Spatiotemporal Variation and Prediction of Habitat Quality in the Landslide Area of Tongwei, Gansu Based on the PLUS-InVEST Model (Postprint)

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Abstract

A study on the spatiotemporal evolution of habitat quality in the landslide area of Tongwei, Gansu is of great significance for the ecological sustainable development of Tongwei County and similar regions in northwestern China. First, the Patch-generating Land Use Simulation (PLUS) model was adopted to predict land use types for 2035, then the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model was employed to analyze and predict the habitat quality of Tongwei County and the landslide area, as well as the spatiotemporal evolution characteristics of habitat degradation in the landslide area for the period 1985-2020 and 2035, finally, the Geodetector was utilized to detect the driving factors of habitat quality changes in the landslide area of Tongwei County. The results indicate that: (1) During 2020-2035, various land use types in Tongwei County experienced mutual expansion and transfer, with the expansion from cropland to grassland being the most prominent; land use types in Tongwei County remain dominated by cropland and grassland, with other land use types accounting for a relatively small proportion. (2) At the spatial scale, habitat quality in both Tongwei County and the landslide area shows an increasing trend from south to north, and both are dominated by low and relatively low grades. Habitat degradation in the landslide area is dominated by moderate and high degradation, showing a decreasing trend from south to north. (3) At the temporal scale, habitat quality in both Tongwei County and the landslide area exhibited a pattern of initial decline, followed by increase, and then decline again during 1985-2035; the linear fitting of the average habitat quality index shows a decreasing trend for Tongwei County, but an increasing trend for the landslide area. The average habitat degradation index displayed a pattern of initial decline followed by increase, with linear fitting showing an upward trend. (4) The Normalized Difference Vegetation Index (NDVI) is the most critical factor influencing the spatial differentiation of habitat quality in the landslide area. The interactions among various factors are primarily characterized by nonlinear enhancement, with the interaction between NDVI and annual average precipitation being the strongest.

Full Text

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Spatiotemporal Variation and Prediction of Habitat Quality in the Tongwei Landslide Area of Gansu Province Based on the PLUS-InVEST Model

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Abstract: The study of spatiotemporal evolution of habitat quality in the landslide area of Tongwei County, Gansu Province, holds significant importance for ecological sustainable development in Tongwei County and similar regions in northwestern China. This study first employs the Patch-generating Land Use Simulation (PLUS) model to predict land use types from 2020 to 2035. Subsequently, the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model is utilized to analyze and predict the spatiotemporal evolution characteristics of habitat quality and habitat degradation in Tongwei County and its landslide areas from 1985 to 2020, with projections to 2035. Finally, the geodetector model is applied to identify the driving factors behind habitat quality changes in the landslide area of Tongwei County. The results demonstrate that: (1) From 2020 to 2035, various land use types in Tongwei County will undergo mutual expansion and transition, with the most pronounced conversion being from arable land to grassland. Arable land and grassland will remain the dominant land use types, while other land use categories will account for relatively small proportions. (2) At the spatial scale, habitat quality in both Tongwei County and the landslide area exhibits an increasing trend from south to north, predominantly characterized by low and relatively low grades. Habitat degradation in the landslide area is dominated by moderate and high degradation levels, showing a decreasing trend from south to north. (3) At the temporal scale, from 1985 to 2035, habitat quality in both Tongwei County and the landslide area follows a pattern of initial decline, subsequent increase, and final decrease. In Tongwei County, the linear trend of average habitat quality index shows a declining trajectory, whereas in the landslide area, it demonstrates an upward trend. The average habitat degradation index follows a pattern of decreasing then increasing, with the linear fit indicating an upward trend. (4) The Normalized Difference Vegetation Index (NDVI) represents the most critical factor influencing spatial differentiation of habitat quality in landslide areas. Interactions among various factors are predominantly characterized by nonlinear enhancement, with the interaction between NDVI and average annual precipitation being the strongest.

Keywords: landslide area; PLUS model; InVEST model; habitat quality; geographical detector; Tongwei County

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1.1 Study Area Overview

Tongwei County is located in central Gansu Province (104°57 -105°38 E, 34°55 - 35°29 N), covering a total area of 2,907 km^2. The terrain is characterized by higher elevation in the northwest and lower elevation in the southeast, with altitudes ranging from 1,376 m to 2,475 m and an average elevation of 1,970.5 m. The region features typical loess hill-gully landforms. Situated at the intersection of China' s east-west and north-south seismic belts, seismic activity directly influences the occurrence of earthquake-induced landslides in the area. These landslides are predominantly medium to large in scale. Land use in the landslide area primarily consists of arable land and grassland, with some construction land in certain sections [Figure 1: see original paper].

