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A Spatial Gradient Dose–Response Framework for Assessing Conservation Effectiveness in Mountainous Protected Area Networks: Evidence from Daxiangling Nature Reserve, China

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Abstract

Assessing conservation effectiveness in mountainous protected areas (PAs) is challenged by weak counterfactuals, spatial confounding, and limited historical baselines. This study develops a spatial gradient dose–response framework using linear mixed-effects models (LMMs) to evaluate conservation-associated ecological responses in Daxiangling Nature Reserve, China, controlling for topography, climate, and neighboring protected area effects. Using 1 km resolution time-series data (2003–2022), we assessed three indicators—Net Primary Productivity (NPP), Fractional Vegetation Cover (FVC), and a human-footprint-derived Ecosystem Integrity Index (EII)—each across state, trend, and stability dimensions. In the state dimension, NPP ($\beta = 0.99$, $p < 0.001$) and EII ($\beta = 1.23$, $p < 0.001$) were significantly higher inside the PA than in the peripheral reference zone, whereas FVC showed no significant difference, indicating indicator-specific sensitivity. NPP exhibited positive spillover to 15–20 km, while EII displayed a “boundary collapse” pattern—sharp decline within 0–5 km followed by distal recovery—suggesting edge effects and possible leakage. In the state dimension, high elevations amplified conservation effects on NPP and FVC. In the stability dimension, high elevations were associated with greater interannual variability across indicators, revealing a state–stability trade-off. Proximity to neighboring national PAs significantly enhanced EII across buffer zones, underscoring network connectivity. Cross-dimensional divergence was pronounced: NPP showed a state–stability trade-off in the PA, while EII exhibited decoupled state and trend signals across the boundary gradient. We recommend: (1) differentiated control in near-boundary zones (0–5 km); (2) prioritizing high-elevation core zones with stability monitoring; and (3) cross-PA patrols and ecological corridors. This framework offers a replicable, baseline-independent diagnostic approach for data-limited mountain systems where traditional counterfactual methods are difficult to apply.

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1. Introduction

Protected areas (PAs) serve as a core policy instrument for addressing biodiversity loss and maintaining ecosystem functions, currently covering approximately 15.5% of the global terrestrial area [1]. Mountainous protected areas are particularly critical as they harbor disproportionately high biodiversity and ecosystem services [2–4], yet their effectiveness assessment faces unique challenges due to the complex topography and frequent embedding within protected area networks. The spatial dynamics of conservation effects involve complex interactions between edge effects and leakage, which can produce ecosystem integrity decline near boundaries extending far beyond classical edge effect ranges [5–8]. Understanding these ‘boundary effects’ is essential for landscape-scale conservation planning and buffer zone design [9].

Two mainstream causal inference methods, Propensity Score Matching (PSM) and Difference-in-Differences (DID), have been developed sequentially in the literature. However, neither can simultaneously address the challenges of lacking historical baseline data and interference from spatial spillover and environmental heterogeneity faced in mountainous PA assessments. PSM constructs a “spatial counterfactual” by matching environmental covariates to correct for site selection bias [10,11]. Nevertheless, in mountainous contexts, this method faces two potential failure mechanisms. First, when the evaluated PA is continuously distributed with surrounding PAs [12], significant spatial spillover effects make it difficult to identify an “unprotected” control group [8]. Second, environmental gradients such as elevation and aspect exhibit continuous heterogeneity, and PSM may struggle to effectively match continuous covariates, thereby failing to separate “conservation effects” from “habitat background differences” [13]. DID and its variants attempt to construct a “temporal counterfactual” through pre–post intervention comparisons to control for time-varying confounders [14–16]. However, its validity depends heavily on the parallel trend assumption and the availability of multi-period data prior to intervention. Systematic ecological surveys before the establishment of early PAs are virtually absent, and high-resolution remote sensing data only became available around 2000 [17,18]. This similarly obstructs the temporal counterfactual pathway of DID [19]. Consequently, both spatial and temporal counterfactuals are difficult to establish in mountainous contexts, prompting alternative frameworks that avoid baseline dependence and spatial confounding.

