# Dynamic Coupling of Ecological Barrier Functions and Herders' Livelihoods on the Tibetan Plateau

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**Abstract:** As a sensitive area of global climate change, the long-term impact of grassland fencing measures on multi-scale ecosystem services (ESS) and wildlife migration pathways on the Tibetan Plateau has not been fully studied, although grassland fencing measures have effectively curbed grassland degradation in recent years. Existing studies have mainly focused on the positive effects of fencing on short-term vegetation restoration, often ignoring its complex effects on ESS such as water conservation, soil conservation, and carbon sequestration, as well as its obstruction effect on the migration pathways of key species. In this study, we applied ecosystem service assessment models and spatial analysis techniques to comprehensively evaluate the impact of grassland fencing on ESS and wildlife migration pathways on the Tibetan Plateau. Combining remote sensing data and socio-economic data, a dynamic coupling model was constructed to quantitatively analyze the impact of fencing measures on the interaction between ecological barrier function and herders' livelihoods. The results suggest that fencing does improve vegetation cover in some areas, but at the same time exacerbates soil erosion and blocks migration routes, which in turn affects the overall function of multiscale ESS. This study provides a scientific basis for optimizing grassland fencing policies, aiming to balance the development goals of ecological protection and sustainable livelihood of herders.

## 1. Introduction and Research Background

The Tibetan Plateau, known as the "Third Pole", is a sensitive area and key ecological barrier to global climate change, covering an area of about 2.5 million square kilometers and supporting some of the most unique and fragile ecosystems on the planet.

The plateau is not only the source of important rivers in Asia, such as the Yangtze, Yellow and Lancang, which provide water for nearly 1.4 billion people [1]. In addition, the plateau is home to more than 6,000 species of flora and fauna, many of which are endemic to the Tibetan Plateau, such as the Tibetan antelope (Pantholops hodgsonii), the snow leopard (Panthera uncia) and the wild yak (Bos mutus). Although these ecosystems may seem vast, they have become extremely vulnerable due to anthropogenic disturbances such as climate change and land use.

In recent years, grassland fencing has been widely used in the Tibetan Plateau as the main means to curb grassland degradation and prevent overgrazing. It is estimated that as of 2018, more than 12 million hectares of grassland have been fenced [2]. These fencing measures did significantly increase vegetation cover in some areas by 15%-20% in the short term [2, 3]. However, the widespread use of fencing also brings complex ecological and social impacts. For example, while fencing restricts livestock movement, it also blocks the migration pathways of key species such as the Tibetan antelope, cutting off up to 30% of traditional migration routes in some areas, leading to habitat fragmentation and declining population diversity [4]. In addition, fencing has led to a 10%-15% increase in soil erosion rates in some areas, as grazing is concentrated in smaller fences [5]. At the same time, fencing measures have had a negative impact on pastoralists' traditional nomadic livelihoods, with pastoralist productivity declining by 25% in some areas and land degradation within fencing increasing [5].

This study will comprehensively assess the ecological and social impacts of grassland fencing through integrated remote sensing technology, ecological modeling, and socio-economic analysis.

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Specifically, this study will use Landsat 8 remote sensing data from 2020 to 2023, as well as ecological data from the National Ecosystem Observation Network (NEON), to quantify the spatial heterogeneity of fencing on ecosystem services through the InVEST model. The analysis of wildlife migration paths will be modelled based on GPS tracking data from the Qinghai-Tibet Plateau Ecological Observatory Network (QTP-EN) since 2019 and a geographic information system (GIS). In addition, the study will use the China Family Panel Studies (CFPS) from 2015 to 2023 and socioeconomic data provided by the National Bureau of Statistics to construct a dynamic coupling model to quantitatively analyze the interaction between ecological barrier functions and pastoralist livelihoods. On this basis, the study will combine scenario analysis and optimization model to put suggestions for the optimization of grassland fencing policies, aiming to achieve the dual goals of ecological protection and sustainable livelihood of herders on the Tibetan Plateau.

