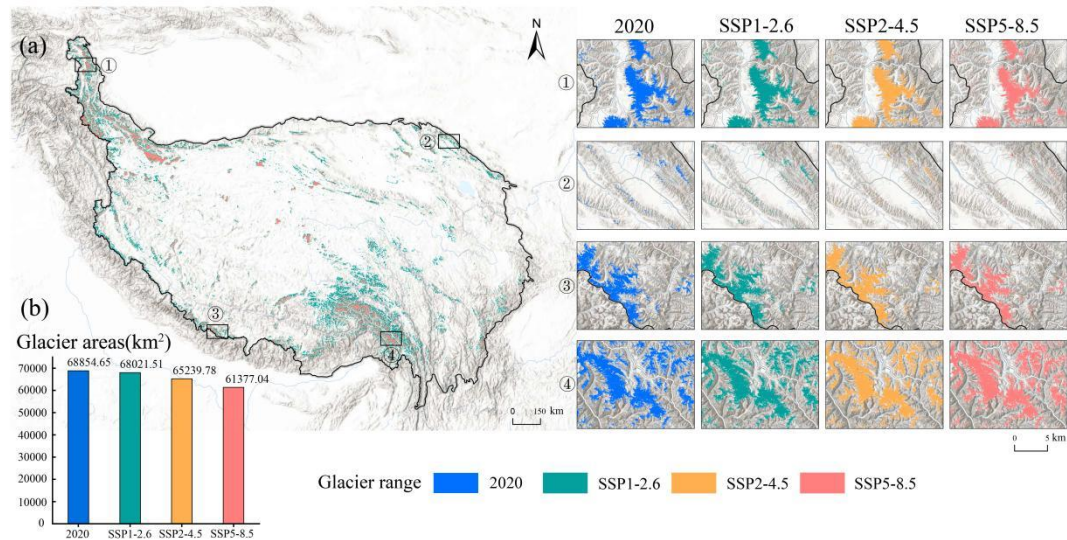


Fig. 3 Multi-scenario glacier extent on the QTP. (a) The spatial distribution of glaciers under the baseline scenario in 2020 and the three climate scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5, with the local enlarged maps of four typical regions on the right (①-④); (b) Comparison of the total glacier area of the QTP under different scenarios (unit: km^2)

Spatial distribution of glacier tourism suitability based on multi-scenario. Based on multi-scenario simulation results, the spatial distribution of glacier tourism suitability on the QTP exhibited three characteristics, revealing the evolution patterns of glacier tourism areas under climate change impacts (Fig. 4).

First, the structure of the glacier tourism suitability has undergone significant changes, showing a continuous decrease in high-suitability areas and steady expansion in low-suitability areas. In 2020, high-suitability areas covered $39.45 \times 10^4 \text{ km}^2$, accounting for 15.27% of the QTP. These zones were primarily distributed at glacier fronts, and glacier tongue terminations with favorable viewing conditions. However, in the SSP5-8.5 scenario in 2035, the area of above zones decreased to $23.45 \times 10^4 \text{ km}^2$ (9.08%). Spatial analysis indicated that these disappearing high-suitability zones were primarily located around lower-elevation temperate glaciers, such as the Midui glacier, Laigu glacier, and Renlongba glacier in Tibet, which are more sensitive to climate change. Conversely, low-suitability areas expanded significantly from $198.45 \times 10^4 \text{ km}^2$ (76.89%) in 2020 to $223.58 \times 10^4 \text{ km}^2$ (86.63%) under the SSP5-8.5 scenario. This dynamic shift reflected the

decline in the quality of scenic resources and the diminished value of the tourist experience resulting from glacial retreat.

Second, the spatial distribution of suitability exhibited pronounced polarization, with the accelerated shrinkage of moderately suitable areas intensifying tourism spatial fragmentation. Moderately suitable areas (encompassing both relatively low and relatively high suitability) exhibited continuous contraction across all three climate scenarios. Their total area decreased from $20.20 \times 10^4 \text{ km}^2$ in 2020 to $11.07 \times 10^4 \text{ km}^2$ under the SSP5-8.5 scenario. This change has led to a shift in the spatial distribution of suitability from a continuous and gradual lineage pattern to a binary pattern with high and low extremes, and the intermediate buffer zones have gradually disappeared. Additionally, the remaining high-suitability areas were mainly distributed in large valley glaciers and ice caps at extremely high altitudes, such as the core glacier areas of the Himalayas and the West Kunlun Mountains, and the landscape connectivity between these patches has weakened. This spatial polarization phenomenon implied that future glacier tourism development will face more severe spatial selection constraints, and the design of tourism routes and the layout of service facilities will be limited.

Third, significant differences existed in the rate of change of suitability under different climate scenarios. Comparing the three emission scenarios, under the SSP1-2.6 strong mitigation path, the proportion of high-suitability areas retained was 66.7%, while under the SSP5-8.5 high emission path, only 59.4% were retained. The preservation of moderately suitable areas showed an even more pronounced difference, with the SSP1-2.6 scenario retaining approximately 14% more relatively high-suitability areas than the SSP5-8.5 scenario. This difference reflected the protective effect of climate policy choices on glacial ecosystems by controlling the rate of temperature increase. From a temporal perspective, the degradation process of the suitability level in the SSP1-2.6 scenario was relatively gentle, while in the SSP5-8.5 scenario, the degradation of the suitability level was more rapid.