Beyond methodological limitations, existing assessment systems suffer from single-indicator reliance and fragmented frameworks [20,21]. Early studies depended on structural indicators such as forest coverage [10,22], while recent work has introduced functional indicators including Net Primary Productivity (NPP) [14,23]. However, systematic frameworks integrating ecosystem “structure-function integrity” remain lacking. More critically, ecosystems possess three irreplaceable dimensions—mean, stability, and trend [24,25]—yet existing studies have generally overlooked that these dimensions may exhibit inconsistent responses [26,27].

Consequently, critical gaps exist. First, there is a lack of methodological frameworks for mountainous contexts that operate without historical baselines or strict spatial counterfactuals. Second, multidimensional assessment systems integrating state, trend, and stability are absent. Third, empirical evidence is needed on how conservation effects vary with elevation and protected area network connectivity. Addressing these gaps is particularly relevant to landscape planning, where decisions about protected area boundaries, buffer zone widths, and landscape connectivity require robust evidence on the spatial extent and environmental dependencies of conservation effects.

To address these critical gaps, this study proposes a spatial gradient dose–response assessment framework integrated with Linear Mixed-Effects Models (LMMs) [28,29]. Rather than assuming a strictly isolated treatment-control contrast, this framework concep-

tualizes protected areas as high-conservation-intensity nodes embedded in a broader landscape matrix of varying management influence [2]. Protected area zoning is modeled as a fixed effect, while topography, climate dynamics, and distance to neighboring protected areas are incorporated as covariates, with spatial blocks treated as random intercepts to account for block-level spatial dependence [30]. This approach is not intended to replace PSM or DID as a strict causal identification strategy, but rather provides a complementary and operational framework for data-limited mountainous contexts where pre-establishment baselines and uncontaminated spatial controls are difficult to obtain. This study establishes a three-dimensional state–trend–stability assessment system using NPP, Fractional Vegetation Cover (FVC), and a human-footprint-derived Ecosystem Integrity Index (EII), providing a feasible pathway for assessing conservation-associated ecological gradients under data-limited conditions.

This study selects Daxiangling Nature Reserve in Sichuan Province, China as a case study. Established in 2003 with elevations ranging from 1150 to 3481 m, this reserve is affected by persistent cloud cover limiting historical remote sensing data and is embedded within a continuous protected area network—characteristics that make it ideal for testing this framework. This study addresses two concise questions: (1) How do conservation-associated ecological responses vary across spatial gradients, elevation, and protected area network connectivity? (2) Do NPP, FVC, and the HFI-derived EII show divergent responses across state, trend, and stability dimensions? Accordingly, this study aims to provide a baseline-independent diagnostic framework for assessing conservation-associated gradients in data-limited mountainous protected area networks and to support evidence-based buffer-zone and connectivity management.

2. Materials and Methods

2.1. Study Area

Daxiangling Provincial Nature Reserve is located in southwestern Yingjing County, Sichuan Province, China (102°29′36″–102°52′24″ E, 29°28′33″–29°43′54″ N), covering 29,000 ha. Established in 2003 and upgraded to provincial status in 2014, it constitutes an important component of the giant panda protected area network [31]. The reserve is situated in the transition zone between subtropical monsoon and alpine climates of the Qinghai-Xizang Plateau, with elevations ranging from 1150 to 3481 m and characterized by fragmented terrain and pronounced vertical differentiation [3,32].

The complex topography shapes diverse vertical vegetation zones: evergreen broad-leaved forests (<1800 m), montane mixed coniferous–broadleaf forests (1800–2400 m), sub-alpine dark coniferous forests (2400–3000 m), and alpine shrub meadows (>3000 m). This region has long been affected by persistent cloud cover and complex terrain, limiting availability of early optical remote sensing observations [19,33]. Additionally, Daxiangling is embedded within a continuous protected area network including Wawushan, Erlangshan, Labahe, and multiple other PAs, forming a dense protected area network pattern that generates superimposed effects from different protected areas [8,34]. These characteristics—data limitations due to cloud cover and network embedding—make Daxiangling an ideal case for testing the proposed framework under data-limited conditions (Figure 1).