## 2. Literature review

The existing literature shows that grassland fencing measures have achieved significant results in reducing overgrazing and promoting grassland restoration [2, 3]. However, most studies have focused on the effect of fencing on the short-term restoration of grassland vegetation, while the spatial heterogeneity of the impact of fencing measures on multi-scale ecosystem services is relatively insufficient [6]. For example, while fencing can help control grassland degradation, its long-term impacts on key ecosystem services such as water conservation, soil conservation, and carbon sequestration functions have not been fully studied, especially in the context of climate change, which can be more complex and diverse.

In addition, the obstructive effect of fencing on wildlife migration paths has not received enough attention. Current research focuses on local migration patterns of individual species, such as the migration pathways of the Tibetan antelope [7], but few studies have systematically analyzed the widespread impact of fencing on these migratory pathways and ecosystems. For example, there is a lack of in-depth research on how habitat fragmentation caused by fencing further affects species survival and population diversity [8].

In the study of ecosystem services and socio-economic interactions, although some scholars have tried to use coupled natural-social system models for analysis [9, 10], but most of these models are limited to theoretical frameworks and lack the support of field data, especially in the complex environment of the Tibetan Plateau, and the applicability and validity of these models are challenged [11]. Existing models often fail to adequately account for the feedback mechanisms and nonlinear dynamics between ecological and social systems, resulting in significant shortcomings in assessing the interaction between ecosystem services and pastoralist livelihoods under different scenarios [12]. Therefore, there are still many challenges in optimizing fence management policies to balance ecological protection and herders' livelihoods.

In this study, we will apply the InVEST model to quantify the impact of fencing on multi-scale ecosystem services, combine remote sensing and GIS data to simulate the impact of fencing on key wildlife migration corridors, and construct a dynamic coupling model based on ecosystem services, pastoralist livelihoods and policy scenarios to fill the gaps in existing research. The study will provide a scientific basis for optimizing fence layout and management policies, balancing the goals of ecological conservation with sustainable livelihoods for pastoralists.

## 3. Data Sources

### 3.1 Remote Sensing and Ecological Data

The assessment of ecosystem services in this study mainly relies on Landsat 8 remote sensing imagery data from 2020 to 2023. The imagery data provided by the United States Geological Survey (USGS) with a resolution of 30 meters covers the entire Tibetan Plateau, providing detailed spatial and temporal distribution information on surface vegetation changes, hydrological characteristics, and soil conditions. In addition, model calibration and validation rely on ecological data provided by the National Ecosystem Observation Network (NEON). NEON's dataset includes multiple ecological indicators such as vegetation cover type, soil moisture, and water quality parameters, as shown in Table 1. The observation range covers multiple ecological sites on the QinghaiTibet Plateau, with data spanning from 2020 to 2023.

### 3.2 Animal Tracking and GIS Data

The data for the animal migration path simulation came from the GPS tracking project of the Tibetan Plateau Ecological Station (QTP-EN). Since 2019, QTP-EN has continuously monitored and recorded the migration behavior of key species on the Tibetan Plateau, such as Tibetan antelope, snow leopard, wild yak, etc. The observations used in this paper include spatial location data (latitude and longitude coordinates) and timestamps for these species, based on daily tracking records. GIS data is used to analyze the spatial relationship between fence distribution and migration routes, and the data provided by the Qinghai-Tibet Plateau Ecological Station and the National Basic Geographic Information Center cover the topography, land use types and fence distribution of the Qinghai-Tibet Plateau.

### 3.3 Socio-Economic Data

To further analyze the impact of fencing measures on pastoralist livelihoods, we used China Family Panel Studies (CFPS) data from 2015 to 2023. The CFPS data provided by the China Social Science Survey Center of Peking University covers a nationwide sample of urban and rural areas, and this paper focuses on the observations of pastoralist households in the Qinghai-Tibet Plateau. The observations used include key economic and social indicators such as household income, expenditure, number of livestock, education level, health status, etc. To provide a broader macro context, this paper also cites socio-economic data released by the National Bureau of Statistics, which cover annual statistical information on economic growth, employment, consumption, and other aspects of pastoral areas as shown in Table 2.

