Postprint: Effectiveness Assessment of Natural Vegetation Protection and Restoration in the Ebinur Lake Wetland National Nature Reserve Based on the Normalized Difference Vegetation Index

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Abstract

The Ebinur Lake Wetland National Nature Reserve serves as a crucial ecological barrier in the arid region of northwestern China, and evaluating its vegetation protection effectiveness holds significant importance for regional ecological security maintenance and ecological civilization construction. However, current research lacks assessments of vegetation protection effectiveness across different protection levels (pre-establishment, autonomous region-level, and national-level) and within typical internal zones (human activity areas or ecological restoration areas) of this reserve. Based on the Normalized Difference Vegetation Index (NDVI) from 1995 to 2022, this study employed the Mann-Kendall trend test, stability analysis, geographical detector, and Hurst index to evaluate vegetation restoration effectiveness. The results indicate: (1) Vegetation cover in the reserve has increased significantly, with degraded areas comprising only 1.75%; vegetation cover stability demonstrates pronounced spatial heterogeneity, with relatively low-fluctuation and medium-fluctuation areas being predominant. (2) The establishment of the reserve has generated positive impacts on vegetation cover, with the degree of vegetation improvement exhibiting a stepwise ascent; the improvement effect became most substantial following the upgrade to a national nature reserve. Nevertheless, the interaction between vegetation recovery and human activities is complex, and the degree of improvement may be associated with original land use conditions. Land use type constitutes the primary driving factor of vegetation cover change, manifesting strong influence when interacting with other factors. (3) Hurst index analysis indicates that future vegetation changes in the reserve will exhibit significant divergence, with 50.26% of the area showing reverse persistence. Specifically, areas that

have improved historically but may degrade in the future account for 50.07%, necessitating focused attention on these potential degradation zones and the implementation of corresponding protection measures.

Full Text

Preamble

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Evaluation of Natural Vegetation Protection and Restoration Effectiveness in Ebinur Lake Wetland National Nature Reserve Based on Normalized Difference Vegetation Index

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Abstract: Ebinur Lake Wetland National Nature Reserve constitutes a crucial ecological barrier in the arid region of northwestern China, and assessing its vegetation protection effectiveness holds significant importance for regional ecological security maintenance and ecological civilization construction. However, current assessments lack evaluation of vegetation protection effectiveness across different protection levels (pre-establishment, autonomous region level, and national level) and within typical internal zones (human activity areas or ecological restoration zones). Based on the Normalized Difference Vegetation Index (NDVI) from 1995 to 2022, this study evaluates vegetation restoration effectiveness using the Mann-Kendall trend test, stability analysis, geographic detector, and Hurst index methods. The results demonstrate that: (1) Vegetation cover in the reserve increased significantly, with degraded areas accounting for only 1.75% of the total area; vegetation cover stability exhibited pronounced spatial heterogeneity, with relatively low fluctuation and medium fluctuation areas predominating. (2) The establishment of the reserve exerted positive impacts on vegetation cover, with improvement showing a staged progression that became most pronounced after upgrading to national-level status. However, interactions between vegetation restoration and human activities are complex, and the degree of improvement may correlate with original land use conditions. Land use type emerged as the primary driver of vegetation cover change, demonstrating strong influence when interacting with other factors. (3) Hurst index analysis reveals significant future vegetation change disparities, with 50.26% of the area showing reverse persistence. Specifically, 50.07% of areas that improved in the past may degrade in the future, necessitating focused attention on these potential degradation zones and implementation of appropriate conservation measures.

Keywords: protection effectiveness; NDVI; trend analysis; stability analysis; Ebinur Lake Wetland National Nature Reserve

Introduction

Ebinur Lake Wetland National Nature Reserve (hereafter "the Reserve") represents a typical wetland ecosystem in the arid region of northwestern China, possessing unique ecological value and strategic importance. As a critical stopover for migratory birds in Central Asia and a key barrier for maintaining regional ecological balance, the Reserve harbors abundant salt- and drought-tolerant flora, rare and endangered fauna, valuable medicinal herbs, and resources such as saltpeter and brine shrimp. These resources play vital roles in biodiversity conservation, climate regulation, and water source conservation. Established as an autonomous region-level nature reserve in 2007 and upgraded to national status in 2013, its ecological protection value has gained widespread recognition. However, under the dual pressures of global climate change and human activities, the Reserve currently faces severe ecological challenges including river desiccation, soil salinization, vegetation degradation, desertification, and sandification, which threaten both biodiversity and regional ecological security.

