

Spatiotemporal evolution and future projections of habitat quality along the Duku Highway tourist corridor

Yiran Ding

Xinjiang Normal University

Ping Jiang

jiangp23@xjnu.edu.cn

Xinjiang Normal University

Yue Zhang

Xinjiang Normal University

Zhi Wang

Xinjiang Normal University

Guzainuer Keremu

Xinjiang Normal University

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1 **Spatiotemporal evolution and future projections of habitat quality along the Duku**

2 **Highway tourist corridor**

3 **Yiran Ding¹, Ping Jiang^{1,2}, Yue Zhang^{1,2}, Zhi Wang¹, Guzainuer Keremu¹**

4 ¹ College of Geographical Science and Tourism, Xinjiang Normal University, Urumqi 830054, China.

5 ² Xinjiang Laboratory of Arid Zone Lake Environment and Resources, Xinjiang Normal University,
6 Urumqi 830054, China.

7 ✉ Corresponding author: Ping Jiang, Xinjiang Laboratory of Arid Zone Lake Environment and
8 Resources, Xinjiang Normal University, Urumqi 830054, China. Tel.: +86-18599051142; E-mail:
9 jiangp23@xjnu.edu.cn.

10 **Abstract**

11 The impact of tourist roads on habitat quality remains uncertain, particularly along seasonally operated
12 highways in ecologically sensitive regions. This study assesses the spatiotemporal evolution of habitat
13 quality along the Duku Highway corridor in the central Tianshan Mountains of China from 2000 to 2024
14 and projects changes for 2030 using the InVEST and PLUS models. Results indicate that, despite land
15 use changes (grassland −2.81%, built-up land +0.75%), habitat quality remained highly stable.
16 High-quality areas consistently accounted for over 70% of the total region, although they decreased by
17 1.607% between 2000 and 2008, while low-quality areas expanded by 0.902%. Land use conversions
18 influenced habitat quality: cropland-to-water conversion had a positive effect, whereas
19 forest-to-unused-land conversion had a negative impact; in later periods, unused-land-to-grassland
20 conversion contributed positively, reflecting ecological restoration. Projections for 2030 suggest that
21 habitat quality will remain virtually unchanged, with high-quality areas increasing marginally from
22 70.842% to 70.853% and low-quality areas decreasing slightly. By focusing specifically on a tourist

✉ Yiran Ding e-mail: 2751317402@qq.com
Yue Zhang e-mail: zhangyuxinjiang@163.com
Zhi Wang e-mail: 2499894408@qq.com
Guzainuer Keremu e-mail: 3188662361@qq.com

highway corridor, this study fills a research gap and provides a scientific baseline for evaluating ecological outcomes in similarly sensitive areas.

Key word: habitat quality; tourist highway corridor; land use change; Duku highway; InVEST model

1. Introduction

Habitat quality, defined as the capacity of an ecosystem to provide essential resources and conditions for wildlife, serves as a key indicator of regional biodiversity and ecosystem health (Hillard et al. 2017; Riedler et al. 2018). In recent years, the growth of self-driving tourism has accelerated the expansion of tourist roads across diverse landscapes (Zhang et al. 2023). These roads directly alter land cover, fragment habitats, and intensify human disturbance (Averill-Murray et al. 2023; Yang et al. 2023; Zhang et al. 2024). Policy shifts may further compound these effects by reshaping land use patterns (Liao et al. 2023; Zhu et al. 2025). Whether these changes lead to alterations, particularly declines, in habitat quality along tourist road corridors remains unknown, and clarifying this question is of value for guiding sustainable regional development.

A variety of methods has been developed to assess habitat quality, which can be broadly categorized into indicator-based and model-based approaches (Wu et al. 2021). Indicator-based methods often rely on costly field surveys and lack cross-regional comparability (Vellend et al. 2013). In contrast, model-based methods, such as the Habitat Suitability Index (HSI), the Social Value of Ecosystem Services (SoIVES) model, and the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model, are increasingly adopted due to their systematic and reproducible nature (Zhu 2022; Huang et al. 2023; Li et al. 2025). The InVEST model is widely used because it employs land cover data to assess current habitat quality and project future scenarios (Wang et al. 2025). Reliable simulation of land use and land cover change is a prerequisite for such assessments, as land use change—together with factors such as

topography, road networks, and urban expansion— is a primary driver of habitat degradation (Zhang et al. 2022; He et al. 2023; Mi et al. 2024; Zambrano et al. 2025; Xu et al. 2025; Wu et al. 2025).

Researchers have increasingly integrated land use simulation models with the InVEST framework, establishing a robust methodological foundation for habitat quality assessments (Lei et al. 2022; Wei et al. 2022; Li et al. 2022). However, most existing studies have focused on watersheds, urban areas, or forests (Wang et al. 2023; Xie et al. 2023; Wu et al. 2024; Zhao et al. 2025; Brumelis et al. 2026; Angelstam et al. 2026), little attention has been paid to the impact of road construction, particularly tourist roads, on habitat quality. Tourist roads possess distinct characteristics—seasonality, concentrated human activity, and linear disturbance patterns—that may exert unique pressures on habitat quality. Yet it remains unclear whether these pressures inevitably lead to degradation or whether, under certain conditions (e.g., natural constraints, policy controls, or seasonal closure), habitat quality can remain stable.