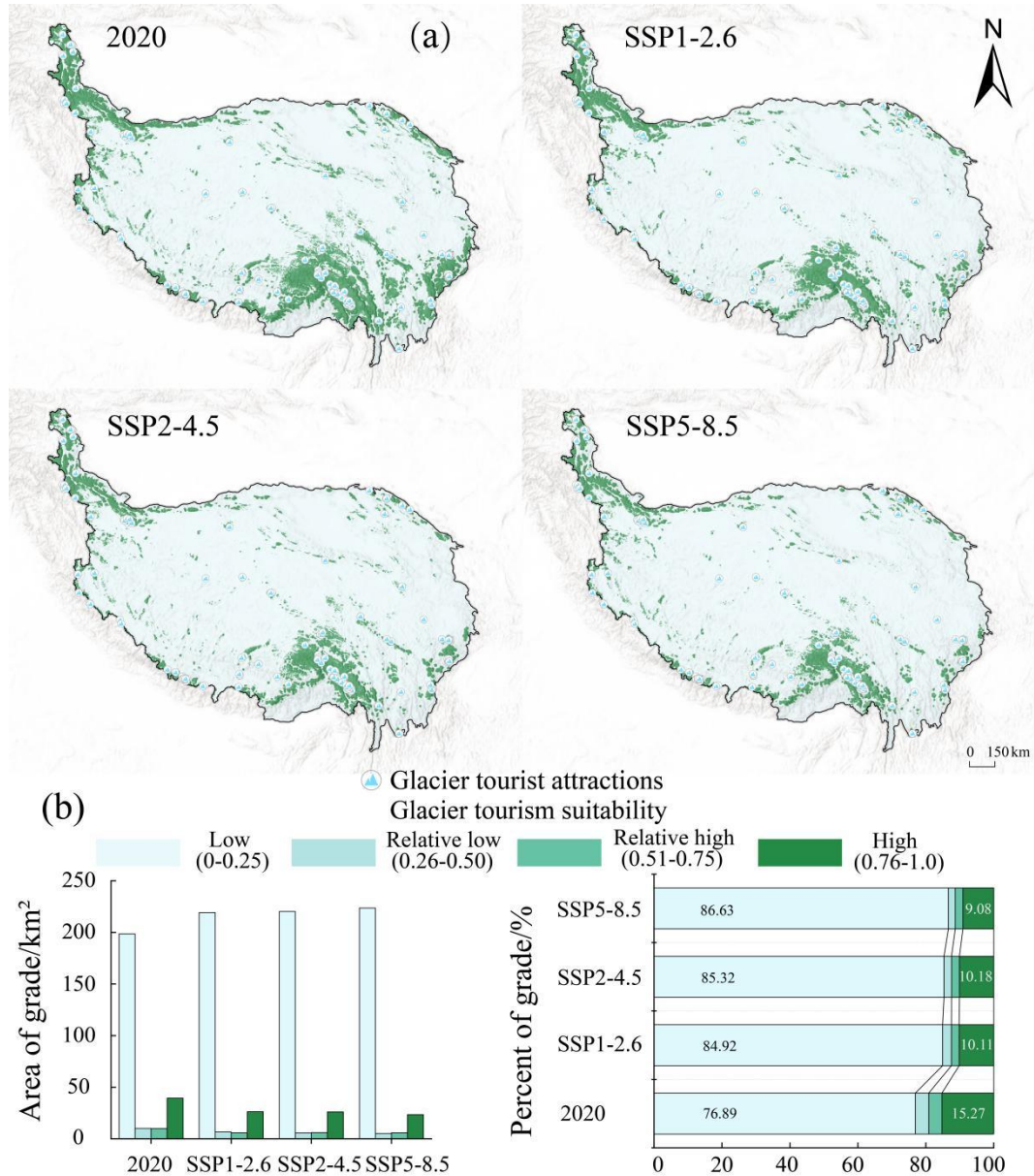


Fig. 4 Spatial distribution of scenario-based glacier tourism suitability on the QTP. (a) Spatial distribution of glacier tourism suitability under the 2020 and the three climate scenarios of SSP1-2.6, SSP2-4.5, and SSP5-8.5, with the locations of glacier tourism attractions overlaid; (b) Area statistics (left, unit: km²) and proportion statistics (right, unit: %) of each level of glacier tourism suitability under different scenarios, with the suitability levels divided into low (0-0.25), relatively low (0.26-0.50), relatively high (0.51-0.75), and high (0.76-1.0).

Analysis of influencing factors for glacier tourism suitability. To delve into the influencing factors of glacier tourism suitability on the QTP, this study employed the SHAP model to conduct interpretability analysis on the outputs of the XGBoost algorithm. It systematically revealed the patterns of influencing factors across three dimensions: the SHAP value, the feature value, and the feature contribution rate.

First, SHAP feature contribution analysis indicated that the direction and intensity of each factor's impact on glacier tourism suitability vary significantly (Fig. 5a). Results showed that glacier viewing accessibility exhibited the strongest negative effect, with its feature values significantly negatively correlated with SHAP values. That is, the closer to the glacier, the higher the accessibility for viewing, and the higher the tourism suitability—consistent with the glacier's role as a core attraction. Glacier resource scale and tourism facility density exhibited clear positive promotion effects, with their feature values concentrated on the positive half of the SHAP axis. This

indicated that areas with larger glaciers and more complete tourism service facilities possess greater tourism development potential. Additionally, the DEM and ultraviolet index showed a negative inhibitory effect, while the climate comfortable degree made a stable positive contribution to the suitability, reflecting the significant supporting role of ecological security and human comfort in the plateau environment for the conduct of tourism activities.

Second, feature importance ranking further identified the dominant and secondary factors influencing glacier tourism suitability (Fig. 5b). The results showed that the convenience of glacier viewing (2.108) was the primary condition determining the spatial distribution of glacier tourism suitability. Glacier resource scale (0.615) and glacier resource density (0.478) ranked second and third respectively, further validating the dominant position of glacier resources in tourism development. Following closely were relief intensity (0.432) and tourism facility density (0.326), representing infrastructure and topography-related factors. Notably, traditional tourism development factors like road network density (0.280) and traffic accessibility (0.168) showed relatively lower importance in this study. This reflected that in the unique context of the QTP, the spatial foundation of glacier resources and natural environmental conditions exert a more critical influence on tourism suitability than human-made infrastructure.

Third, single-factor feature contribution analysis revealed specific thresholds and nonlinear relationships for each factor's impact on suitability (Fig. 6). Taking the most significant factor—glacier viewing accessibility—as an example, when distance values fell below 20 km, its SHAP contribution rate rose rapidly, indicating higher marginal benefits for glacier tourism suitability within this range. However, beyond 25 km, the contribution rate growth flattened. For glacier resource density, increases below 0.1 significantly enhance suitability. Beyond this threshold, the positive effect diminished, indicating a saturation point for glacier density. NDVI exhibited a positive influence on suitability below 200, but shifted to a significantly negative contribution between 200 and 255, indicating that moderate vegetation conditions are more conducive to the sustainable development of glacier tourism activities. Factors such as surface roughness, surface cutting depth, and ultraviolet index showed no clear trends and contribute little to the spatial distribution of glacier tourism suitability on the QTP.

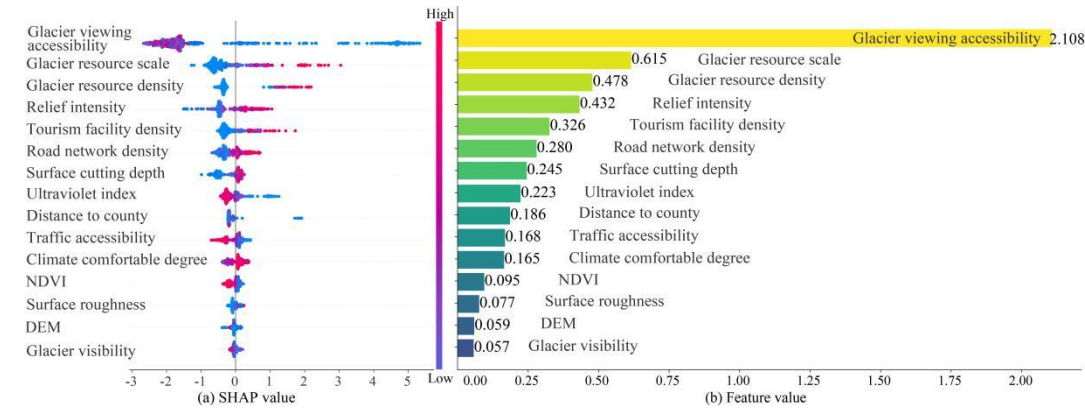


Fig. 5 SHAP values and relative importance of indicator factors. (a) SHAP feature contribution plot, the positive or negative sign of the SHAP value on the horizontal axis represents the promoting or inhibiting effect of the factor on the suitability result, and the color intensity reflects the magnitude of the feature value; (b) Factor importance ranking plot, the horizontal axis represents the absolute value of the SHAP value of each factor, and the larger the value, the stronger the influence of the factor on the suitability.