Despite implementing ecological restoration projects such as wetland recovery and returning farmland to forest that have achieved positive results, systematic evaluation of vegetation restoration effectiveness remains lacking. Existing research primarily focuses on basin-scale ecological element analysis in the Ebinur Lake watershed, including snow dynamics, soil salinization, carbon sequestration capacity, microbial diversity, vegetation changes, and groundwater. Vegetation protection and restoration studies have concentrated on spatiotemporal vegetation changes and driving forces at the watershed scale, with three main deficiencies: (1) Most studies employ discontinuous time series or short-term observation data, making it difficult to accurately reflect long-term vegetation trends; (2) Assessments of vegetation restoration effectiveness across different protection levels (pre-establishment, autonomous region level, and national level) and typical zones (human activity areas or ecological restoration areas) are absent; (3) Predictive studies on the future sustainability of vegetation changes are similarly lacking. These research gaps severely constrain comprehensive assessment of vegetation restoration effectiveness and impact scientific formulation and optimization of ecological protection strategies.

Vegetation restoration effectiveness evaluation constitutes a critical research area in ecological protection, with its core objective being systematic assessment of restoration outcomes following conservation measures. Common evaluation methods include direct comparison, standard threshold analysis, expert assessment, indicator system methodology, remote sensing and GIS assessment, and statistical and model analysis. Remote sensing and GIS technology, offering advantages of efficiency, economy, and comprehensiveness, has become an essential tool for vegetation protection effectiveness assessment. The Normalized Difference Vegetation Index (NDVI), a widely applied indicator for monitoring vegetation changes, effectively reflects spatiotemporal vegetation characteristics. Landsat series remote sensing imagery, with its high spatiotemporal resolution and continuous observation capabilities, provides reliable data support for monitoring ecological restoration.

Previous studies using Landsat data have revealed significant vegetation coverage increases following reserve establishment, demonstrating notable ecological protection effectiveness. Additionally, research indicates that reserves with higher administrative levels and independent management institutions achieve better vegetation protection outcomes, providing important methodological support for evaluating vegetation restoration effectiveness.

This study systematically investigates vegetation protection effectiveness across different protection levels and typical internal zones using Landsat NDVI data from 1995 to 2022, employing Mann-Kendall trend testing and stability analysis. Furthermore, geographic detector methods identify primary influencing factors of vegetation cover, while Hurst index predictions assess future vegetation sustainability. The findings provide scientific foundations for ecological management and sustainable wetland development in the Reserve, offering significant implications for optimizing ecological protection strategies.

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1. Materials and Methods

1.1 Study Area Overview

Ebinur Lake Wetland National Nature Reserve (82°36 ~83°50 E, 44°30 ~45°09 N) is located on the southwestern margin of the Junggar Basin in Xinjiang, representing an important ecological region in the Eurasian continent' s interior. The Reserve contains Xinjiang' s largest saltwater lake (Ebinur Lake), primarily fed by meltwater from alpine glaciers and mountain precipitation. Characterized by a typical temperate continental arid climate with hot summers and cold winters, the area has an average annual temperature of 6–8°C, annual precipitation of 105 mm, and annual evaporation of 1315 mm. The Reserve exhibits rich plant diversity and represents a concentrated area of desert vegetation.

1.2 Data Sources and Processing

Landsat series remote sensing imagery was obtained from the Geospatial Data Cloud (https://www.gscloud.cn/) at 30 m spatial resolution. Data processing included radiometric calibration, atmospheric correction, projection transformation, and masking. Elevation data were acquired from the same platform (http://www.gscloud.cn/), with slope and aspect derived from elevation data. Soil type and soil erosion data were sourced from the Chinese Academy of Sciences' Resource and Environmental Science Data Center (https://www.resdc.cn/). Precipitation, temperature, and evapotranspiration data were obtained from the National Tibetan Plateau Scientific Data Center (https://data.tpdc.ac.cn/home). Land cover data were derived from the annual 30 m resolution land cover dataset for China released by Wuhan University (https://zenodo.org/records/12779975). All data were reprojected and resampled to match the remote sensing imagery using ArcGIS 10.8 software, with a 1 km × 1 km fishnet established to extract spatial attribute values for each factor.