The rapid expansion of tourist highways following China's Western Development strategy has brought the Duku Highway, one of the country's most scenic routes, into the spotlight. The highway operates seasonally (typically from June to October), concentrating intense human activity within a short window while allowing ecosystem recovery during the off-season. Moreover, it traverses ecologically fragile mountainous regions. These features raise an open question: do tourism-driven land use changes along the Duku Highway lead to significant habitat degradation, or does the combined effect of natural constraints, policy interventions, and seasonal closure maintain habitat quality? To address this question, the present study takes the Duku Highway corridor as a case study with two objectives: (1) to assess the spatiotemporal evolution of habitat quality between 2000 and 2024 using the InVEST model; and (2) to project land use patterns for 2030 under different development scenarios using the PLUS model and

thereby forecast future habitat quality, with an attempt to preliminarily interpret the underlying causes of observed changes. By revealing the dynamics of habitat quality and evaluating potential future changes, this study aims to provide a scientific basis for ecological conservation and sustainable development along tourist highways in ecologically sensitive regions.

2. Material and methods

2.1. Study area

The Duku Highway corridor in west-central Xinjiang, China (Fig 1) is the focus of this study. As the primary north–south transportation artery in Xinjiang, the highway extends approximately 561 km from Dushanzi District (Karamay City) in the north to Kuqa City (Aksu Prefecture) in the south. The road operates seasonally, typically from early June to mid-October, and remains closed during the remaining months, with exact dates adjusted annually based on weather and road conditions. A 20 km buffer zone on each side of the highway was delineated as the study area.

Natural ecological land dominates the regional land use structure. Grassland accounts for the largest share (62.16%), followed by unused land (21.89%) and built-up land (only 1.01%). Between 2008 and 2012, the Duku Highway was fully reconstructed and upgraded to a Class II highway. As the route has gradually gained popularity as a tourist destination, human activity has intensified. Whether this will affect habitat quality along the highway corridor remains unclear—a gap that this study aims to address by investigating the spatiotemporal evolution of habitat quality along this tourist highway corridor.

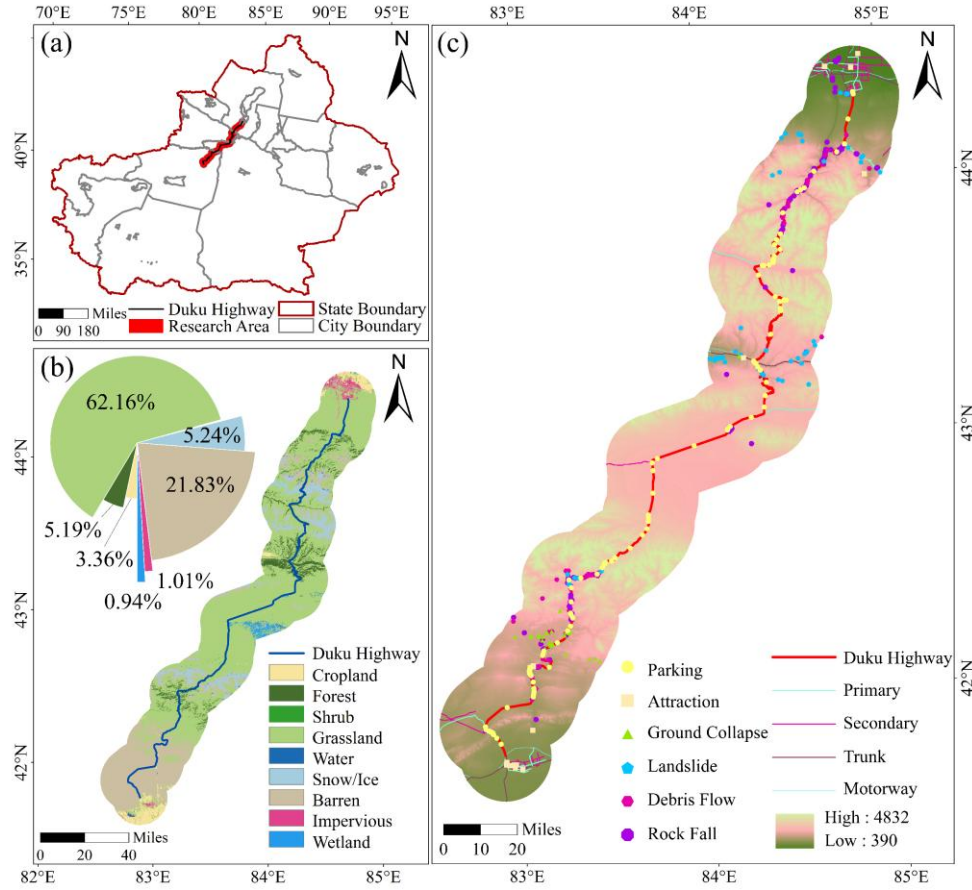


Fig. 1 Geographic location (a), land cover patterns (b), and distribution of key points of interest and major roads (c) for the study area

2.2. Data

Land use data were obtained from the annual China Land Cover Dataset (CLCD, <https://zenodo.org/records/18180184>) compiled by Wuhan University with a spatial resolution of 30 m (Yang et al. 2021). The original land cover types were reclassified into six categories—cropland, forest, grassland, water, unused land, and built-up land—to align with the study's objectives and local conditions.