Since its establishment, Daxiangling Nature Reserve has implemented a set of conservation and management measures, including boundary demarcation, routine patrol and enforcement, restrictions on logging and other extractive activities, forest-fire prevention, wildlife habitat protection, and community-related management around the reserve boundary. These measures are expected to reduce direct anthropogenic disturbance within the protected area and to support forest productivity and habitat integrity. However, the influence of conservation management is unlikely to stop abruptly at the admin-

istrative boundary; near-boundary zones may still be affected by roads, settlements, tourism activities, grazing, resource collection, and other accessibility-related human pressures. Therefore, the observed spatial patterns are interpreted as conservation-associated gradients rather than as definitive evidence that all ecological differences were caused solely by reserve establishment.

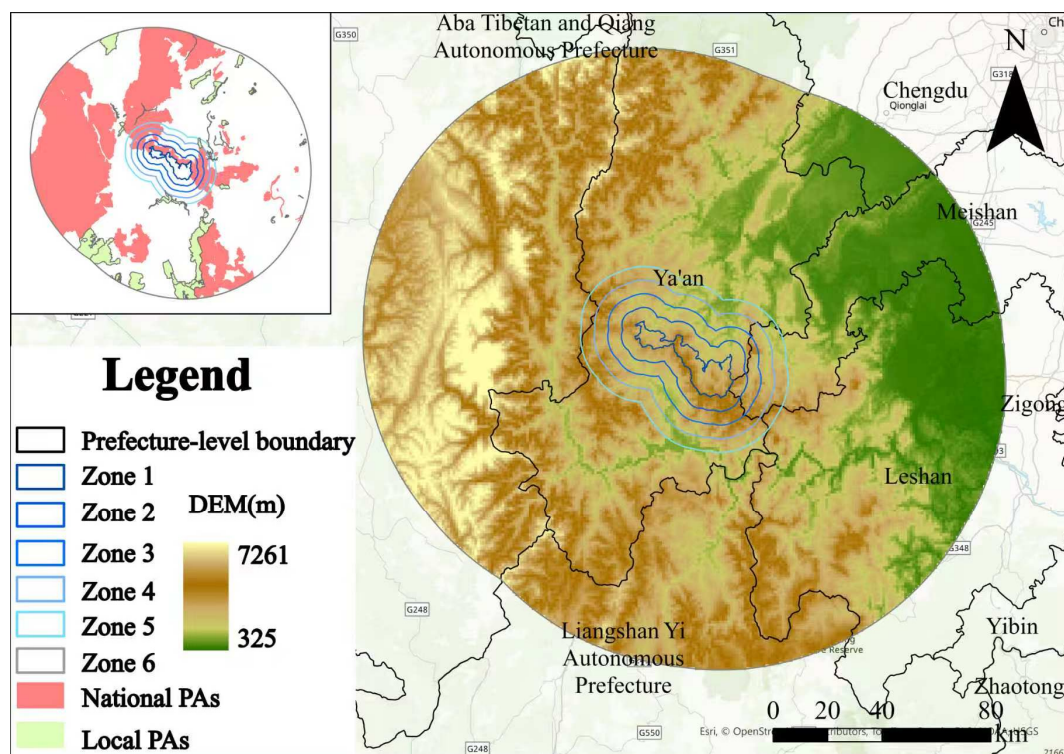


Figure 1. Geographic location of Daxiangling Nature Reserve and the spatial control system. The system consists of six zones: Zone 1 (protected area interior), Zone 2 (0–5 km), Zone 3 (5–10 km), Zone 4 (10–15 km), Zone 5 (15–20 km), and Zone 6 (20–100 km peripheral reference area). The base map is a Digital Elevation Model (DEM), with colors from green (low elevation, 325 m) to red (high elevation, 7261 m). Surrounding national and local protected areas (PAs) are also shown, with National PAs shown in pink and including national nature reserves and nature parks, and Local PAs shown in light green and including provincial- and county-level nature reserves and nature parks, illustrating the continuous protected area network around Daxiangling. PAs within Zone 6 were excluded from the reference area to avoid contamination from other conservation interventions. Distance bands were generated using the CGCS2000 Albers Equal Area projection.