1.3 Research Methods

1.3.1 Trend Analysis and Significance Testing The Theil-Sen Median slope estimation method was employed for trend analysis in long time series data, offering advantages of outlier resistance and high computational efficiency:

$$\text{Sen} = \text{median}\left(\frac{\text{NDVI}_j - \text{NDVI}_i}{j - i}\right), \quad 1 \leq i < j \leq n$$

where n represents the number of observation years, and i and j denote observation years. NDVI_i and NDVI_j represent the NDVI values for years i and j, respectively. $\text{Sen} > 0$ indicates increasing vegetation cover, while $\text{Sen} < 0$ indicates decreasing trends.

The Mann-Kendall test, a non-parametric statistical method requiring no specific distribution assumptions and robust to missing values and outliers, was used to assess trend significance. At significance level $\alpha = 0.05$, trends were classified as: extremely significant increase ($|Z| > 2.58$), significant increase ($1.96 < |Z| \leq 2.58$), micro-significant increase ($1.65 < |Z| \leq 1.96$), no change ($|Z| \leq 1.65$), micro-significant decrease ($1.65 < |Z| \leq 1.96$), significant decrease ($1.96 < |Z| \leq 2.58$), and extremely significant decrease ($|Z| > 2.58$).

1.3.2 Stability Analysis The coefficient of variation (C_v) assesses temporal fluctuation magnitude and is commonly used for stability evaluation, with smaller values indicating greater stability:

$$C_v = \frac{\delta}{\bar{x}}$$

where δ represents standard deviation and $\bar{x}$ represents the mean. Stability was categorized as: low fluctuation ($0.0 \leq C_v < 0.2$), relatively low fluctuation ($0.2 \leq C_v < 0.4$), medium fluctuation ($0.4 \leq C_v < 0.6$), relatively high fluctuation ($0.6 \leq C_v < 0.8$), and high fluctuation ($C_v \geq 0.8$).

1.3.3 Hurst Index The Hurst index describes the sustainability of change trends, enabling better analysis of interannual variation characteristics. The R/S analysis method was employed:

Mean series: $\bar{N}(\tau) = \frac{1}{\tau}\sum_{t=1}^{\tau} N(t)$

Cumulative deviation: $X(t,\tau) = \sum_{t=1}^{\tau}(N(t) - \bar{N}(\tau))$

Range: $R(\tau) = \max_{1\le t\le \tau} X(t,\tau) - \min_{1\le t\le \tau} X(t,\tau)$

Standard deviation: $S(\tau) = \sqrt{\frac{1}{\tau}\sum_{t=1}^{\tau}(N(t) - \bar{N}(\tau))^2}$

The Hurst index follows the relationship $R/S = c\tau^H$, where c is a constant and H is the Hurst index. When $0 < H < 0.5$, the time series exhibits anti-persistence (future trends oppose past trends); when $H > 0.5$, it shows persistence (future trends continue past trends). Values approaching 0 or 1 indicate stronger anti-persistence or persistence, respectively.

Combining trend analysis with Hurst index results reflects the dependence of future vegetation cover trends on past trends. Using MATLAB, future trends were classified into four categories (Table 1).

1.3.4 Geographic Detector Geographic detector methodology, widely applied in ecology, hydrology, meteorology, and socioeconomic research, detects spatial stratified heterogeneity and quantifies the explanatory power of independent variables on dependent variables. Factor detection and interaction detection were employed:

Factor detection quantifies the explanatory power (q) of variable X on Y:

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

where q represents the explanatory power of independent variable X on dependent variable Y; $h = 1, 2, \ldots, L$ are strata; N_h and N are stratum h and total regional units; σ_h^2 and σ^2 are stratum and total variances. In this study, independent variables included soil type, slope, elevation, aspect, soil erosion type, land use type, temperature, precipitation, and evapotranspiration. Categorical variables (soil type, soil erosion type, land use type) used standard classifications, while continuous variables were optimally discretized using R packages.

Interaction detection identifies interactions between driving factors X_1 and X_2, with results showing five possible outcomes (Table 2).