Natural environment data included digital elevation model (DEM), temperature, precipitation, and geological hazard distribution were obtained from the Resource and Environmental Science Data Platform (RAESDP <https://www.resdc.cn/>). The DEM has a resolution of 90 m, whileas the temperature and precipitation data have a resolution of 1 km. Slope was calculated from the DEM using ArcGIS 10.7.

These natural environment data were used to characterize topographic and climatic constraints on land use change and habitat quality.

Socioeconomic data comprised population density, road networks, parking lots, scenic areas, and grassland grazing intensity. Population density data at 100-m resolution were obtained from WorldPop (<http://www.worldpop.org/>). Grassland grazing intensity data were taken from the Long-term High-resolution Grassland Grazing Intensity Dataset (LHGI, 250 m resolution, <http://www.nesdc.org.cn/>) (Wang et al. 2024). Vector data for the road network (including motorways, primary roads, secondary roads, and tertiary roads), parking lots and scenic areas were sourced from OpenStreetMap (OSM <http://www.openstreetmap.org/>). These socioeconomic data served to identify threat factors in the InVEST habitat quality module and driving forces in the PLUS land use simulation model.

All data were resampled to a unified 30-m resolution and projected to WGS_1984_UTM_Zone_44N coordinate system for analysis.

2.3. Methodology

2.3.1. Division of study periods based on policy phases

Four key years—2000, 2008, 2016, and 2024—were divided to represent distinct policy phases that may influence habitat quality along the Duku Highway. The Western Development Strategy, launched in 2000, marked the onset of intensified human activity as Xinjiang prioritized regional development. Between 2008 and 2012, the Duku Highway was upgrade to a Class II Road, representing a period of infrastructure-driven landscape change. A major policy shift occurred in 2016, when regional authorities issued the Implementation Opinions on Strengthening Ecological Civilization Construction, signaling a transition toward ecological prioritization. By 2020, conservation supervision had been further

strengthened, and the policy context had fully transitioned to stringent environmental management; we therefore selected 2024 as the terminal year to capture the outcomes of this mature policy regime.

2.3.2. InVEST model

The habitat quality module of the InVEST model was utilized to assess the spatiotemporal dynamics of habitat quality along the Duku Highway. This module provides fine-scale, spatially explicit estimation of habitat degradation, enabling the calculation of habitat quality indices to be calculated based on land use patterns and identified threat factors(Xu et al. 2024). The habitat quality score for each grid cell was calculated as:

$$Q_{xj} = H_j [1 - \frac{D_{xj}^z}{D_{xj}^z + k^z}]$$

where Q_{xj} is the habitat quality of grid j under land use type x ; D_{xj} is the threat level; H_j is the habitat suitability of grid j ; k and z are scaling constants. Specifically, habitat quality (Q_{xj}) was categorized into five levels—low, relatively low, moderate, relatively high, and high—to facilitate comparative analysis(Xu et al. 2025).

Threat factors were selected according to local conditions and previous studies (Lei et al. 2022; Wei et al. 2022; Li et al. 2022; Wu et al. 2024; Zhang et al. 2024; Niu et al. 2024). For the Duku Highway—where geological hazards are frequent—we identified built-up land, unused land, cropland, and geological hazards as key threat factors (Online Resource 1, 2).

2.3.3. PLUS model

The PLUS (Patch-Generating Land Use Simulation) model is a cellular automaton-based tool widely employed for simulating land use change (Liang et al. 2021). A distinct advantage of this model lies in its ability to characterize patch-level land use dynamics, thereby enabling more realistic simulations of land expansion while quantifying the contributions of multiple driving factors (including

natural, socioeconomic, and policy conditions) to land use transitions. Consequently, the appropriate selection of driving factors is fundamental to capturing the spatial determinants of land use dynamics. Considering the characteristics of the study area and following relevant studies (Liu et al. 2022; Hu et al. 2023; Huang et al. 2024), a total of 12 driving factors across three categories (natural, socioeconomic, and locational) were selected as model inputs (Table 1, Online Resource 3). Land use patterns along the Duku Highway were then simulated under three typical scenarios: natural development, ecological priority, and economic priority (Duan et al. 2024; Li et al. 2024).