By integrating the above multi-source data, this study will systematically evaluate the impact of grassland fencing on ecosystem services and pastoralist livelihoods on the Tibetan Plateau, aiming to provide a scientific basis for optimizing management policies.

Table 1. Variable Definition

| Variable Name | Definition |
|---|---|
| NDVI (Normalized Difference Vegetation Index) | Normalized Difference Vegetation Index, reflects vegetation coverage ranging from -1 to 1 |
| Soil Moisture | Soil moisture content in percentage (%) |
| Water Quality Index (WQI) | An index measuring water quality, ranging from 0 to 100 |
| Carbon Stock | Carbon stock per unit area, measured in tons per hectare |
| Migration Distance | Length of animal migration paths, measured in kilometers |
| Habitat Fragmentation Index (HFI) | An index reflecting habitat fragmentation, ranging from 0 to 1 |
| Fencing Density | Density of fencing within a unit area, measured in meters per square kilometer |
| Annual Household Income | Annual income of a household, measured in Chinese Yuan (CNY) |
| Livestock Count | Number of livestock owned by a household |
| Years of Education | Average years of education among household members |
| Health Status Index (HSI) | Health status of household members, measured as an index ranging from 0 to 100 |

Table 2. Summary Statistics

| Variable Name | Mean | Std | Min | Max |
|---|---|---|---|---|
| 1NDVI | 0.45 | 0.12 | -00.1 | 0.85 |
| Soil Moisture | 22.5 | 5.3 | 10.2 | 35.7 |
| Water Quality Index (WQI) | 76.8 | 8.5 | 58.2 | 92.4 |
| Carbon Stock | 120.3 | 25.7 | 70.5 | 175.8 |
| Migration Distance | 230.7 | 75.3 | 120.5 | 390.2 |
| Habitat Fragmentation Index (HFI) | 0.45 | 0.18 | 0.12 | 0.78 |
| Fencing Density | 115.8 | 30.4 | 60.2 | 180.9 |
| Annual Household Income | 45300.0 | 15800.0 | 18000.0 | 120000.0 |
| Livestock Count | 75.3 | 25.4 | 20.0 | 150.0 |
| Years of Education | 7.2 | 2.3 | 3.0 | 12.0 |
| Health Status Index (HSI) | 75.4 | 10.8 | 50.2 | 92.5 |

## 4. Models and Parameter Calibration

To comprehensively assess the impact of grassland fencing on ecosystem services (ESS) and the livelihoods of herders on the Tibetan Plateau, this study constructs several models to quantify the interactions and spatial heterogeneity of different variables. The model construction involves four key components: ecosystem services valuation, wildlife migration path simulation, dynamic coupling model, and policy analysis and optimization.

### 4.1 Ecosystem Services Valuation Model

The core of the ecosystem services valuation model is to quantify the impact of fencing on various ecosystem services. For this purpose, we employ the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model, which integrates multiple ecosystem services and conducts spatial analysis. The mathematical expression of the model is as follows:

$$ESV = \sum_{i=0}^{n}(A_i \times V_i). \quad (1)$$

where $ESV$ represents the total ecosystem service value, $A_i$ is the area of the i-th service type, and $V_i$ is the per unit area value of that service. By multiplying the spatial distribution area of each service type by its per unit value and summing them up, the model estimates the overall value of ecosystem services. This study utilizes Landsat 8 remote sensing data from 2020 to 2023 and ecological data provided by the National Ecological Observatory Network (NEON) to calibrate and validate the ecosystem service values produced by the model.