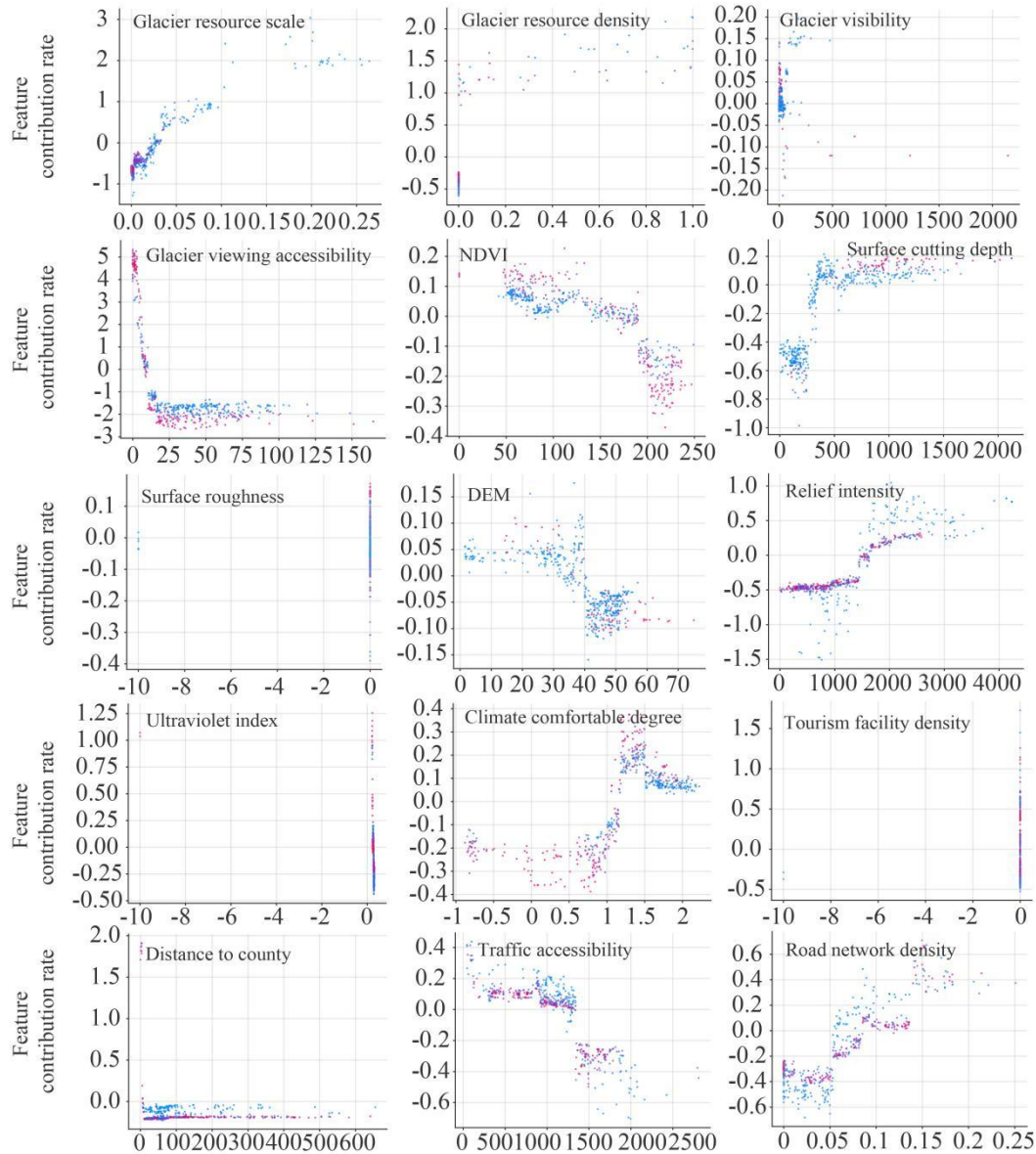


Fig. 6 Single-factor feature contribution rate. Scatter plot of single-factor contribution rate, with the x-axis representing the actual values of each factor and the y-axis representing the corresponding SHAP feature contribution rate. It shows the nonlinear influence patterns and key thresholds of each factor on the suitability of glacier tourism.

Zoning types for glacier tourism development. Based on the spatial overlay analysis of the results from multiple scenarios in 2035, this study divided the glacier tourism suitable areas in the QTP into continuous suitable areas, temporary suitable areas, future suitable areas, and unsuitable areas (Fig. 7), in order to reveal the differentiated characteristics and development potential of glacier tourism in response to climate change.

Continuous suitable zones, serving as stable support areas for glacier tourism development on the QTP, covered a total area of 24.99 km² (9.68%) and were concentrated in large valley glaciers and ice caps above 4,500 m. Spatially, three agglomeration zones were mainly formed: the Laigu glacier group in the middle section of the Nyenchen Tanglha Mountains, the Oytak and Muztag glacier park on the eastern foothills of the Pamir Plateau, and the Rongbu glacier and Qudeng Nima glacier on the northern slopes of the Himalayas. These areas generally had an altitude higher than 4,500 m. The atmospheric processes enable these areas to maintain relatively low temperatures, and the glacier mass balance remains relatively stable. At the same time, the huge glacier reserves give it a significant time lag in responding to climate change. For instance, the Rongbu glacier, with its

thick glacier layer, stored hundreds of years of accumulated glacial resources. Even in high-emission climate scenarios, it can still maintain a relatively stable glacier front.

Temporary suitable zones exhibited a spatial pattern characterized by belt-like encirclement and patchwork mosaics, covering a total area of 24.49 km² (9.49%). These areas were primarily distributed in the peripheral transition zones of the continuous suitable zone, including the mid-to-low altitude regions of temperate glaciers in southeastern Tibet (Midui glacier), the terminal zones of Himalayan glaciers (Karuola glacier), and the glacier front in the eastern Kunlun Mountains (Yuzhu peak glacier). The vulnerability of these areas stemmed from their position at the forefront of glacial systems, making them more sensitive and responsive to climate change. On one hand, their lower elevation renders them more susceptible to warming, resulting in higher glacial melt rates compared to high-altitude zones. On the other hand, these regions often serve as transitional zones between glaciers and surrounding environments, where glacial changes trigger more active periglacial processes, such as the formation of moraines and glacial lakes. Taking the Midui glacier as an example, its glacier tongue has experienced significant thinning and terminal retreat in recent years, directly impacting the safety and scenic quality of nearby viewing platforms.

Future suitable zones exhibited a scattered spatial pattern, covering a total area of only 2.19 km² (0.85%). These areas were primarily distributed on high-altitude bedrock slopes currently covered by glaciers, cirque rear walls, and near ridgelines, forming several potential landscape development points. Examples include the periglacial zone on the northwest slope of Mount Geladandong, the ancient cirque area on the northeast side of Mount Kailash, and the glacially eroded landform zone surrounding the main peak of the Tangula Mountains. As glaciers continue to retreat, these currently ice-covered areas will gradually reveal unique landform, creating new tourist attractions. Their formation primarily stemmed from landform succession during glacial retreat. As glaciers melt, glacially eroded landform like cirques and cirque lakes previously concealed by glacier will gradually emerge. Simultaneously, new glacial landform such as glacial lakes and remnants of icefalls will form. The ancient glacial basin area on the northeastern side of Kangrenbozi Peak, as the glaciers recede, gradually reveals well-preserved ice-eroded triangular surfaces and glacial lakes, which have great potential for scientific research and tourism.