Table 1 Driving factors used in the PLUS model

Type	Driving Factors	Data Source
Natural factors	Precipitation	RAESDP, processed using ArcGIS 10.7
	Temperature	RAESDP, processed using ArcGIS 10.7
	Slope	calculated using ArcGIS 10.7
	DEM	GDC, processed using ArcGIS 10.7
Socioeconomic factors	Population density	World pop, processed using ArcGIS 10.7
	Grassland grazing intensity	Processed using ArcGIS 10.7
	Distance to the motorway	OSM, calculated using ArcGIS 10.7
Locational factors	Distance to primary roads	OSM, calculated using ArcGIS 10.7
	Distance to secondary roads	OSM, calculated using ArcGIS 10.7
	Distance to trunk roads	OSM, calculated using ArcGIS 10.7
	Distance to attractions	OSM, calculated using ArcGIS 10.7
	Distance to parking lots	OSM, calculated using ArcGIS 10.7

2.3.4. Quantitative relationship assessment

To explore how land use evolution influences habitat quality changes, the habitat contribution rate was adopted (Qi et al. 2025). This method quantifies the contribution of each land use conversion type to the overall change in regional habitat quality, thereby identifying the dominant transitions driving increases or decreases in habitat quality. The contribution rate is calculated as:

$$C_{it} = \frac{HQC_{it} \times LA_{it}}{TA} \times 100\%$$

where C_{it} is the habitat contribution rate of the i -th land use transition during period t ; HQC_{it} is the mean change in habitat quality for the transition type and LA_{it} is the area of this type; TA is the total area of the

region.

A habitat contribution rate of zero indicates no net effect on regional habitat quality. Positive values signify improvement, whereas negative values indicate decline. The larger the absolute value, the stronger the transition's impact and the more dominant its role in shaping habitat quality change.

3. Results

3.1. Land use dynamics along the Duku Highway corridor

Land use change is a primary driver of habitat quality variation. Therefore, understanding its spatiotemporal evolution is essential before assessing habitat quality. From 2000 to 2024, grassland remained the dominant land use type along the Duku Highway, consistently accounting for more than 60% of the total area despite a gradual decline from 64.97% to 62.16% (Fig 2, Online Resource 4). Built-up land exhibited the largest proportional increase, rising from 0.26% to 1.01%, particularly in the northern part of the corridor. This expansion was mainly derived from unused land, grassland, and a small portion of cropland. Forest also increased steadily, from 3.58% to 5.19%, with the increase during the first period (2000–2008, 0.93%) being nearly three times that of the subsequent two periods. Cropland first expanded and then contracted slightly, with a net increase from 2.58% to 3.36%. Grassland was the only category that decreased substantially, losing 2.81%, and was progressively replaced by forest, cropland, built-up land, and unused land. Unused land and water area fluctuated, with a net decrease of 0.17% and 0.14%, respectively.

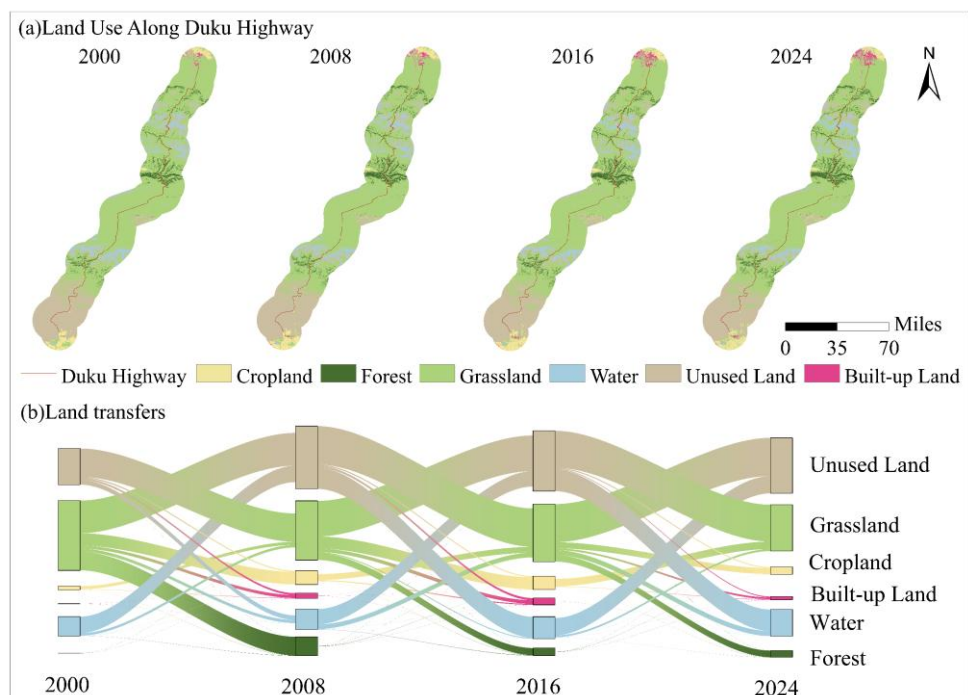


Fig. 2 Spatial distribution of land use types along the Duku Highway corridor in 2000, 2008,2016, and 2024