2. Results and Analysis

2.1 Vegetation Cover Change Trends and Stability Analysis Over 28 Years

From 1995 to 2022, vegetation cover in the Reserve increased significantly, with degraded areas comprising only 1.75% of the total area. Increasing areas accounted for 49.25%, while unchanged areas represented 49.00%. Unchanged vegetation cover was primarily distributed around Ebinur Lake and between the Hongyanchi Management Station and Kek 巴斯陶 Management Station in the north. Degraded areas were concentrated northwest of the Sumuluke Central Station and around the Tuo 托 Management Station, indicating generally good vegetation conditions within the Reserve.

Vegetation stability exhibited pronounced spatial heterogeneity, with coefficient of variation ranging from 0.10 to 2.65. Low fluctuation areas accounted for 4.88%, primarily distributed along the Aqikesu River riparian zone. Relatively low and medium fluctuation areas were most extensive, comprising 87.44% and concentrated near various management stations and central stations. Relatively high and high fluctuation areas accounted for 7.68%, distributed sporadically in southern Ebinur Lake, large areas south of the Sandekumu Management Station, and around the Kuoketala Central Station.

[Figure 2: see original paper]

2.2 Temporal Changes and Comparative Analysis

2.2.1 Temporal Variation of Vegetation Cover From 1995 to 2022, mean annual NDVI showed considerable fluctuation, with an overall trend of initial decline followed by increase at a rate of 0.0021/a. After establishment as an autonomous region-level reserve in 2007, NDVI fluctuated significantly, maintaining a decline-then-increase pattern but with an increased rising rate of 0.0034/a. Following upgrade to national status in 2013, NDVI increased stably with a relatively gentle growth rate of 0.0036/a. Overall, vegetation cover continued increasing across all stages, with conditions improving significantly.

[Figure 3: see original paper]

2.2.2 Comparative Trend and Stability Analysis Vegetation cover showed distinct differences across protection stages, with increasing trends becoming progressively significant (Figure 4). Pre-establishment, increasing areas accounted for 40.16%, primarily in the western and southern parts of the Reserve; decreasing areas comprised 18.35%, concentrated north and east of the Aqikesu River to the southern desert margin. After autonomous region-level designation, increasing areas expanded to 56.94%, mainly around Kuoketala Central Station, Sandekumu Management Station, and Kek 巴斯陶 Management Station; decreasing areas reduced to 8.35%, distributed southeast of Bird Island Central Management Station, southwest of Yanchiqiao

Management Station, and in eastern desert areas. Following national-level upgrade, vegetation improved dramatically, with increasing areas reaching 74.02% (44.35% extremely significant) and decreasing areas dropping to 1.89%, mainly south of Sumuluke Central Station and along the Aqikesu River riparian zone.

Stability analysis revealed significant differences across protection stages, showing an initial increase followed by decrease (Figure 5). Pre-establishment, low and relatively low fluctuation areas accounted for 68.85%, while relatively high and high fluctuation areas comprised 10.28%, mainly east of Kek 巴斯陶 Management Station, southeast of Bird Island Central Management Station, and southwest of Yanchiqiao Management Station. After autonomous region-level designation, low and relatively low fluctuation areas increased to 85.61%, indicating enhanced stability; relatively high and high fluctuation areas decreased to 3.33%, concentrated around the Jing River estuary, Bo River estuary Management Station, southeast of Maoyinhong Management Station, and surrounding saline-alkali lands southeast of Ebinur Lake. Following national-level upgrade, low and relatively low fluctuation areas accounted for 68.56%, while relatively high and high fluctuation areas increased to 10.10%, distributed southeast of Stone House Management Station and north/south of Ebinur Lake.

Integrated trend and stability analyses indicate that reserve establishment significantly and positively impacted vegetation cover. After autonomous region-level designation, vegetation cover increased with enhanced stability, demonstrating effective ecological restoration. However, following national-level upgrade, despite the most significant improvement, increased vegetation cover coincided with decreased stability along Ebinur Lake' s northern shore, suggesting restoration potential but also ecological risks requiring long-term monitoring.