Unsuitable zones constituted the bulk of the study area, covering a total of 206.44 km² (79.98%). This zone primarily included two categories: first, non-glacial areas within the study region that lack glacial resources, such as vast forests, alpine grasslands, deserts, and urban settlements, which do not meet the basic prerequisites for glacier tourism; second, areas where glaciers exist but are inaccessible for tourism due to extreme elevation and steep terrain.

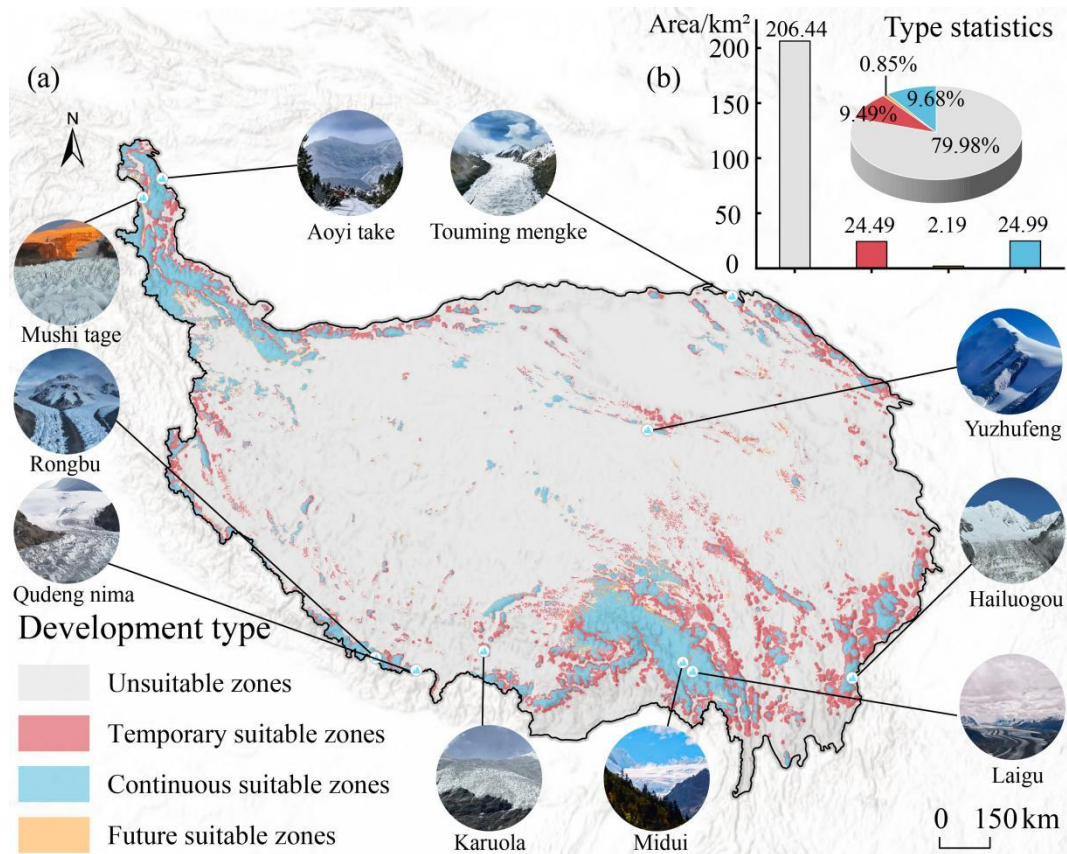


Fig. 7 Zoning types for glacier tourism on the QTP. (a) Based on the spatial distribution of glacier tourism development zones formed by multiple scenarios superimposition, the zone types include continuous suitable zones, temporary suitable zones, future suitable zones, and unsuitable zones; at the same time, typical glacier tourism destinations such as Mushi tage, Aoyitak, Touming Mengke, Rongbu, Qudengnima, Karuola, Midui, Yuzhufeng, Hailuogou, and Laigu are marked; (b) Area statistics of each development zone (left, unit: km²) and proportion statistics (right, unit: %).

Discussion

The dynamic simulation framework effectively reveals the future evolution pathways of glacier tourism suitability. The dynamic simulation framework constructed in this study revealed that glacier tourism suitability on the QTP will undergo profound spatial restructuring under future climate change. This manifested as the systematic contraction of high-suitability areas, intensified spatial polarization, and differentiated response patterns across distinct climate pathways. This finding overcame the limitations of traditional static suitability assessment methods. While prior studies have advanced factor weighting and spatial identification (Huang et al., 2025; Shen et al., 2025), these remain single-point assessments based on current resource and environmental conditions, failing to capture the dynamic differentiation patterns of suitability under future climate scenarios. By integrating SSP scenarios with a glacier size-climate change response model, this study achieved a paradigm shift from identifying current conditions to simulating future scenarios.

Results indicated that under the high-emission SSP5-8.5 scenario, the area of glacier tourism zones with high-suitability on the QTP decreased by over 40% compared to the 2020. This abrupt retreat aligned with the IPCC report's findings on accelerated global glacier melt (IPCC, 2023), though this study translated it into impacts on the spatial patterns of glacier tourism suitability. Second, the spatial pattern shifted from a continuous gradient-based spectrum to a polarized binary pattern, consistent with glaciological research on the heterogeneity of glacial retreat. Previous studies indicated that glacial melt is not uniform but strongly dependent on glacier type, scale, and topographic features. For instance, temperate glaciers responded to climate change much faster than cold glaciers, inevitably leading to uneven evolution of their derived tourism landscape resources (Yao et al., 2012). Furthermore, compared to static indicator models used in evaluating glacier

tourism development on the Tibetan Plateau (Yu et al., 2022; Wang et al., 2020a), this study's dynamic simulation framework not only elevated climate factors from background variables to core drivers but more importantly revealed how climate change directly reshapes the spatial extent and stability of glaciers-the core tourism attraction-thereby triggering cascading effects on regional tourism suitability patterns.

Comparative analysis of different scenarios identifies key determinants for the viability of plateau glacier tourism. By systematically comparing the SSP1-2.6, SSP2-4.5, and SSP5-8.5 pathways, this study quantified the fundamental effects of different climate policy choices on glacier tourism in the QTP. Findings indicated that under the low-emission pathway (SSP1-2.6), the retention rate of glacier tourism areas with high-suitability (66.7%) in 2035 was significantly higher than that under the high-emission pathway (SSP5-8.5) (59.4%). This provided crucial quantitative evidence for understanding the sustainability of tourism resources under different warming scenarios. This finding aligned with the IPCC Sixth Assessment Report's emphasis that different emission pathways will lead to markedly divergent regional impacts over the coming decades (IPCC, 2022). While localized engineering measures such as artificial snowmaking and localized heat footprint control, or short-term management practices, may delay landscape loss at individual tourist sites and maintain their short-term scenic value, (Xie et al., 2025), such interventions offer only localized and time-limited buffering effects under unchanged macro-emission pathways. They cannot replace systematic emission reduction policies and long-term climate governance (Wang et al., 2019).