3.2. Habitat quality dynamics along the Duku Highway corridor

3.2.1. Habitat quality assessment and spatio-temporal evolution

The results of the statistical analysis of habitat quality by level are shown in Fig 3 and Table 2. Within the selected four time points, the habitat quality of the Duku Highway corridor exhibited high spatial consistency. High-quality areas, corresponding to extensive grassland and forest, dominated the region, accounting for approximately 70% of the total area. While low-quality areas were concentrated in the unused land in the south and the mountainous zones along the route, representing about 23% of the area, and medium-quality habitats were mainly located in the major built-up areas at the northern and southern ends of the corridor.

From a temporal perspective (Table 2), the entire study period generally exhibited a pattern of alternating expansion and contraction between high- and low-quality habitat areas. Specifically, the most significant changes were a reduction in high-quality habitat areas (a 1.607% decrease in area proportion)

and an expansion of low-quality habitat areas (a 0.902% increase in area proportion). These changes occurred primarily between 2000 and 2008. In addition, the proportion of low-quality habitat underwent a process of significant increase followed by a gradual decline, a trend that may correspond to the stabilization of built-up areas following their rapid expansion.

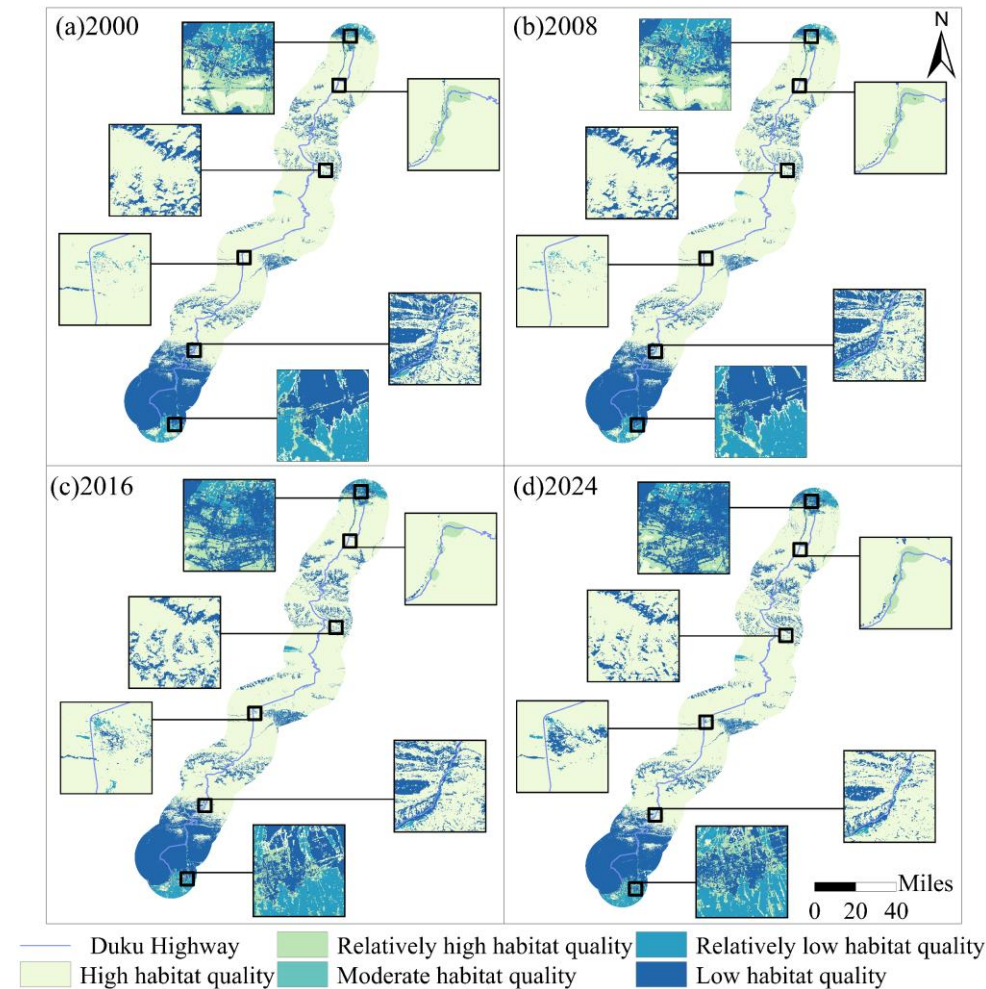


Fig. 3 Spatial distribution of habitat quality along the Duku Highway corridor in 2000, 2008, 2016, and 2024

Table 2 Areal proportions of each habitat quality across the four study periods (2000, 2008, 2016, and 2024)

Habitat quality class	Time Points			
	2000	2008	2016	2024
Low Habitat Quality	23.209%	24.111%	23.868%	23.783%