Daxiangling is also embedded in a broader protected area network, with surrounding reserves and nature parks such as Wawushan, Erlangshan, Labahe, and other national- and local-level protected areas forming a continuous conservation landscape. These neighboring protected areas may enhance ecological connectivity and generate positive spillover effects, but they may also contaminate peripheral reference samples if their influence is not considered. For this reason, the analysis explicitly quantified distance to neighboring national- and local-level protected areas and incorporated the distance to the nearest national protected area (dnat) into the final LMMs as a key covariate, while distance to local-level protected areas (dloc) was retained as a control variable.

2.2. Construction of Spatial Control System and Distance Quantification

(1) Spatial Control System and Buffer Zone Delineation

Using 1 km × 1 km grids as basic spatial analysis units, a core zone–buffer gradient–peripheral reference area spatial control system was constructed based on Euclidean distance from each grid centroid to Daxiangling’s boundary. Grids within the reserve boundary were defined as Zone 1 (protected area, PA); areas outside at 0–5 km, 5–10 km, 10–15 km, and 15–20 km were sequentially delineated as Zone 2, Zone 3, Zone 4, and Zone 5. The 5 km interval was selected for three reasons. First, at the 1 km grid resolution, a 5 km band contains sufficient grid cells to stabilize estimated marginal means while still retaining near-boundary ecological gradients. Second, it provides a management-relevant scale for distinguishing near-boundary disturbance zones, intermediate buffer zones, and outer spillover zones. Third, previous studies on protected area edge effects and leakage commonly evaluate external impacts within approximately 10–20 km ranges [5–8,35], making the 0–20 km gradient appropriate for testing whether conservation-associated responses attenuate, spill over, or reverse across space.

This system treats Zone 1 as the highest formal conservation-intensity zone, Zone 2–Zone 5 as external gradient zones with potentially declining but not necessarily monotonic conservation influence, and Zone 6 as a peripheral reference area. Importantly, the framework does not assume that protection effects must decrease linearly with distance. Instead, the zoning structure is used to empirically test whether ecological responses show positive spillover, leakage, edge-related decline, or non-monotonic recovery across distance bands.

(2) Precise Quantification of Distance to Neighboring Protected Areas

To incorporate spatial spillover from adjacent PAs as confounding factors, Euclidean distance from each 1 km grid centroid to the nearest protected area boundary was calculated using ArcGIS Pro 3.6’s Generate Near Table tool. To account for heterogeneous effects from management level differences, two distance metrics were calculated: (1) *dnat*: distance to nearest national PAs (all national nature reserves and nature parks); and (2) *dloc*: distance to nearest local PAs (all provincial- and county- nature reserves and nature parks). Grids within a PA recorded distance as 0; outside grids recorded precise distance values. Given that conservation spillover effects typically exhibit nonlinear decay with distance, continuous distance was ln-transformed as $\ln(dnat + 1)$ and $\ln(dloc + 1)$, which conforms to spatial heterogeneity characteristics while avoiding logarithm-of-zero problems.

(3) Justification of Zoning Thresholds and Environmental Comparability

The 5 km interval was selected to balance spatial resolution, near-boundary ecological sensitivity, and management interpretability. Because the basic analytical unit was a 1 km × 1 km grid, each 5 km band contained multiple grid rows and reduced unstable estimates that may arise from overly narrow distance bands. The 0–5 km band was interpreted as the near-boundary zone where edge effects, road accessibility, settlements, tourism, grazing, and other access-mediated human pressures are most likely to concentrate. The 5–20 km external bands were not assumed to represent a strictly monotonic weakening of protection; instead, they were used to test whether ecological responses attenuated, spilled over, reversed, or recovered along the external distance gradient.

The 20 km threshold was defined as an operational distance for reducing the expected direct spillover influence of Daxiangling Nature Reserve, not as a strict ecological boundary beyond which all protected area effects disappear. Accordingly, Zone 6 was interpreted as a distant peripheral reference area rather than a perfectly untreated counterfactual. To reduce potential contamination from other conservation interventions, officially designated protected areas within Zone 6 were excluded, distance to the nearest

national protected area (*dnat*) was included as a covariate and interaction term, and environmental comparability and potential confounding were evaluated descriptively prior to modeling, while DEM, slope, *dnat*, *dloc*, and climate-dynamic variables were controlled in the LMM. Remaining uncertainty associated with the zoning threshold is addressed explicitly in the Discussion rather than being treated as fully eliminated.