Based on this, multi-scenario comparisons provided quantitative evidence for scientifically informed policy implementation. High-emission pathways amplified long-term losses in glacier mass and area, leading to a significant rise in the equilibrium line and rapid shortening of glacier length—a conclusion already clearly demonstrated in long-term mass balance studies in Norway and elsewhere (Nesje, 2023). Simultaneously, low-elevation forefields and glacier tongues typically lost their tourism functionality first under high-emission scenarios, triggering cascading impacts on local economies and community livelihoods (Strong et al., 2023; Dhungana et al., 2025). Therefore, strategies to protect glacier tourism resources should prioritize emissions reduction while incorporating scenario-based adaptation. Coordinate national-regional emission reduction actions with local adaptive management, while integrating scenario projections into long-term tourism planning and fiscal arrangements. This provided transition and transformation funding for the most impacted communities and enhances policy implementation capacity (Gerber et al., 2025; Welling et al., 2019). This study expanded existing literature with multi-scenario quantitative evidence, clearly indicating that long-term glacier tourism sustainability requires prioritizing climate mitigation actions at the core of conservation efforts, rather than relying solely on localized engineering or short-term management measures.

The dominant role of glacier accessibility in influencing tourism suitability and implications for planning. The accessibility of glacier viewing, as the primary factor influencing glacier recreation value, far surpassed the importance of facility factors such as transportation accessibility in traditional tourism development. This finding aligned with empirical research on glacier tourism. In their study of glacier tourism in the Alps, Salim and Ravanel (2023) discovered that the “last chance tourism” motivation makes proximity to the glacier a decisive attraction for visitors. The anticipation of witnessing or experiencing glacial changes up close significantly enhanced preference for glacier-proximate locations (Burrill et al., 2025), corroborating the threshold effect observed in this study where accessibility contribution rapidly increases within 20 km. Furthermore, polar and alpine tourism research indicated that glacier or ice cave experiences possessed strong emotional and cognitive appeal, leading visitors to bear higher time and financial costs for proximity despite inadequate transportation or facilities (Wang et al., 2020b). Collectively, these findings revealed that glacier tourism development in frigid regions must shift from transportation-dominated approaches to proximity-dominated ones, making glacier proximity experiences an important element of planning and management.

However, the accessibility of glacier tourism also brought significant ecological disturbances and safety risks, necessitating regulation through refined management. Field observations indicated that human activities in ice caves and periglacial zones can cause pronounced local thermal

disturbances, leading to short-term temperature increases of up to 1.59°C (Alexander, 2021). This directly impacted the structural stability of glacier bodies and visitor safety. Furthermore, visitor congregations and associated service activities near glaciers exacerbated local environmental pollution and ecological disturbance, with mountain ecosystems and glacial hydrological processes exhibiting heightened vulnerability in these sensitive zones (Padha et al., 2022; Miserendino et al., 2018). Therefore, adaptive polar tourism research emphasized the need to establish a multi-objective planning system centered on advancing the proximity to glaciers. This approach aims to ensure visitor experience quality while systematically reducing the direct impact of human activities on the glacial fringe environment. Key measures include establishing glacier-proximity buffer zones, controlling visitation intensity and scale, and implementing engineering and management strategies such as viewing facilities, guided pathways, and environmental interpretation (Gerber et al., 2025).

Dynamic suitability assessment as a tool for balancing glacier tourism and environmental protection under climate change. This study anticipated that the core value of the glacier tourism zoning system constructed through dynamic suitability assessment lies in transforming the analytical capabilities of multi-scenario climate modeling and machine learning into a governance framework of spatial identification, strategic response, and institutional application (Fig. 8). This framework provided decision-making support for balancing glacier tourism development and ecological conservation on the QTP under climate change, thereby promoting the sustainable socioeconomic development of glacier regions (Salim et al., 2021b).

First, the zoning system revealed the spatial foundation for differentiated adaptation, corresponding to the spatial identification layer. Traditional static assessments struggled to reflect the dynamic threats of climate change (Yu et al., 2022), whereas the dynamic zoning results of this study essentially represented a systematic classification of plateau glacier tourism spaces based on the stability of glacier resources, climate response sensitivity, and comprehensive development potential across different regions. Within this framework, the continuous suitable area was the core tourist area of the system, the temporary suitable zones represented a critical transition belt, the future suitable zones signified strategic opportunity space, and the unsuitable zones delineated conditionally constrained areas.

Second, differentiated management strategies must be proposed for each zone to form a strategic response layer. For the continuous suitable zones, efforts should focus on optimizing utilization and enhancing value. Under strict protection, high-quality, sustainable ecotourism activities such as glacier sightseeing and glacier-walking experiences should be guided to strengthen its long-term support function (Wang et al., 2020a). For temporary suitable zones, the core strategy lies in resilient regulation and orderly transition. This requires establishing dynamic monitoring and early warning systems, implementing adaptive utilization plans, and preemptively planning resilient transition pathways for communities and industries. For future suitable zones, current strategies should prioritize protection and forward-looking assessments to safeguard natural glacial succession processes. Future value should be prudently evaluated to provide reserves for long-term decision-making. For unsuitable zones, their primary function should be clearly defined as non-glacial tourism development, with strategies implementing strict protection or maintaining the status quo.

Third, translate spatial strategies into governance practices through institutional design, establishing an application layer for these systems. Embed the aforementioned zoning and strategy frameworks into existing planning and management systems, clarifying the responsibilities and collaborative mechanisms for action among governments at all levels, administrative departments, and communities. For instance, governments can translate optimization strategies for continuous suitable zones into land allocation guarantees for tourism priority areas within territorial spatial plans; convert resilience-based regulatory requirements for temporary suitable zones into dynamic permits from natural resource management departments or community co-management agreements; and designate future suitable zones as strategic reserve areas, subject to ecological protection red line controls. This institutional transmission pathway enables macro-level climate policy choices to be concretized into distinct regional management models through zoning typologies. For instance, under high-emission scenarios, institutional resources should prioritize monitoring, early warning systems, and livelihood safeguards in temporary suitable zones. Conversely, under strong

mitigation pathways, institutional resources can focus more on supporting product innovation and brand development in sustainably suitable zones.

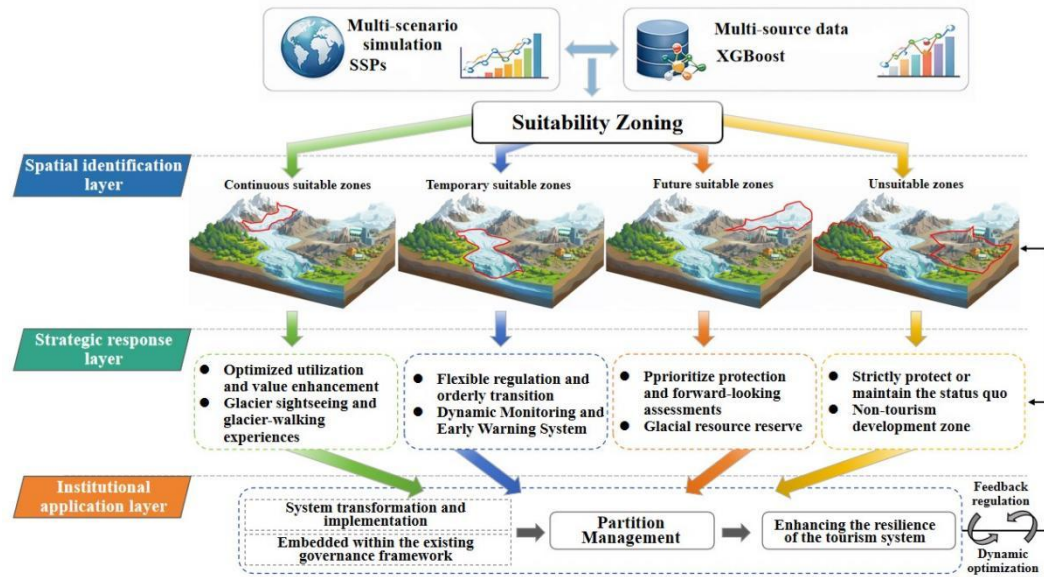


Fig. 8 Multi-level regulatory framework for glacier tourism development

Conclusion

This study broke through the traditional static evaluation framework for the suitability of glacier tourism, and constructed an analytical framework that incorporates climate change, glacier evolution, and tourism suitability responses. By integrating multi-source data and model methods, a transformation from current situation identification to future scenario simulation was achieved. Furthermore, a differentiated development zoning system for glacier tourism based on multi-scenario superposition was proposed, providing a dynamic practical approach for glacier tourism development in the context of climate change.