Relatively Low Habitat Quality	2.584%	3.083%	3.395%	3.359%
Moderate Habitat Quality	0.012%	0.011%	0.012%	0.013%
Relatively High Habitat Quality	1.344%	1.551%	1.700%	2.003%
High Habitat Quality	72.850%	71.243%	71.025%	70.842%

3.2.2. Contribution of land use conversions to habitat quality

To clarify how habitat quality changes are influenced by land use conversions, the habitat contribution rate was quantified for each study period. The results (Fig 4) the largest positive contribution consistently came from the conversion of unused land to grassland. Conversely, the conversion of grassland to unused land resulted in the greatest negative impact on habitat quality. Overall, conversions from grassland and water into unused land, cropland and built-up areas exerted negative effects on habitat quality and were identified as the primary causes of low-quality habitat expansion. In contrast, conversions into water, grassland, and forest—especially those originating from unused land—generally promoted habitat quality improvement, which in turn led to fluctuations in the extent of high-quality habitat areas. Notably, the interaction coefficient between built-up land and other land use types remained near zero throughout the study period, suggesting that the direct impact of built-up expansion was limited, likely because built-up land accounted for only a small fraction (1.01% in 2024) and was concentrated at the northern and southern ends of the corridor.

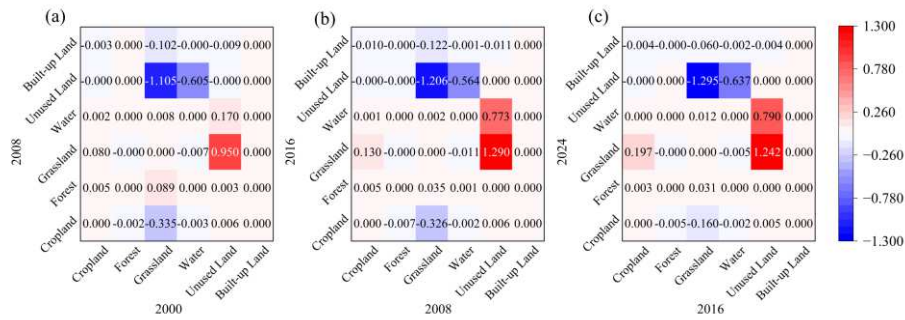


Fig. 4 Contribution of land use conversions to habitat quality change across three periods. (a) 2000–2008; (b) 2008–2016; (c) 2016–2024

3.3. Habitat quality projections for 2030

3.3.1. Model validation and prediction of land use patterns for 2030 under different scenarios

As land use projections serve as the fundamental basis for habitat quality assessments, land use data from two equidistant time periods and corresponding driving factor data from the same periods were used to forecast land use. A PLUS model was first constructed using the period 2016–2020 as the baseline to predict land use patterns for 2024. The predicted results were then validated against the actual land use patterns observed in 2024. The resulting Kappa coefficient was 0.89, with an overall accuracy of 0.94 (Online Resource 5), indicating excellent agreement between the simulated and observed land use patterns.

Based on this validated model, the baseline was adjusted to the period 2018–2024, and land use along the Duku Highway corridor was projected for 2030 under three typical scenarios (Online Resource 6). The results indicate that by the end of the 15th Five-Year Plan period, the overall land cover pattern in the region will not undergo substantial changes (Table 3). The proportions of major land cover types remain largely unchanged or even constant across the three scenarios, suggesting that variations in spatial constraint scenarios have a very limited impact on the stability of land use patterns.

Table 3 Areal proportions of land use categories under three development different scenarios for 2030

	Nature Development	Ecological Priority	Economic Priority
Cropland	3.485%	3.485%	3.485%
Forest	5.191%	5.191%	5.191%
Grassland	62.212%	62.319%	62.212%
Water	5.517%	5.516%	5.517%
Unused Land	22.561%	22.462%	22.554%
Built-up Land	1.034%	1.027%	1.041%

3.3.2. Spatio-temporal distribution of habitat quality in 2030

As the projected land use patterns for 2030 differ only slightly across the three scenarios, the natural development scenario was selected as an example for habitat quality analysis (Online Resource 8). The results (Fig 5) show that the spatial pattern of habitat quality in the study area in 2030 remains relatively stable, similar to that observed in 2024. Areas where habitat quality changes between 2024 and 2030 are mainly distributed at both ends of the Duku Highway corridor, mostly corresponding to a decline in habitat quality, and coincide with the expansion of built-up land, the core areas directly disturbed by human engineering activities. In contrast, habitat quality in other areas only sporadic changes, suggesting that the overall ecosystem along the Duku Highway corridor is highly stable.

Quantitative results on the areal proportions of different habitat quality levels (Fig 6) further confirmed the highly stable nature of habitat quality in the study area and send a relatively positive signal: contrary to the pre-2024 trend characterized by a reduction in high-quality areas and an expansion of low-quality areas, the region may be moving toward a gradual improvement in habitat quality in the coming period. Specifically, the proportion of high-quality areas remained above 70% in both 2024 and 2030, with a slight increase from 70.842% to 70.853%. Low-quality areas decreased marginally from 23.783% to 23.597%, while relatively low-quality areas rose from 3.359% to 3.484%, and relatively high-quality areas increased slightly from 2.003% to 2.053%.