2.2.3 Analysis of Typical Area Vegetation Cover Changes To deeply analyze vegetation cover changes before and after establishment in typical zones (human activity areas or ecological restoration areas), four representative areas were selected around Kek 巴斯陶, Sandekumu, Bird Island Central, and Birch Forest Management Stations, with land use types of: built-up area and grassland, grassland, flooded vegetation and grassland, and grassland, respectively.

All typical areas showed significant improvement and degradation across stages (Figure 6). Around Kek 巴斯陶 and Sandekumu Management Stations, vegetation cover showed continuous improvement. Kek 巴斯陶' s improvement areas increased from 50.60% to 79.09% and 97.52%, with degradation decreasing to 2.22% and 1.56%. Sandekumu' s improvement areas increased from 71.93% to 90.99% and 98.36%. However, Bird Island Central Management Station showed complex changes: improvement areas fluctuated from 68.97% to 29.87%, then to 55.88% and 81.24%, while degradation areas varied from 30.18% to 74.45%, then to 18.76% and 24.62%. Birch Forest Management Station experienced continuous degradation, with improvement areas at 56.14% and 0.36%, and degradation at 43.86% and 99.92% pre- and post-establishment, respectively.

Stability analysis revealed distinct fluctuations across typical areas (Figure 7). Around Kek 巴斯陶 Management Station, low and relatively low fluctuation areas showed decline-then-increase patterns (66.13%$→79.10→$67.15%), while high and relatively high fluctuation areas showed opposite trends, with the most significant changes in northwestern and southern parts. Around Sandekumu Management Station, low and relatively low fluctuation areas gradually decreased from 97.60% to 95.77% and 94.50%, while medium fluctuation increased from 2.10% to 3.33% and 4.88%, and relatively high/high fluctuation areas showed minimal presence. Around Bird Island Central Management Station, low and relatively low fluctuation areas declined from 57.90% to 56.14% and 46.42%, while relatively high and high fluctuation areas increased from 2.51% to 0.36% and 51.66%. Around Birch Forest Management Station, vegetation changes were relatively stable, with low and relatively low fluctuation areas accounting for 98.71% and 99.92% pre- and post-establishment, respectively, and no relatively high/high fluctuation areas.

Integrated analyses demonstrate dual impacts of reserve establishment on typical area vegetation cover. After autonomous region-level and national-level designation, distinct patterns emerged: Kek 巴斯陶 showed significant increase with enhanced stability, indicating successful ecological restoration; Sandekumu showed gradual significant increase but decreased stability; Bird Island Central and Birch Forest showed significant changes with increased stability, indicating good restoration effects but with localized challenges remaining. Therefore, targeted ecological management and conservation measures are needed for different zones.

[Figure 6: see original paper]

[Figure 7: see original paper]

2.3 Future Change Analysis

Hurst index analysis reveals that vegetation changes in the Reserve show slightly higher anti-persistence (50.26%) than persistence (49.74%), indicating that areas with past vegetation increase may decrease in the future, while past decrease areas may increase. Combining trend analysis with Hurst index results yields four future trend categories (Table 1): (1) Degradation-to-improvement areas account for 0.19%, distributed around the Bortala River estuary and Tuo 托 Management Station; (2) Continuous degradation areas comprise 0.44%, mainly at Sumuluke Central Station and Kek 巴斯陶 Management Station; (3) Continuous improvement areas represent 49.30%, distributed across various management stations and around Ebinur Lake; (4) Improvement-to-degradation areas constitute 50.07%, primarily in the Reserve' s southeastern region. No unchanged areas were identified. Continuous degradation and improvement-to-degradation areas require prioritized long-term monitoring.

[Figure 8: see original paper]

2.4 Driver Factor Analysis

Geographic detector analysis indicates that land use type, evapotranspiration, precipitation, and elevation significantly influence NDVI (Figure 9). Land use type showed the highest q values (0.507–0.868), remaining stable and high after reserve establishment. This reflects effective governance and ecological policies that standardized wetland land use patterns, reducing negative ecosystem impacts and maintaining relative NDVI stability. Precipitation showed lower but variable q values, with enhanced influence as increased precipitation provided more favorable vegetation growth conditions. Temperature also showed significant q values; warming accelerates vegetation growth cycles but intensifies evapotranspiration, causing complex soil moisture effects.