2.3. Data Sources and Preprocessing

The main data included: (1) nature reserve boundary data; (2) ecological indicator data including Net Primary Productivity (NPP), Fractional Vegetation Cover (FVC), and Human Footprint Index (HFI); and (3) natural environmental factor data including elevation (DEM), slope, temperature, and precipitation (Table 1). All spatial datasets were first harmonized to the CGCS2000 datum and then projected to the CGCS2000 Albers Equal Area projection for spatial overlay, buffer construction, area calculation, and Euclidean distance measurement. Raster datasets were resampled to 1 km resolution using bilinear interpolation. The 1 km resolution balanced data availability (MODIS NPP at 500 m, FVC at 250 m), computational efficiency, and conservation management planning scale.

Table 1. Data sources and characteristics of ecological and environmental variables.

Data Name	Spatial Resolution	Time Period	Data Source
Nature reserve vector boundaries	/	/	Resource and Environment Science and Data Center, Chinese Academy of Sciences
NPP data	500 m	2003–2022	Google Earth Engine MOD17A3HGF
FVC data	250 m	2003–2022	National Earth System Science Data Center
Human footprint data	1000 m	2003–2022	UEMM Team, China Agricultural University (36)
Elevation (DEM)	30 m	/	Geospatial Data Cloud ASTER GDEM 30M
Slope	12.5 m	/	NASA Earthdata SRTM
Temperature	1000 m	2003–2022	National Earth System Science Data Center
Precipitation	1000 m	2003–2022	National Tibetan Plateau/Third Pole Environment Data Center

The 2003–2022 time series data underwent completeness checks for each grid unit, excluding units with missing values exceeding 10% of total duration. Ecological indicator data were subjected to biophysical threshold checks (e.g., NPP outside 0–2000 g C m^{−2} year^{−1} range), removing outliers beyond reasonable ranges. To characterize human activity disturbance intensity, an HFI-derived Ecosystem Integrity Index (EII) was constructed as $EII_i = 50 - HFI_i$, where HFI ranges from 0 to 50 [36]; thus, EII ranges from 0 to 50, with higher values indicating weaker human disturbance and higher potential integrity. This index should be interpreted as a human-footprint-based proxy rather than a comprehensive biodiversity-based integrity metric, because it does not directly include species diversity, habitat fragmentation, trophic structure, population viability, or ecosystem process information.

2.4. Indicator System

This study assessed conservation effectiveness across three ecological dimensions: (1) state dimension (Mean): multi-year average ecosystem level; (2) trend dimension (Trend): long-term change direction; and (3) stability dimension (Stability): interannual fluctuation degree.

(1) State Index

Multi-year arithmetic means of NPP, FVC, and EII from 2003 to 2022 were calculated to characterize ecosystem state level. Mean annual temperature and precipitation were initially extracted as potential co-variables, but they were subsequently excluded from the final model because they were strongly collinear with elevation in this mountainous region. DEM was retained to represent the dominant long-term spatial environmental gradient, while climate trend and climate stability variables were retained to represent temporal climate dynamics during 2003–2022 that are not fully captured by elevation alone. This modeling choice was supported by VIF diagnostics and model comparison results reported in the Appendix A.1.

(2) Trend Index

Theil–Sen median trend analysis combined with Mann–Kendall significance testing assessed temporal trends in ecological indicators and climate variables from 2003 to 2022. The Theil–Sen trend slope (β) was calculated as Equation (1):

$$\beta = \text{median} \frac{x_j - x_i}{j - i} (1 < i < j < n) \quad (1)$$

where x_i and x_j represent the indicator values in year i and year j , respectively, and n is the length of the time series. $\beta > 0$ indicates an increasing trend, while $\beta < 0$ indicates a decreasing trend.