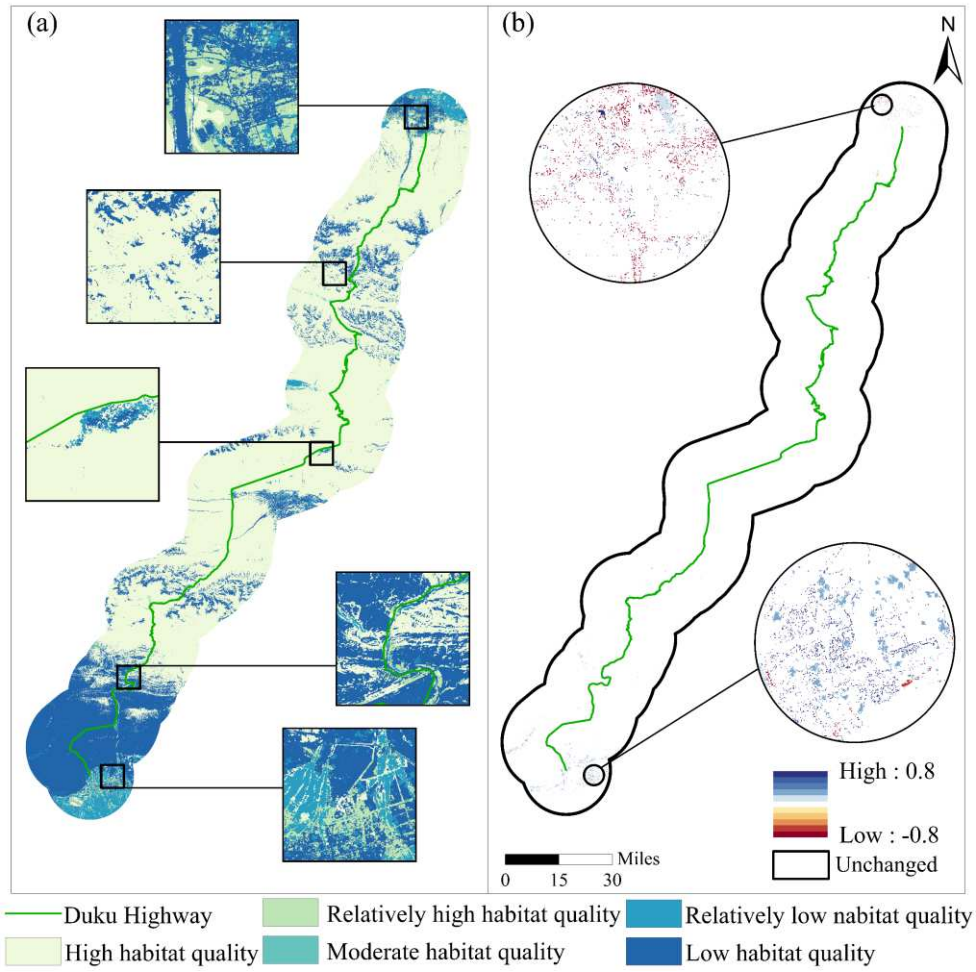


Fig. 5 Predicted habitat quality of the Duku Highway corridor in 2030 under the natural development scenario (a) and spatial differences in habitat quality between 2024 and 2030 (b)

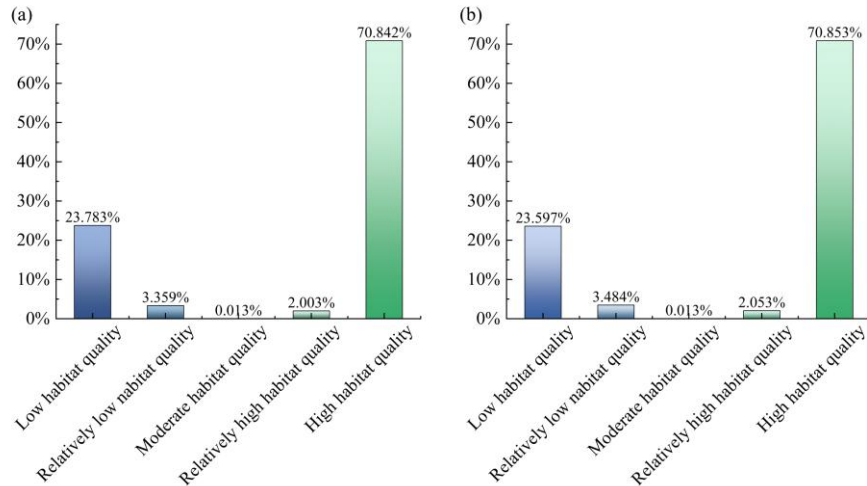


Fig. 6 Areal proportions of each habitat quality class in 2024 (a) and 2030 (b) under the natural development scenario