The research findings indicated: First, the suitability pattern for glacier tourism will undergo significant changes. Under the SSP5-8.5 high-emission scenario, the area of the highly-suitability in 2035 will shrink from 39.45 km² in 2020 to 23.45 km²; while the area of the moderately suitable zone will expand from 198.45 km² to 223.58 km², showing a significant spatial polarization trend. Second, significant differences in climate trajectories had a significant impact on the persistence of suitable areas. Under the SSP1-2.6 low-emission scenario, the retention rate of high-suitability areas was 66.7%, which was higher than 59.4% in the SSP5-8.5 scenario, highlighting the protective effect of emission reduction policies on glacier tourism resources. Third, the convenience of glacier viewing was the dominant influencing factor. The SHAP contribution value was 2.108, which can explain 37.21% of the spatial distribution of glacier tourism suitability. Especially within a 20 km range, it has the most significant effect on enhancing the suitability. Fourth, the research identified four types of zones: continuously suitable zone (9.68%), temporarily suitable zone (9.49%), future suitable zone (0.85%), and unsuitable zone (79.98%).

The theoretical contribution of this study lies in the following: First, it broke through the traditional analytical logic of tourism suitability research based on a single-point static evaluation, and constructed a dynamic analysis framework for glacier evolution and tourism suitability under the context of climate change. Secondly, it revealed that climate change was not merely an external background variable, but indirectly affected the spatial distribution of tourism activity suitability by reshaping the spatial pattern of glacier landscapes, the stability of resources, and the accessibility for viewing, thereby enriching the cascade effect theory of the impact of climate change on the tourism system.

This study has several limitations. First, PLUS is a land-change simulation model rather than a glacier-dynamics or mass-balance model; glacier thickness, flow, ablation, accumulation, debris cover, and refreezing are not explicitly represented. Second, the projections depend on the selected climate and socioeconomic inputs, the definition of the 2035 time horizon, the resampling of multi-resolution data to 1 km, and assumptions about future NDVI, infrastructure, and service

facilities. Third, random sample splitting and conventional 10-fold cross-validation may overestimate transferability when nearby samples are spatially autocorrelated; future work should include spatial block validation and sensitivity analyses for negative-sample rules, probability thresholds, and random seeds. Fourth, XGBoost and SHAP characterize predictive associations rather than causality, and SHAP importance is specific to the fitted model and sample. Fifth, tourist perceptions, behavior, willingness to travel, community preferences, policy constraints, ecological carrying capacity, and site-specific geohazards were not directly measured. Finally, the zoning classes are screening categories rather than development recommendations. Future research should combine physically based glacier models, multi-model climate ensembles, finer-resolution hazard and ecological data, spatial validation, visitor and community research, and policy analysis to quantify uncertainty and evaluate management feasibility.

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Data availability

The data from this study have been organized into two supplementary data/code packages. The PLUS package includes the currently available 1-km-resolution, georeferenced 2010/2020 glacier/ non-glacier maps, grids for six driving factors, expansion and constraint maps, transfer matrices, land-use demand tables for SSP1 – 2.6, SSP2 – 4.5, and SSP5 – 8.5, parameter files, audit and validation reports, checksums, a reference implementation of the Python LEAS+CARS model, and the official PLUS GUI workflow. The XGBoost – SHAP package includes model-ready C1 – C15 sample tables, a fixed training/testing split, a study area mask, a variable dictionary, preprocessing and configuration files, Optuna experiment logs, serialized models, validation and spatial sensitivity results, SHAP values and graphics, scenario prediction rasters, scripts, environment descriptions, and checksums. The above materials will be accessible as supplementary files. The current archive does not include source data; specific source data can be found in Table 1, which provides a detailed record of the data used in this study. The calculation steps for each indicator are provided in Appendix C.

Declarations

Competing interests: The authors declare no competing interests

Ethical approval: This article does not contain any studies with human participants performed by any of the authors.

Informed consent: This article does not contain any studies with human participants performed by any of the authors

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Appendix A. Parameter settings and accuracy verification of the PLUS model

1. Model parameter settings

This study used the PLUS model version 1.3.5. The parameter settings were as follows (Table A1).

Table A1

Parameter facilities

Parameter name	Parameter value	Explanation
Neighborhood size	3×3	Uses a 3×3 moving window to calculate the neighborhood effect
Threshold for generating clusters	0.6	Controls the probability of generating random cluster seeds
Expansion coefficient	0.8	Expansion intensity coefficient for glacier transformation to non-glacier areas
Number of random seeds	2024	Ensures the reproducibility of the simulation results
Number of iterations for simulation accuracy	100	Maximum number of iterations for model training

2. Model accuracy verification

Overall Accuracy (OA) and Kappa coefficient were used as the evaluation indicators for model accuracy. With the glacier range in 2010 as the initial state, the glacier changes from 2010 to 2020 were simulated and compared with the actual glacier range in 2020 for verification. The results were shown in Table A2.

Table A2

Accuracy verification results

Accuracy metric	Reported value	Interpretive benchmark used in the study
OA	0.8723	0.85 or above is considered good
Kappa coefficient	0.8267	0.80 or above is excellent

The simulation accuracy of the PLUS model for the changes in the glacier range on the QTP meets the research requirements, can effectively reflect the spatial heterogeneity characteristics of glacier retreat, and can be used for glacier range prediction in multiple scenarios in 2035.

Appendix B. Sample selection and accuracy verification of XGBoost algorithm

1. Dataset division and sample size

This study employed stratified random sampling to construct the training and validation datasets for the XGBoost algorithm, ensuring the uniformity of the sample space distribution and avoiding geographical biases. The sample selection rules were as follows.

Positive samples: A total of 185 samples were collected from developed glacier tourist attractions, officially certified glacier viewing platforms, and well-known glacier tourist sites documented in literature on the QTP, covering major glacier distribution areas such as southeastern Tibet, the Himalayas, the Pamir Plateau, and the Qilian Mountains.

Negative samples: 1,850 negative samples were selected at a 1:10 ratio from areas highly prone to geological disasters, core zones of ecological red lines, extremely high-altitude regions above 6,000 m that are inaccessible to humans, and desert and grassland areas without glacier distribution.

All 2,035 samples were randomly divided into training and testing sets in a 7:3 ratio. The positive and negative samples are uniformly distributed across the study area, covering all regions

with glacier tourism potential and major ecological constraint zones on the QTP, effectively avoiding geographical bias in the model caused by spatial clustering of samples.