The Mann–Kendall standardized statistic (Z_{MK}) was calculated using Equation (2). The Mann–Kendall statistic S and the sign function $\text{sgn}(\cdot)$ are defined in Equations (3) and (4), respectively:

$$Z_{MK} = \begin{cases} \frac{S - 1}{\sqrt{\text{var}(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S + 1}{\sqrt{\text{var}(S)}}, & S < 0 \end{cases} \quad (2)$$

$$S = \sum_{i=0}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (3)$$

$$\text{sgn}(x_j - x_i) = \begin{cases} 1, & x_j - x_i > 0 \\ 0, & x_j - x_i = 0 \\ -1, & x_j - x_i < 0 \end{cases} \quad (4)$$

In the trend significance test, $|Z_{MK}| \geq 1.96$ and $|Z_{MK}| \geq 2.58$ correspond to significance levels of $\alpha = 0.05$ and $\alpha = 0.01$, respectively. This study used $\alpha = 0.05$ as the threshold for trend significance. Trend direction was determined by the Theil–Sen slope (β), whereas trend significance was determined by the Mann–Kendall statistic. Accordingly, trends were classified as significant increase when $Z_{MK} \geq 1.96$ and $\beta > 0$, non-significant increase when $|Z_{MK}| < 1.96$ and $\beta > 0$, non-significant decrease when $|Z_{MK}| < 1.96$ and $\beta < 0$, and significant decrease when $Z_{MK} \leq -1.96$ and $\beta < 0$. Cases with $|Z_{MK}| < 1.96$ and β values close to zero were interpreted as no significant trend (Appendix A.2).

(3) Stability Index

The reciprocal of the coefficient of variation ($1/CV$) was used to characterize the stability index of ecological indicators (NPP , FVC , EII) as well as temperature and precipitation from 2003 to 2022. CV was calculated as Equation (5):

$$CV = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - x_{\text{mean}})^2} / x_{\text{mean}} \quad (5)$$

where CV is the coefficient of variation, x_i is the indicator value in year i , and x_{mean} is the mean indicator value from 2003 to 2022. Higher stability index values indicate smaller interannual fluctuations and greater ecosystem stability. Based on $1/CV$ classification, stability was divided into five categories: high stability (>10.00), relatively high stability (5.00 – 10.00), moderate stability (3.33 – 5.00), relatively low stability (2.00 – 3.33), and low stability (<2.00) (Appendix A.3). The $1/CV$ index characterizes temporal predictability as engineering resilience, not full ecological resilience—the latter also involves disturbance absorption magnitude, resistance to alternative stable states, and recovery rates [27,37].

2.5. Statistical Analysis

All continuous variables were Z-score standardized; buffer distance was ln-transformed to linearize its non-linear relationship with connectivity and align with scale-dependent ecological process models [38,39].

(1) Linear Mixed-Effects Model

Nine parallel Linear Mixed-Effects Models (LMMs) [28,29] were constructed using mean, trend, and stability of NPP, FVC, and EII as response variables. Zone 1 to Zone 6 were the core explanatory variables. The final dataset comprised 8456 cells. Each LMM included 24 fixed-effect parameters and one random-effect parameter, yielding sample-to-parameter ratio approximately 497:1 (Appendix B.1), well above the recommended minimum of 10:1 [28].

To ensure the comparability of effect parameters across response variables, consistent interaction terms were retained in all models. If an interaction term reached statistical significance ($p < 0.05$) in any candidate model, it was retained in the final models for all response variables to maintain a consistent model structure. Pre-analysis showed that the $Zone \times DEM$ and $Zone \times dnat$ interactions were significant ($p < 0.001$) in most LMMs; therefore, these two interaction terms were included as unified interaction terms in all final models. The final model structure was:

$$Y_{ij} = \beta_0 + \sum_{k=1}^5 \beta_k Zone_{ik} + \beta_6 dnat_i + \beta_7 dloc_i + \beta_8 DEM_i + \beta_9 Slope_i + \beta_{10} Temp_trend_i + \beta_{11} Temp_sta_i + \beta_{12} Prcp_trend_i + \beta_{13} Prcp_sta_i + \sum_{k=1}^5 \gamma_k (Zone_{ik} \times DEM_i) + \sum_{k=1}^5 \delta_k (Zone_{ik} \times dnat_i) + u_j + \varepsilon_{ij} \quad (6)$$

where Y_{ij} is the z-standardized response variable for grid i in block j ; $Zone_{ik}$ is the zoning dummy variable for Zone k , with $k = 1, \dots, 5$ and Zone 6 used as the reference category; $dnat_i$ and $dloc_i$ represent the log-transformed and standardized distances to the nearest national- and local-level protected areas, respectively; DEM_i , $Slope_i$, $Temp_trend_i$, $Temp_sta_i$, $Prcp_trend_i$, and $Prcp_sta_i$ are standardized environmental covariates; u_j is the random intercept for BlockID; and ε_{ij} is the residual error term.