4. Discussion

This study provides the first assessment of habitat quality dynamics along a tourist highway corridor, taking the seasonally operated Duku Highway in the central Tianshan Mountains as a case study. The results indicate that, despite land use changes—primarily the expansion of construction sites and cropland (Fig 2)—as well as rapidly growing tourist volumes driven by the highway’s increasing popularity, habitat quality remained highly stable over the past two decades, with high-quality areas consistently accounting for more than 70% of the total region (Table 2). Projections for 2030 under three development scenarios suggest that this stability is likely to persist, with even a marginal improvement in high-quality areas (Fig 5, 6). These findings imply that, under certain conditions of strong natural constraints and stringent policy controls, a tourist highway may coexist with ecological conservation without causing substantial habitat degradation (Xie 2020; Qin et al. 2024; Ma et al. 2025).

The observed stability can be attributed to three interacting factors. First, natural constraints fundamentally limit large-scale land conversion. The Duku Highway traverses the ecologically fragile central Tianshan Mountains, characterized by high elevation, steep terrain, uneven water distribution,

and low carrying capacity (Liu et al. 2025; Liu et al. 2026; WEN Di 2026). These conditions make extensive land development physically challenging. Second, stringent policy interventions have reinforced ecological stability. The region is designated as a national key ecological functional zone, subject to ecological red lines, nature reserves, and prohibited development zones, mandating “green development under ecological constraints” (Chen et al. 2020; Wei et al. 2025; Zhao et al. 2025). The policy shift toward ecological prioritization in 2016 likely prevented further habitat degradation and even allowed slight recovery. Third, the highway’s seasonal operation (typically June to October) provides a natural recovery window of approximately six months annually. During the closed period, ecosystem processes can recuperate from the concentrated disturbance of the tourist season. This intermittent disturbance pattern has been shown in other temporary road closure systems to reduce habitat fragmentation and lower wildlife mortality (Lamb et al. 2018; Whittington et al. 2019). Additionally, tourist activities are largely confined to the roadside, with limited incursion into natural ecological lands, further minimizing direct disturbance.

The impact of land use changes on habitat quality varied across periods (Fig 4). An increase in water area promotes habitat quality improvement (Yang et al. 2022) , as exemplified by the positive contribution of unused land-to-water conversion during 2000–2008. The consistent positive contribution of unused-land-to-grassland conversion points to successful ecological restoration, possibly driven by policy-induced revegetation or natural succession following reduced human pressure (Fan et al. 2024; He et al. 2026). Conversely, the persistent negative contribution of grassland-to-unused-land conversion highlights ongoing grassland degradation, primarily due to overgrazing and construction activities (Leng et al. 2025).

Although this study provides a scientific reference for habitat quality assessments in the specific

context of tourist highway corridors and offers a baseline for evaluating the ecological outcomes of similar tourist roads in ecologically sensitive regions, several limitations should be acknowledged. First, the InVEST and PLUS model parameters were derived from literature, which may introduce uncertainty. Second, the upcoming Duku Expressway pilot project (scheduled from 2025 to 2032) was not assessed; its construction may cause habitat degradation, and future evaluation is needed.

5. Conclusion

This study assessed habitat quality along the Duku Highway corridor from 2000 to 2024 and projected changes for 2030 using the InVEST and PLUS models. The results indicate that, despite land use changes (grassland -2.81% , built-up land $+0.75\%$, forest $+1.61\%$), habitat quality remained highly stable. High-quality areas consistently accounted for more than 70% of the total region, while low-quality areas remained around 24%. The most pronounced shifts occurred between 2000 and 2008, with high-quality areas decreasing by 1.607% and low-quality areas increasing by 0.902%. These changes can be partly explained by the contribution of land use conversions: unused land-to-grassland conversion provided a positive effect, while grassland-to-unused-land conversion had a negative impact; in later periods, unused-land-to-grassland conversion contributed more positively, reflecting ecological restoration. Projections for 2030 indicate that habitat quality will remain virtually unchanged. High-quality areas are projected to increase marginally from 70.842% in 2024 to 70.853% in 2030, while low-quality areas decrease slightly from 23.783% to 23.597%. This exceptional stability is attributed to the combined effects of natural constraints (high elevation, steep terrain, low carrying capacity) and stringent policy controls (ecological red lines, nature reserves, development-restricted zones), reinforced by the highway's seasonal closure policy, which provides an annual recovery window of approximately six months. By focusing specifically on a tourist highway corridor, this study fills a research gap and

suggests that, under strong natural and policy constraints, a tourist highway may coexist with ecological conservation without causing substantial degradation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Credit authorship contribution statement

Yiran Ding: Writing – original draft, Methodology, Formal analysis, Data collection. **Ping Jiang:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Yue Zhang:** Methodology, Data collection. **Zhi Wang:** Methodology, Data collection. **Keremu Guzainuer:** Methodology, Data collection.

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