Interaction analysis revealed significant enhancement between driving factors (Figure 10), showing bi-factor enhancement and nonlinear enhancement. Land use type interactions with other factors regulate vegetation growth by altering soil properties (nutrient content, texture), water distribution (surface runoff, groundwater recharge), and local microclimate (temperature, humidity). Unreasonable land expansion intensifies nutrient loss and water competition, while forest restoration improves soil structure and local climate. Evapotranspiration changes, regulated by vegetation type and climate, affect water use efficiency and soil salinization processes. In arid and semi-arid regions, high evapotranspiration can cause rapid soil water loss and intensify water stress, with warming creating complex feedback mechanisms.

[Figure 9: see original paper]

[Figure 10: see original paper]

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3. Discussion

From 1995 to 2022, vegetation conditions in the Reserve improved significantly, with increasing areas reaching 49.25%. Vegetation cover showed staged significant increases across protection levels: pre-establishment (40.16%), autonomous region level (56.94%), and national level (74.02%), with the fastest growth in the third stage. This change correlates with policies such as returning farmland to forest, ecological migration, and integrated ecological restoration of mountains, rivers, forests, farmlands, grasslands, and deserts. However, vegetation stability showed an initial increase followed by decrease, with low and relatively low fluctuation areas declining from 68.85% to 85.61% and then to 68.56%. Higher-level reserve establishment provides richer management resources and more effective protection measures, improving vegetation conditions over long-term observation. However, after autonomous region-level designation, differences in vegetation growth and adaptation capabilities, combined with external environmental changes, may cause short-term instability. Following national-level upgrade, although vegetation recovery was significant province-wide, some areas still face severe challenges, particularly from historical human activities such as overgrazing, agricultural expansion, and fishing that have caused profound ecosystem impacts.

Future vegetation changes show complex spatiotemporal dynamics, with over 50% of areas shifting from improvement to degradation. This may relate to climate change, soil fertility dynamics, topography, and surrounding land use changes. Climate fluctuations affect ecosystem carbon, water, and energy exchange, while soil fertility and water resource allocation changes weaken long-term vegetation stability. Discontinuous protection measures or edge effects may also accelerate degradation. Moreover, biological interactions within ecosystems may influence vegetation community succession, where increased species diversity may accompany partial vegetation degradation.

Geographic detector analysis shows land use type significantly influences vegetation growth, with q values of 0.507–0.868, consistent with Ebinur Lake Basin and Reserve-related studies. Significant interactions exist among driving factors, showing bi-factor and nonlinear enhancement. Land use type interactions alter soil properties, water distribution, and microclimate, directly or indirectly regulating vegetation growth. Climate change analysis from 1995 to 2022 shows precipitation, temperature, and evapotranspiration significantly affect vegetation growth. In conclusion, vegetation dynamics result from combined natural and anthropogenic factors, with complex mechanisms revealing spatial heterogeneity in vegetation changes that provide scientific basis for Reserve ecological restoration and management. Future efforts should implement zoned gradient management strategies based on continuous monitoring and ecological restoration concepts, enhancing soil fertility, rationally planning land use, and protecting biodiversity to maintain stable vegetation recovery and promote coordinated ecosystem and socioeconomic development.

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4. Conclusions

This study evaluated natural vegetation protection and restoration effectiveness in Ebinur Lake Wetland National Nature Reserve from 1995 to 2022, yielding three main conclusions:

1) **Significant vegetation cover increase with spatial heterogeneity in stability.** Vegetation cover increased substantially, with degraded areas comprising only 1.75% of the total area. Stability showed pronounced spatial heterogeneity: low fluctuation areas accounted for 4.88%, relatively low and medium fluctuation areas dominated at 87.44%, while relatively high and high fluctuation areas represented 7.68%.

2) **Positive impacts of reserve establishment with complex human activity interactions.** Reserve establishment significantly benefited vegetation cover, with improvement most pronounced after national-level up-

grade. However, stability decreased post-upgrade, and interactions between vegetation restoration and human activities proved complex. Land use type emerged as the primary driver, exerting the greatest influence.

3) **Significant future vegetation change disparities requiring targeted monitoring.** Hurst index analysis revealed 50.26% of the area showing anti-persistence. Notably, 50.07% of historically improved areas may degrade in the future, primarily in the Reserve' s southeastern region, requiring focused attention and preventive management measures.

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