1.2 Data Sources

Land use data (1985-2020) were obtained from the China Land Cover and Dynamic Dataset (https://zenodo.org/records/8176941). Climate and environmental data, including annual average temperature (1985-2020) and annual average precipitation (1985-2020), were sourced from the Qinghai-Tibet Plateau Data Center (http://www.gscloud.cn) with a resolution of 1 km. Digital Elevation Model (DEM) data were obtained from the Geospatial Data Cloud (https://www.gscloud.cn). Evapotranspiration data were derived from the National Aeronautics and Space Administration (https://www.nasa.gov/). The Normalized Difference Vegetation Index (NDVI) was obtained from the Geospatial Data Cloud. Slope and aspect data were extracted using Geographic Information Systems. Socioeconomic data, including population density, were sourced from the University of Florida' s Department of Geography and Emerging Pathogens Institute (https://www.worldpop.org/) and the Chinese Academy of Sciences' Resources and Environmental Sciences Data Center (https://www.resdc.cn/). Distance variables (to secondary, tertiary, and quaternary roads; to national, provincial, county, and township roads; to towns; and to the county government) were obtained from the Geographic Remote Sensing Ecology Network (https://www.gisrs.cn). All data were projected uniformly to the WGS_{{{1984}}{{UTM}}}{{{zone}}_{{48N}}} coordinate system with a spatial resolution of 30 m.

To investigate the driving forces of habitat quality change in the landslide area, eleven factors were selected: average annual temperature (X_1), average annual precipitation (X_2), slope (X_3), aspect (X_4), evapotranspiration (X_5), NDVI (X_6), DEM (X_7), distance to rivers (X_8), distance to roads (X_9), population density (X_{10}), and GDP (X_{11}).

1.3.1 PLUS Model

To provide data support for future habitat quality assessment in landslide areas, the Patch-generating Land Use Simulation (PLUS) model was employed to predict land use changes from 2020 to 2035. The PLUS model integrates a rule mining method based on land expansion analysis with a cellular automaton model based on a multi-type random seed mechanism. The land expansion analysis strategy extracts the expansion portions of various land use types during land use change and employs a random forest algorithm to mine the relationships between different land use expansions and their contributing factors, thereby obtaining development probabilities and influence weights of driving factors for each land use type.

The rule mining method based on land expansion analysis is calculated as:

$$P_{d,k}(x) = \sum_{n=1}^{N} \frac{1}{M} h_n(X)$$

where $P_{d,k}(x)$ represents the probability of spatial unit i converting to land use type k; d takes values of 0 or 1, indicating whether the plot can be converted to land use type k; X represents driving factors; $h_n(X)$ is the land use prediction type calculated when the decision tree is n; I is the decision tree index function; and M is the total number of decision trees.

Based on the development probability constraints of various land use types, the cellular automaton improved by randomly generating multi-type patch seeds and a threshold decreasing mechanism dynamically simulates future land use conditions. The cellular automaton model with multi-type random seed mechanism is calculated as:

$$TP_{i,k}^{t} = P_{d,k}(X) \times \Omega_{i,k}^{t} \times D_k^t$$

where $TP_{i,k}^{t}$ is the overall conversion probability of spatial unit i to land use type k at time t; $P_{d,k}(X)$ is the growth probability of land use type k at spatial unit i when d takes a value of 1; $\Omega_{i,k}^{t}$ is the neighborhood weight of land use type k at spatial unit i at time t; and D_k^t is the impact of future demand for land use type k, an adaptive driving coefficient that depends on the gap between the current land quantity and the target demand for land use type k during iteration t.

Neighborhood weights reflect the expansion capacity of various land use types, with parameters ranging from 0 to 1. Larger values indicate greater expansion capacity of the land use type. This study employs the PLUS model to calculate expansion capacity using land use data from 1985 to 2020.

1.3.2 InVEST Model

The InVEST model was utilized to analyze habitat quality and habitat degradation in Tongwei County and its landslide areas. By establishing relationships between different land use types and threat sources, and using land use type data from the landslide area, the model delineates the response degree of different land use types to threat sources, thereby simulating the patterns of habitat quality and degradation in Tongwei County and its landslide area. The model assumes that habitat quality is proportional to ecosystem stability.

The habitat quality is calculated as:

$$Q_{xj} = H_j \times \left(1 - \frac{D_{xj}^z}{D_{xj}^z + k^z}\right)$$

where Q_{xj} is the habitat quality index of grid x in habitat type j, with a value range of [0, 1]; H_j is the habitat suitability of habitat type j; k is the half-saturation constant, defaulting to 0.5, representing half of the maximum relative habitat degradation degree in Tongwei County; D_{xj} is the habitat degradation index of grid x in habitat type j; and z is the model default parameter.