2. Model accuracy verification results

A comprehensive evaluation of the classification performance of the XGBoost algorithm was conducted by using multi-threshold classification performance analysis, 10-fold cross-validation, and ROC-AUC curves, to avoid the limitations of a single indicator.

2.1. Classification performance at different probability thresholds

The XGBoost algorithm outputs the probability of glacier tourism suitability for each grid cell (0-1), and this probability needs to be classified into suitable/unsuitable categories by setting a reasonable threshold. This study tested the model's classification performance at 9 thresholds within the range of 0.1 to 0.9. The results are shown in Table B1.

Table B1

Evaluation indicators of the model's classification at different thresholds

Probability threshold	Accuracy	Precision	Recall	F1 value	Specificity	False Positive Rate (FPR)
0.1	0.8457	0.7624	0.9828	0.8584	0.7093	0.2911
0.2	0.8914	0.8271	0.9825	0.8985	0.8012	0.2004
0.3	0.9181	0.8704	0.9647	0.9153	0.8733	0.1273
0.4	0.9275	0.8979	0.9648	0.9293	0.8919	0.1094
0.5	0.9367	0.9268	0.9459	0.9352	0.9278	0.0737
0.6	0.9272	0.9432	0.9090	0.9267	0.9457	0.0553
0.7	0.9091	0.9607	0.8550	0.9047	0.9648	0.0360
0.8	0.8826	0.9783	0.7821	0.8695	0.9827	0.0181
0.9	0.8094	0.9762	0.6368	0.7710	0.9823	0.0183

The results showed that as the probability threshold increases, the model's accuracy, precision, and specificity first rise and then decline, while the recall rate showed a continuous downward trend. When the threshold was 0.5, the F1 value reached its maximum (0.9352), simultaneously achieving a relatively high recall rate (0.9459) and precision (0.9268). This enabled a reduction in the error rate while minimizing the false negative judgments of the glacier tourism suitability area. Therefore, in this study, 0.5 was selected as the classification threshold for glacier tourism suitability.

2.2. 10 cross-validation results

To further evaluate the generalization ability and stability of the model, and to avoid the bias caused by a single random division of the dataset, this study adopted the 10-fold cross-validation method. All 2035 samples were randomly divided into 10 non-overlapping subsets. Each time, 9 subsets were selected as the training set, and 1 subset was selected as the test set. This process was repeated 10 times, and the mean and standard deviation of each evaluation metric were calculated. The results were shown in Table B2.

Table B2

Mean values of model evaluation metrics under 10-fold cross-validation

Accuracy	Precision	Recall	F1 value
0.8673	0.8618	0.8754	0.8695

The overall classification accuracy of the model under 10-fold cross-validation was 86.73%, and the prediction accuracy for the minority class (positive class) was 86.18%, with a relatively high recall rate (87.54%). In the process of capturing positive class samples, the cost of misclassifying negative class samples was relatively low. In addition, the calculation results of the F1 value also

indicated a good balance between precision and recall, and the overall classification performance of the model was excellent.

2.3. ROC curve and AUC value evaluation

To further comprehensively measure the dynamic changes in the model's ability to capture positive samples while misclassifying negative samples, this study used the ROC curve and AUC area for measurement. By plotting the fitted ROC curve of the model (Fig. B1) and calculating the corresponding AUC area, it was found that the left-upward convex trend of the ROC curve was obvious and the distance from the ROC curve of the pure random classifier (the blue dotted line in the figure) was far. At this time, the AUC value was 0.9237, indicating that the model had good classification performance and has reached the ideal state.

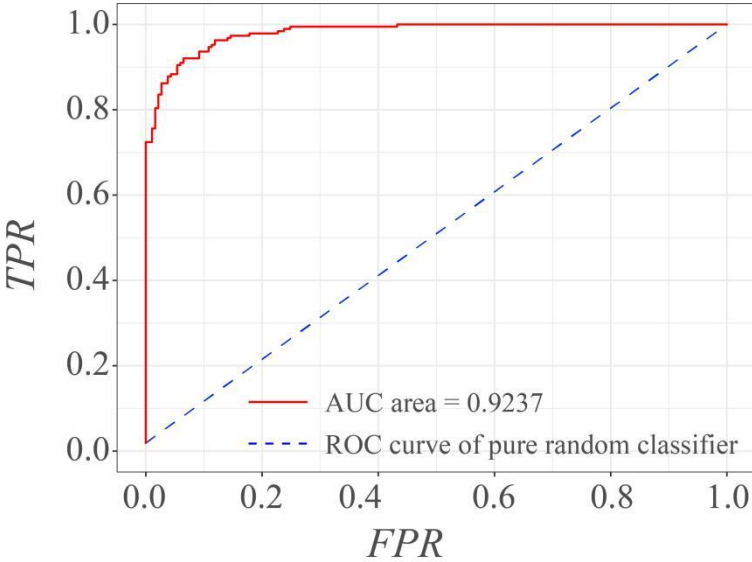


Fig. B1 Model fitting ROC curve and AUC area

Appendix C. Calculation steps for indicators in the feature matrix

Table C1

Calculation steps for evaluation characteristics matrix indicators of glacier tourism suitability

Indicator level	Calculation steps
C1 Glacier resource density	1. Collect vector point data of developed glacier tourist attractions, official viewing platforms, and well-known glacier tourist spots on the QTP; 2. Use the Kernel Density tool in ArcGIS Pro; 3. Input the above glacier tourist spot data, set the search radius automatically calculated by the Silverman empirical rule, and output the grid resolution as 1km×1km. The weights are classified according to the grade of the scenic area, with 5A, 4A, 3A, 2A, and A set to 5, 4, 3, 2, and 1 respectively; 4. Obtain the distribution density of glacier tourism resources per unit area, with the unit being individuals/km², reflecting the spatial clustering degree of glacier tourism resources.
C2 Glacier resource scale	1. Re-classify the 30m resolution glacier raster data. Assign value 1 to the glacier areas and 0 to the non-glacier areas. 2. Use the ArcGIS Pro Focal Statistics tool, set the neighborhood as a 1km × 1km rectangle, and select the statistical type as SUM. 3. Execute the formula in the raster calculator: Glacier resource size = Focal Statistics result / ((1000/30)²), where (1000/30)² is the total number of 30m pixels within a 1km grid.