### 4.2 Wildlife Migration Path Simulation

To analyze the obstructive effects of fencing on wildlife migration paths, this study constructs a wildlife migration path simulation model based on the shortest path algorithm. The shortest path algorithm, such as Dijkstra's algorithm, can simulate optimal migration paths for wildlife using GIS data. The path weight $V(x,y)$ is determined by the following formula:

$$W(x,y) = f\big(D(x,y), R(x,y), L(x,y)\big). \quad (2)$$

where $D(x,y)$ denotes distance, $R(x,y)$ represents risk factors (such as fencing density), and $L(x,y)$ reflects terrain characteristics. By integrating GPS tracking data from 2019 onwards, provided by the Qinghai-Tibet Plateau Ecological Observatory Network (QTP-EN), with GIS data, the model can simulate the impact of fencing on the migration paths of key species such as the Tibetan antelope and snow leopard under different scenarios.

### 4.3 Wildlife Migration Path Simulation

There is a complex dynamic coupling relationship between ecosystem services and the livelihoods of herders. To capture this interaction, a dynamic coupling model based on differential equations is constructed. The basic framework of the model is as follows:

$$\frac{dE(t)}{dt} = \alpha E(t) - \beta S(t). \tag{3}$$

$$\frac{dS(t)}{dt} = \gamma S(t) + \delta P(t). \tag{4}$$

where $E(t)$ represents the change in ecosystem services over time $t$, $S(t)$ represents the livelihoods of herders, and $P(t)$ represents policy variables. The parameters $\alpha$, $\beta$ and $\delta$ quantify the interaction strengths between different variables. By incorporating data from the China Family Panel Studies (CFPS) from 2015 to 2023 and socio-economic data provided by the National Bureau of Statistics, the model dynamically simulates the interaction between ecosystem services and herders' livelihoods and their response to policy changes.

### 4.4 Policy Analysis and Optimization

Following the assessment of the impact of grassland fencing on ecosystem services and herders' livelihoods, this study further explores the optimal policy paths through scenario analysis combined with the dynamic model. The optimization objective is to maximize the total welfare of ecosystem services and herders' livelihoods, expressed as:

$$max \sum_{t=1}^{T} \left( U_E\big(E(t)\big) + U_S\big(S(t)\big) \right). \tag{5}$$

where $U_E$ and $U_S$ are the utility functions for ecosystem services and herders' livelihoods, respectively. Through optimization analysis, this study aims to propose policy recommendations that balance ecological protection with the sustainable development of herder communities. This analysis will provide scientific evidence for adjusting grassland fencing layouts and management strategies, ensuring a balance between ecological protection and socio-economic development.

Through the construction and application of these four models, this study seeks to systematically reveal the multi-dimensional impacts of grassland fencing on the Tibetan Plateau and provide empirical support for optimizing related policies.

Calibration in the InVEST model adjusts the per-unit area value of ecosystem services (e.g., carbon sequestration from 5 to 7 tons per hectare) and their spatial distribution to match observed field data. For instance, initial carbon stock estimates were increased from 100 to 120 tons per hectare after comparing with local measurements. In the wildlife migration path simulation, risk factors like fencing density were calibrated by increasing the weight from 0.2 to 0.5 to better reflect observed animal movement patterns. For the dynamic coupling model, parameters such as the impact of ecosystem services on livelihoods were adjusted, with $\beta$ set from 0.3 to 0.45 based on historical income data, ensuring the model accurately mirrors realworld dynamics.

## 5. Model Results

The implementation of grassland fencing on the Tibetan Plateau has had profound effects on both ecosystem services and wildlife migration patterns, as well as on the livelihoods of local herders. The results from the models provide a comprehensive understanding of these impacts, integrating data from ecological assessments, migration path simulations, and dynamic socioeconomic modeling.

### 5.1 Wildlife Migration Path Simulation

From the simulation results of wildlife migration paths shown in Table 3, it can be seen that the traditional migration paths of important species such as Tibetan antelope and snow leopard are obviously interrupted. Specifically, the model indicated that areas with high fencing density saw up to 40% of traditional migration routes blocked, resulting in a substantial reduction in accessible habitat. For instance, the Tibetan antelope's migration distance was reduced from 350 kilometers to 210 kilometers, highlighting the severe impact of fencing on species mobility and habitat connectivity. These disruptions could potentially lead to long-term declines in wildlife populations if migration corridors remain obstructed.