The habitat degradation index is calculated as:

$$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \left(\frac{w_r}{\sum_{r=1}^{R} w_r}\right) r_y i_{rxy} \beta_x S_{jr}$$

where D_{xj} is the habitat degradation index of grid x in habitat type j; Y_r is a set of grids on the threat raster layer r; r_y indicates whether grid y provides threat source r; w_r is the threat weight of threat factor r; β_x is the resistance of grid x to disturbance; S_{jr} is the sensitivity level of habitat j to threat factor r; and i_{rxy} is the impact distance of threat factor r in grid y on habitat in grid x.

Threat factors exhibit linear decay and exponential decay in space. The calculations are:

Linear decay: $i_{rxy} = 1 - \left(\frac{d_{xy}}{d_r}\right)$

Exponential decay: $i_{rxy} = \exp\left(-\frac{2.99 d_{xy}}{d_r}\right)$

where d_{xy} is the linear distance between grid x and grid y; and d_r is the maximum influence distance of threat factor r.

Based on the InVEST model manual and existing research findings, and considering land use conditions in Tongwei County, arable land, construction land, and bare land with high human disturbance intensity were designated as threat factors to habitat quality. Influence weights, maximum influence distances, and impact types were set according to relevant research results, while habitat suitability of different land use types and relative sensitivity to threat factors were also established .

1.3.3 Geodetector

Habitat quality changes are associated with natural and socioeconomic factors. Land use change, driven by natural environmental changes and human activities, is a known major driver affecting habitat quality. To explore the driving forces of habitat quality change in the landslide area, the land use factor was excluded, and habitat quality driving forces were detected for other factors. All driving force factors were unified to a 30 m resolution. Landslide surfaces and vector surfaces were converted to points, driving factor values were extracted to the points, and the resulting table was exported for geodetector analysis.

To investigate driving factors of habitat quality in the landslide area, the geodetector model was employed. This model considers spatial heterogeneity among factors and has been widely applied in ecological environmental management, land use, and other fields. The calculation formula is:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2}$$

where q is the detection result of habitat quality impact factors, with a value range of [0, 1]; h is the classification number of factors; L is the total number of evaluation units; N_h and N are the total numbers of grids in each zone and the entire region, respectively; and σ_h^2 and σ^2 are the variances of habitat quality in each zone and the entire region, respectively.

Factor interaction detection examines the explanatory power of interactions between pairs of factors on habitat quality, which is divided into five types .

2.1.1 Land Use Expansion Analysis

Considering the natural environment and socioeconomic conditions of Tongwei County, eleven factors were selected: average annual temperature, average annual precipitation, slope, aspect, evapotranspiration, NDVI, DEM, distance to rivers, population density, GDP, and distance to roads. Combining these with a random forest algorithm, the contribution magnitude of different expansion factors to each land use type was determined.

The study revealed that the most significant factor contributing to arable land expansion is slope, followed by aspect and distance to secondary roads, all with contribution degrees exceeding 0.15. For forest land expansion, the most influential factors are NDVI and distance to secondary roads, with contribution degrees exceeding 0.12. For grassland expansion, slope is the most important factor, followed by aspect and distance to secondary roads, with contribution degrees exceeding 0.15. For construction land expansion, the most critical factor is distance to the county government, followed by distance to towns and distance to quaternary roads, all with contribution degrees exceeding 0.12 [Figure 2: see original paper].

2.1.2 Accuracy Validation

Based on the PLUS model, land use types in Tongwei County for 2020 were simulated and compared with actual land use types in 2020 for accuracy validation. The Kappa coefficient reached 0.82, and the overall accuracy (OA) reached 0.91, indicating high credibility and accuracy of the simulation results. Therefore, based on the 2020 land use types, the PLUS model can simulate land use types in Tongwei County for 2035 under natural development scenarios [Figure 3: see original paper].

2.1.3 Land Use Change Analysis

From 2020 to 2035, various land use types in Tongwei County will undergo mutual conversion, with the most significant transition being from arable land to grassland, while conversion from grassland to arable land will be relatively limited. Forest land will experience slight expansion into arable land, while water bodies and unused land will remain essentially unchanged. Land use types will continue to be dominated by arable land and grassland, with forest land, water bodies, bare land, and construction land accounting for relatively small proportions [Figure 4: see original paper].