	4. Obtain the proportion (0-1) of the glacier area in each 1km grid, reflecting the visual size and grandeur of the glacier landscape.
C3 Glacier visibility	1. Discretize the glacier boundaries into point features uniformly, with a sampling interval of 1km, ensuring that all glacier distribution areas are covered; 2. Use the Viewshed tool in ArcGIS Pro, inputting 1km resolution DEM data, and using the above glacier points as observation points; 3. Set the observation point height to 1.7m (the average height of the human eye), the target height to 0m (the surface of the glacier), and the maximum visible distance to 50km; 4. Overlay all individual Viewshed analysis results, and count the number of glacier points that each grid cell can see; normalize the results to the 0-1 range through extreme value standardization, with a larger value indicating better visibility of the glacier landscape.
C4 Glacier viewing accessibility	1. Extract the vector data of the outer boundary of the glacier grid; 2. Use the Euclidean Distance tool in ArcGIS Pro, input the vector of glacier boundaries, and output the straight-line distance from each 1km grid to the nearest glacier boundary, with the unit being kilometers; 3. Since the closer the distance, the higher the convenience, in the subsequent standardization process, negative extreme value standardization is adopted to convert the distance values into convenience indices ranging from 0 to 1.
C5 NDVI	Obtain directly from the data website
C6 Surface cutting depth	1. Use 90m resolution SRTM DEM data and resample it to 1km×1km; 2. Utilize the ArcGIS Pro Focus Statistics tool, set the neighborhood as a 3×3 rectangle, and calculate the average elevation (MEAN) and the minimum elevation (MIN) within the neighborhood; 3. Execute the formula using the raster calculator: Surface Erosion Depth = Average Elevation - Minimum Elevation, with the unit being meters, reflecting the depth of erosion and cutting of the surface.
C7 Surface roughness	1. Based on a 1km resolution DEM, the slope was calculated using the ArcGIS Pro Slope tool, with the unit being degrees. 2. The standard formula was executed using the raster calculator: Surface Roughness = $1 / \cos(\text{slope} \times \pi / 180)$, where π is taken as 3.1415926. 3. The larger the value, the more intense the surface undulation and the poorer the ecological restoration ability.
C8 Elevation	Obtain directly from the data website
C9 Relief intensity	1. Use 30m resolution SRTM DEM data and resample it to 1km×1km; 2. Use the ArcGIS Pro focal statistics tool, set the neighborhood as a 5×5 rectangle (corresponding to an 5km×5km analysis window, suitable for the large-scale topographic features of the QTP), and calculate the maximum elevation (MAX) and minimum elevation (MIN) within the neighborhood respectively; 3. Execute the formula using the raster calculator: Topographic roughness = Maximum elevation - Minimum elevation, with the unit in meters, reflecting the ruggedness of the glacier surface topography.
C10 Ultraviolet index	1. Prepare the data of sunshine duration and temperature. 2. Call the raster calculator by month, and use the monthly solar radiation forecast equation in the paper to calculate the monthly total solar radiation Q (Yuan et al., 2022).

	3. The raster calculator executes: Ultraviolet radiation intensity $Q_{uv} = Q \times 0.043$. 4. Introduce the cloud attenuation coefficient R (the standard value in the paper is adopted): Clear sky ($0 \leq \text{cloud cover} < 3$) takes 0.992, partly cloudy ($3 \leq \text{cloud cover} < 5$) takes 0.896, mostly cloudy ($5 \leq \text{cloud cover} < 8$) takes 0.726, and cloudy days ($\text{cloud cover} \geq 8$) takes 0.316; when there is no cloud cover data, the entire QTP is defaulted to the average value of 0.9 in the paper. 5. The raster calculator executes: Ultraviolet index $= (Q_{uv} \times R) / 2.5$;
C11 Climate comfortable degree	The comprehensive evaluation is conducted using the temperature-humidity index (THI), wind effect index (WEI), and clothing index (ICL). The weights are determined through the CRITIC method: 1. Single-index calculation: Prepare data such as temperature, precipitation, wind speed, relative humidity, and sunshine duration, and call the raster calculator in ArcGIS Pro. Calculate according to the following formulas: - $THI = (1.8T + 32) - 0.55(1 - RH) \times (1.8T - 26)$, where T is the temperature ($^{\circ}\text{C}$), and RH is the relative humidity (%); - $WEI = (10\sqrt{V} + 10.45 - V)(33 - T) + 8.55S$, where V is the wind speed (m/s), and S is the sunshine duration (h/d); - $ICL = \frac{33 - T}{0.155 \times H} - \frac{H + aR \cos \alpha}{(0.62 + 19\sqrt{V})H}$; where H represents 75% of the human body's metabolic rate. When considering light activity, the metabolic rate H is set at $87 \text{ W} \cdot \text{m}^{-2}$; $a = 0.06$ indicates the human body's absorption of solar radiation. $R = 1367 \text{ W} \cdot \text{m}^{-2}$; α represents the solar altitude angle, and β is the average latitude. The solar altitude angle in summer is $(90^{\circ} - \beta + 23^{\circ}26')$, while in winter it is $(90^{\circ} - \beta - 23^{\circ}26')$, in spring and autumn are both $(90^{\circ} - \beta)$. 2. Comprehensive calculation: Climate comfort $= 0.476 \times THI + 0.293 \times WEI + 0.231 \times ICL$. Normalize to the range of 0 to 1 using extreme value standardization, and the larger the value, the more comfortable the climate.
C12 Tourism facility density	1. Obtain POI data (hotels, guesthouses, tourist centers, shopping points, etc.) for tourism reception facilities in the QTP from the OpenStreetMap; 2. Assign weights based on the importance of the facilities: tourist center 10, star hotel 8, ordinary guesthouse 5, dining place 3, shopping place 2; 3. Use the kernel density analysis tool in ArcGIS Pro, input the weighted POI points, set the search radius to 20km, and output resolution 1km; 4. Obtain the weighted spatial density of tourism facilities, with the unit being individuals/km², reflecting the regional tourism reception capacity.
C13 Distance to county	1. Obtain the vector data of county-level administrative boundaries across the country, and extract the coordinate point data of the county government's location; 2. Use the Euclidean distance tool in ArcGIS Pro, input the county government point, and output the straight-line distance from each 1km grid to the nearest county government location, with the unit being kilometers; 3. The closer the distance, the more convenient it is for supply and rescue. Subsequently, negative extreme value standardization is adopted.
C14 Traffic accessibility	1. Obtain the OpenStreetMap (OSM) road network data and classify it into expressways, national highways, provincial highways, county highways, and township highways; 2. Set the travel speed according to the road grade: expressway 120 km/h, national highway 80 km/h, provincial highway 60 km/h, county highway 40 km/h, and township highway 20 km/h;

		3. Build the road network data set in ArcGIS Pro Network Analyst and set the impedance field as travel time (hours) = road length / travel speed; 4. Based on the OD cost matrix, starting from the 14 prefecture-level cities in the QTP as the origin, and each 1 km grid as the destination, calculate the shortest travel time; 5. Obtain the shortest reachable time for each grid, with the unit being hours, and subsequently apply negative standardization.
C15	Road network density	1. Classify the OSM road network by grade and extract the vector data of expressways, national highways, provincial roads, county roads, and township roads respectively; 2. Assign weights based on the traffic capacity of the roads: expressways 12, national highways 8, provincial roads 6, county roads 4, and township roads 3; 3. Use the ArcGIS Pro Line Density analysis tool, input the weighted road vector data, set the search radius to 30km, and output resolution 1km; 4. Obtain the weighted road network density, with the unit of km/km², reflecting the development degree of the internal transportation network in the region.
Standardized processing		To eliminate the dimensional differences among different indicators, the extreme value standardization was uniformly adopted to convert all indicators to the 0-1 range: 1. Positive indicators (the larger the value, the better): Standardized value = $(X - X_{min}) / (X_{max} - X_{min})$ Including: glacier resource density, glacier resource scale, glacier visibility, NDVI, climate comfortable degree, tourism facility density, road network density 2. Negative indicators (the smaller the value, the better): Standardized value = $(X_{max} - X) / (X_{max} - X_{min})$ Including: glacier viewing accessibility, surface cutting depth, surface roughness, elevation, relief intensity, ultraviolet index, distance to county, traffic accessibility Where X is the original value of the indicator, and X_{max} and X_{min} are the maximum and minimum values of the indicator in the study area.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Data.zip](#)