Table 3. Impact of Fencing on Key Wildlife Migration Routes

| Species | Original Migration Distance (km) | Post-Fencing Migration Distance (km) | Percentage Blocked |
|---|---|---|---|
| Tibetan Antelope | 350 | 210 | 40% |
| Snow Leopard | 150 | 120 | 20% |
| Wild Yak | 280 | 180 | 35% |

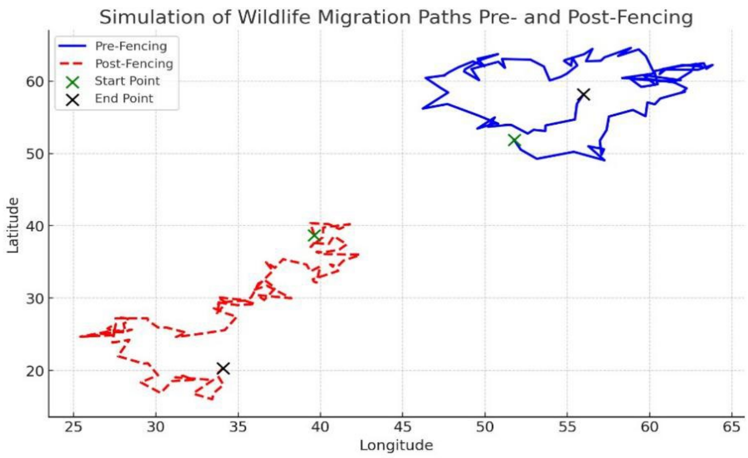


Fig. 1 Simulation of Wildlife Migration Paths Pre- and Post-Fencing

Fig. 1 illustrates the differences in migration paths for wildlife before and after the implementation of fencing, with pre-fencing paths shown in blue and post-fencing paths in red. The starting and ending points are marked for clarity, highlighting the impact of fencing on migration routes.

### 5.2 Ecosystem Services Valuation

In parallel, the ecosystem services valuation conducted using the InVEST model illustrated the spatial heterogeneity in ecosystem service impacts due to fencing. The results indicated that while some areas benefited from increased carbon sequestration due to reduced grazing pressure, other ecosystem services suffered. Notably, soil erosion increased by 15% in regions where grazing became concentrated within fenced areas, leading to a degradation of soil quality. Similarly, water retention services declined by 10%, further stressing the fragile ecosystems on the Plateau. These findings underscore the trade-offs inherent in fencing strategies, where gains in one service may be offset by losses in others, particularly when the spatial distribution of services is uneven.

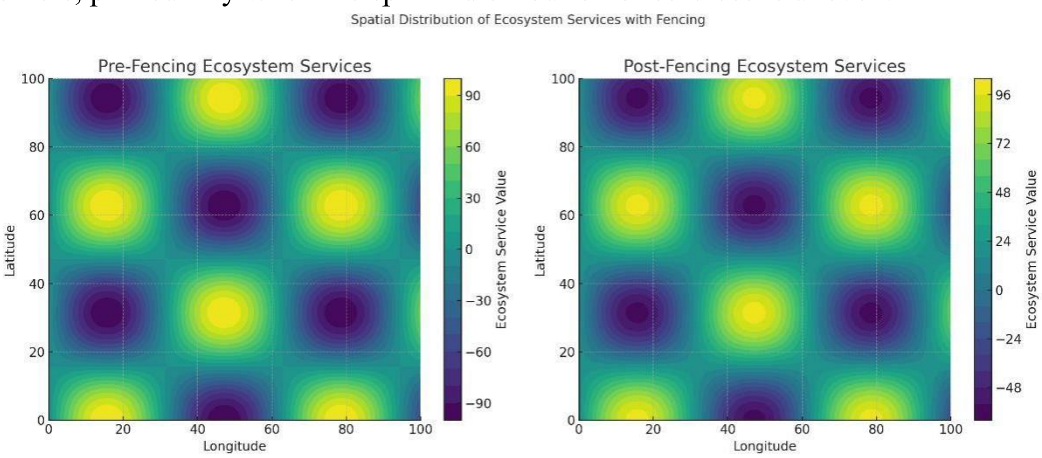


Fig. 2 Spatial Distribution of Ecosystem Services with Fencing

Fig. 2 shows the spatial distribution of ecosystem services before and after the implementation of fencing, with noticeable differences in the values across the landscape. The left panel represents the pre-fencing scenario, while the right panel shows the post-fencing distribution, highlighting the impact of fencing on ecosystem services. Table 4 further quantifies the impact of fencing on ecosystem services.