2.2 Habitat Quality in Tongwei County

To more accurately characterize the spatial evolution patterns of habitat quality, the habitat quality in Tongwei County was divided into five grades using equal interval methods based on landslide area conditions and existing research: low (0-0.2), relatively low (0.2-0.4), medium (0.4-0.6), relatively high (0.6-0.8), and high (0.8-1.0) [Figure 5: see original paper].

Spatially, low-grade habitat quality in Tongwei County is concentrated primarily in southern and central regions where human activities are frequent and land use is dominated by arable land. Relatively high and high-grade habitat quality is concentrated mainly in northern areas where the Huajialing National Nature

Reserve is located and human disturbance is minimal. Overall, habitat quality in Tongwei County generally increases from south to north, with low and relatively low grades predominating [Figure 5: see original paper].

Temporally, from 1985 to 2035, habitat quality in Tongwei County is dominated by low and relatively low grades, with significant changes in the area proportions of each grade. The area proportions of low, medium, and high grades show upward linear trends, while those of relatively low and relatively high grades show downward linear trends [Figure 6: see original paper]. The average habitat quality index ranges from 0.269 to 0.293, exhibiting an overall pattern of decline followed by increase and subsequent decline, with a downward linear trend. The average habitat quality index decreased to 0.269 in 2020 and is projected to decrease to 0.272 in 2035 [Figure 7: see original paper].

2.3 Habitat Quality in Landslide Area

Spatially, low and relatively low-grade habitat quality in the landslide area is concentrated primarily in central and southern landslide zones of Tongwei County, medium-grade habitat quality is concentrated mainly in northern and western landslide zones, and relatively high-grade habitat quality is concentrated in northern landslide zones. Low and relatively low-grade habitat quality accounts for large proportions in the landslide area, with widespread distribution and obvious fragmentation. No high-grade habitat quality areas appear in the landslide area, indicating that habitat quality in landslide areas is lower than that in Tongwei County overall [Figure 8: see original paper].

Temporally, from 1985 to 2035, habitat quality in the landslide area is dominated by low and relatively low grades, with significant changes in area proportions. The proportion of low-grade habitat quality increased from 31.02% to 33.36%, showing an upward linear trend. The proportion of relatively low-grade habitat quality decreased from 65.70% to 62.92%, showing a downward linear trend. The proportion of medium-grade habitat quality increased from 3.60% to 3.05%, showing an upward linear trend. The proportion of relatively high-grade habitat quality decreased from 0.22% to 0.12%, showing a downward linear trend. The proportion of high-grade habitat quality decreased from 0.04% to 0.04% [Figure 9: see original paper].

The average habitat quality index in the landslide area ranges from 0.239 to 0.254, with an overall upward linear trend. The average habitat quality index increased to 0.239 in 2020 and is projected to increase to 0.241 in 2035, following a pattern of initial decline, subsequent increase, and final decline [Figure 10: see original paper].

2.4 Habitat Degradation in Landslide Area

Habitat degradation in the landslide area was classified into four types: mild degradation (0–0.24), moderate degradation (0.24–0.38), high degradation (0.38–

0.48), and extreme degradation (0.48–0.70] [Figure 11: see original paper].

Spatially, habitat degradation in Tongwei County landslide area generally decreases from south to north, with higher degradation in southern landslide zones and lower degradation in northern zones [Figure 11: see original paper]. Temporally, from 1985 to 2035, the combined area proportion of moderate and high degradation exceeds 60.00%. Mild degradation accounts for less than 15.00%, while extreme degradation accounts for approximately 25.00%. Linear trends show decreasing proportions for mild and moderate degradation, and increasing proportions for high and extreme degradation. The average habitat degradation index shows an upward linear trend. Projections for 2035 indicate that the proportion of extreme degradation will increase while other degradation types will decrease, with the average habitat degradation index reaching 0.48 [Figure 12: see original paper] [Figure 13: see original paper].

2.5 Driving Forces of Habitat Quality in Landslide Area

Single-factor detection results reveal significant differences in the explanatory power of various driving factors on habitat quality in the landslide area. The explanatory power (q-values) in descending order are: NDVI (0.42) > average annual precipitation (0.38) > average annual temperature (0.35) > DEM (0.31) > evapotranspiration (0.28) > slope (0.25) > aspect (0.22) > distance to rivers (0.18) > GDP (0.15) > population density (0.12) > distance to roads (0.10). These results indicate that natural factors dominate the spatial distribution pattern of habitat quality in the landslide area, with NDVI being the most influential driving factor. Among socioeconomic factors, GDP has a relatively large impact with a q-value of 0.15 .

Interaction detection results show that all pairwise interaction q-values exceed single-factor q-values, with interactions displaying either nonlinear enhancement or dual-factor enhancement, predominantly the former. The interaction between average annual precipitation and NDVI (X_2 X_6) exhibits the strongest effect with a q-value of 0.68, followed by average annual precipitation average annual temperature (X_2 X_1) and average annual temperature NDVI (X_1 X_6), with q-values of 0.61 and 0.58, respectively. The interaction between NDVI and GDP (X_6 X_{11}) shows significant dual-factor enhancement with a q-value of 0.52, while other factor interactions demonstrate nonlinear enhancement [Figure 14: see original paper].

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3 Discussion

Accurately predicting future land use structure remains challenging. Although the PLUS model demonstrates good simulation performance, subjective factors affecting prediction results cannot be avoided, particularly since land use is easily influenced by policies. Therefore, improving model prediction accuracy requires full integration with actual land use conditions. Field investigations reveal that Tongwei County actively implemented pilot programs for the Grain for Green Project in 2000, with substantial areas of farmland returned to forest. In 2002, the project was only implemented in Lidian Township and Pingxiang Town with limited area, but survival rates gradually improved and reached peak levels, with ecological benefits becoming increasingly apparent. The second round of Grain for Green Project began to demonstrate ecological benefits only after 2005. Based on actual conditions in Tongwei County, this study selected a 15-year interval for predicting future land use structure using the PLUS model, fully considering policy impacts on land use structure.

Comparisons of expansion factors with large contributions to land use conversion show results generally consistent with previous research. Habitat quality in Tongwei County changed significantly in 1982, closely related to policy factors. Following the issuance of the 1982 and 1983 No. 1 Central Documents, which clarified the agricultural production responsibility system of household-based production contracting, Tongwei County experienced arable land expansion, and correspondingly, land use types in landslide areas shifted toward arable land. This study indicates that the average habitat quality index in Tongwei County declined from 1985 to 2000, then increased with the implementation of the Grain for Green Project in 2000. When setting threat factor parameters in the InVEST model, field investigations should be strengthened to improve simulation accuracy while drawing on previous research findings.

Tongwei County is located in the arid and semi-arid region of northwest China, significantly influenced by average annual temperature and precipitation, with limited high habitat quality areas. Meanwhile, individual landslide zones are relatively small and do not intersect with high habitat quality areas. In Dingxi City and other areas in central Gansu, high population density, low vegetation coverage, and dominance of arable land result in mean habitat quality values of 0.27–0.31, consistent with this study' s findings. NDVI is the most critical factor affecting spatial differentiation of habitat quality in landslide areas. The interaction between any two factors has greater impact on spatial differentiation of habitat quality than single factors, with the interaction between NDVI and average annual precipitation being the strongest. All factor interactions exhibit nonlinear enhancement or dual-factor enhancement, predominantly the former.

Habitat quality change results from the combined effects of natural and socioeconomic factors. This study employs the geodetector model to analyze impacts on the spatiotemporal evolution pattern of habitat quality and identify dominant controlling factors. However, data acquisition and quantification of other socioeconomic factors present considerable challenges, resulting in slightly insufficient socioeconomic factor support, which requires further breakthroughs in future research.

4 Conclusions

This study reveals that: (1) From 2020 to 2035, land use types in Tongwei County will undergo mutual conversion, with the most significant transition being from arable land to grassland and limited conversion from grassland to arable land. Land use types will remain dominated by arable land and grassland, with other types accounting for relatively small proportions.

(2) Spatially, habitat quality in Tongwei County and its landslide area increases from south to north from 1985 to 2035, with overall low habitat quality dominated by low and relatively low grades. Habitat degradation in landslide areas is dominated by moderate and high degradation, decreasing from south to north.

(3) Temporally, the average habitat quality index in Tongwei County follows a pattern of decline, then increase, and subsequent decline from 1985 to 2035, with a downward linear trend, projected to reach 0.272 in 2035. In contrast, the average habitat quality index in landslide areas follows the same pattern but with an upward linear trend, projected to reach 0.241 in 2035. The average habitat degradation index shows a pattern of decreasing then increasing, with an upward linear trend projected for 2035. Overall, habitat quality in landslide areas shows an upward trend based on linear fitting.

(4) NDVI is the most critical factor influencing spatial differentiation of habitat quality in landslide areas. Interactions between any two factors have greater impact than single factors, with the interaction between NDVI and average annual precipitation being the strongest. All factor interactions exhibit nonlinear enhancement or dual-factor enhancement, predominantly the former. Natural factors play a dominant role in habitat quality changes in landslide areas, while socioeconomic development also influences these changes.

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Note: Figure translations are in progress. See original paper for figures.