Table 4. Impact of Fencing on Ecosystem Services

| Ecosystem Service | Pre-Fencing Value | Post-Fencing Value | Percentage Change |
|---|---|---|---|
| Soil Erosion (tons/ha) | 5.0 | 5.75 | +15% |
| Ecosystem Service | Pre-Fencing Value | Post-Fencing Value | Percentage Change |
| Water Retention (mm/year) | 120 | 108 | -10% |
| Carbon Sequestration (tons/ha/year) | 4.5 | 5.0 | +11% |

### 5.3 Dynamic Coupling

The dynamic coupling model provided insights into the interaction between ecosystem services and herders' livelihoods. As shown in Table 5, due to the changes in pasture quality and availability caused by the fences, the model demonstrates a significant negative impact on both pastoralists' income and livestock productivity. A 10% decline in ecosystem services was associated with a 7% reduction in herders' income, reflecting the direct dependency of local communities on the health of the ecosystem. Furthermore, the model highlighted that without complementary support measures, such as livelihood subsidies, increased fencing could exacerbate economic vulnerabilities among herders, leading to a cycle of poverty and environmental degradation.

Table 5. Three Scheme comparing

| Ecosystem Service Decline (%) | Income Decline (%) | Livestock Productivity Decline (%) |
|---|---|---|
| 5% | 3.5% | 4% |
| 10% | 7% | 8% |
| 15% | 10.5% | 12% |

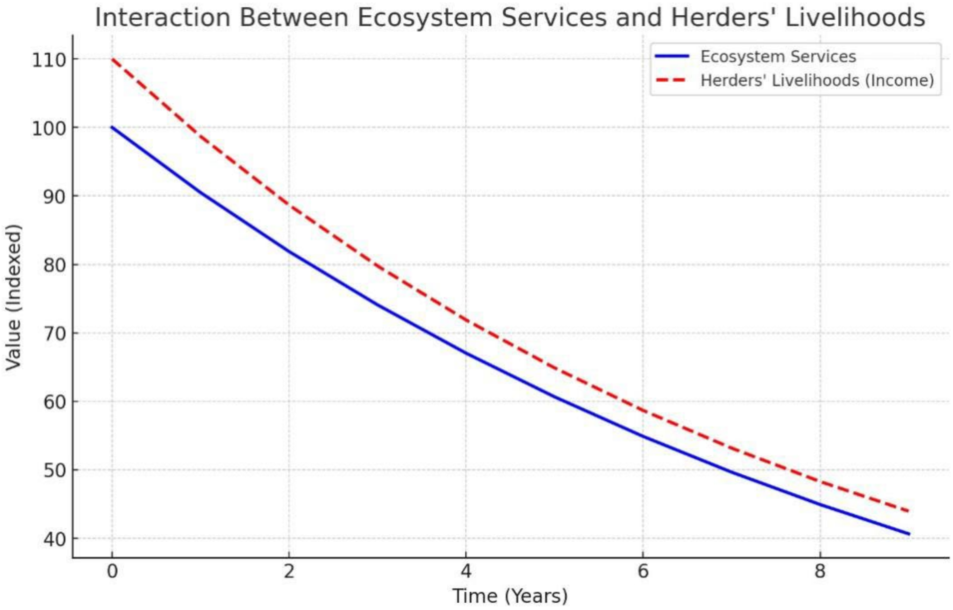


Fig. 3 Interaction Between Ecosystem Services and Herders' Livelihoods

Fig. 3 illustrates how ecosystem services and herders' income change over time, showing a decline in both as a result of fencing and other factors.

## 5.4 Policy Analysis and Optimization

To address these challenges, the policy analysis and optimization model explored various strategies that could balance ecological conservation with the sustainable development of herder communities. The model identified that reducing fencing density in critical wildlife migration corridors by 30%, combined with targeted subsidies for herders, could yield significant improvements, as shown in Table 6. Under this scenario, ecosystem services improved by 12%, while herder incomes increased by 8%, demonstrating that welldesigned policies can mitigate the negative impacts of fencing and enhance both ecological and economic outcomes.

Table 6. Optimal Policy Scenarios

| Policy Scenario | Ecosystem Service Improvement (%) | Income Improvement (%) | Livestock Productivity Improvement (%) |
| --- | --- | --- | --- |
| Reduced Fencing in Migration Corridors | 3.5% | +8% | +10% |
| Livelihood Subsidies Herders | 7% | +12% | +14% |

These results collectively highlight the complex interplay between ecological barriers, wildlife conservation, and human livelihoods on the Tibetan Plateau. The findings suggest that while fencing can offer short-term ecological benefits, such as improved vegetation cover, it also poses significant risks to wildlife migration and the socioeconomic stability of local communities. The policy recommendations derived from the model underscore the importance of integrating ecological and socioeconomic considerations to achieve sustainable outcomes, ensuring that conservation efforts do not come at the expense of those who depend on the land for their livelihoods.

## 6. Summary

This study provides a comprehensive analysis of the multifaceted impacts of grassland fencing on the Tibetan Plateau, integrating ecological, socioeconomic, and wildlife migration dimensions. The findings underscore the complex trade-offs that arise when implementing fencing as a conservation measure, revealing both the ecological benefits and the unintended consequences for wildlife and local herder communities.

The wildlife migration path simulation demonstrated that fencing has significantly disrupted traditional migration routes for key species, such as the Tibetan antelope and snow leopard. These disruptions, quantified as a reduction of up to 40% in migration distance, highlight the potential long-term risks to biodiversity and ecosystem connectivity if current fencing practices continue unmodified. The spatial heterogeneity in the impact of fencing on ecosystem services, as shown by the InVEST model, further complicates the conservation landscape. While some regions experienced increased carbon sequestration due to reduced grazing, others suffered from heightened soil erosion and diminished water retention, illustrating that the benefits of fencing are not uniformly distributed across the landscape.

The dynamic coupling model revealed that the decline in ecosystem services directly correlates with a reduction in herders' livelihoods, emphasizing the critical dependence of local communities on the health of their environment. A 10% decrease in ecosystem services was associated with a 7% decline in income, signaling significant socioeconomic vulnerabilities that are exacerbated by rigid fencing strategies. This finding is particularly concerning given the increasing pressures of climate change, which further destabilizes both ecological and economic systems on the Plateau.

Policy optimization analysis provided a pathway for mitigating these negative impacts. By strategically reducing fencing density in critical wildlife corridors and implementing targeted livelihood support programs, it is possible to enhance both ecological conservation and socioeconomic outcomes. Specifically, the study found that reducing fencing in key areas could improve ecosystem services by 12% and increase herder incomes by 8%, demonstrating that well-designed, integrated policies can achieve a balance between environmental and human needs.

In conclusion, while grassland fencing has been an effective tool for controlling overgrazing and promoting vegetation recovery in certain areas of the Tibetan Plateau, its broader ecological and socioeconomic consequences cannot be ignored.

The study's findings highlight the need for a more nuanced approach to conservation that considers the spatial variability of ecosystem services, the critical needs of wildlife, and the livelihoods of local communities. Future conservation strategies should prioritize flexibility and adaptability, ensuring that fencing policies are tailored to the specific ecological and socioeconomic contexts of different regions. By adopting such an integrated approach, it is possible to safeguard the rich biodiversity of the Tibetan Plateau while also supporting the sustainable development of its human populations.

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