BlockID was constructed using $5 \text{ km} \times 5 \text{ km}$ spatial blocking ($n = 342$ blocks), selected because (1) it approximates landscape heterogeneity scale in mountainous terrain; (2) it balances sufficient replication (minimum 10 observations per block) with capturing spatial autocorrelation. BlockID was set as random intercept to control block-level spatial clustering.

Prior model comparisons indicated that adding random slopes (e.g., $Zone | \text{BlockID}$) did not significantly improve model fit (likelihood ratio test: $\chi^2 = 4.32$ – 6.78 , $df = 5$, $p > 0.05$ for all models) and caused convergence difficulties (Hessian non-positive definite in 7 of 9 models). Thus, random intercept structure was adopted (Appendix B.3).

Prior VIF testing showed strong collinearity among *DEM*, mean temperature, and mean precipitation ($VIF > 5$). Because temperature and precipitation means in this mountain region largely reflect the same vertical gradient represented by *DEM*, including all three variables would inflate standard errors and obscure the interpretation of the *Zone* $\times$ *DEM* interaction. Therefore, *DEM* was retained as the main spatial background variable, whereas mean temperature and mean precipitation were removed. Climate trend and stability indicators were retained because they represent interannual dynamics during 2003–2022 rather than static background gradients. Final model predictors had $VIF < 3$, satisfying collinearity control requirements.

Models were fitted using Restricted Maximum Likelihood (REML) for unbiased variance component estimates [29]. Marginal R^2 (fixed effects), conditional R^2 (fixed + random effects), and ICC were calculated [30]. Model selection showed that distance to national protected areas (*dnat*) provided the dominant protected area network signal. Therefore, *dnat* was retained in both the main-effect and zone-interaction terms, while distance to local protected areas (*dloc*) was retained as a main-effect covariate to control for local protected area proximity; its zone interaction was not included in the final model (Appendix B.4). This result does not imply that local protected areas are ecologically unimportant; rather, it indicates that, within the present model and spatial extent, national protected area proximity better captured the dominant network-connectivity signal.

(2) Conservation Effect Identification and Spillover Effect Testing

Post hoc comparisons of conservation-associated differences were derived from estimated marginal means (EMMs) of the LMMs. The Zone 1–Zone 6 contrast was interpreted as an adjusted net difference associated with the protected area relative to the peripheral reference area, rather than as a strict causal treatment effect. Spillover-associated differences were calculated as *Zone_k* ($k = 2–5$) minus Zone 6, with the effective range defined as the farthest buffer zone exhibiting continuous significant positive effects ($p < 0.05$). Distance-decay patterns were assessed through visual inspection of EMM gradients across Zone 2 to Zone 5, while recognizing that non-monotonic responses may reflect boundary effects, leakage, human accessibility, or neighboring protected area connectivity.

For models with interactions (all nine models contained *zone* $\times$ *DEM* and *zone* $\times$ *dnat*), predicted differences between Zone 1 and Zone 6 were calculated at three *DEM* and *dnat* levels: low (mean $- 1$ SD), average, and high (mean $+ 1$ SD), analyzing how net effects varied with elevation and distance to neighboring protected areas. *DEM* was selected because it dominates mountain ecosystem vertical differentiation and may modulate conservation effect intensity. *Dnat* reflects landscape background connectivity and may influence conservation effectiveness spillover. *Zone* $\times$ *Slope* did not enter optimal models for any response and was excluded. Multiple comparisons used Holm correction.

All statistical analyses were performed in R 4.3.0. Mixed-effects models were fitted using `lme4` and `lmerTest`; estimated marginal means and pairwise contrasts were obtained using `emmeans` [40]; model fit and variance components were summarized using `performance` and `MuMIn`; collinearity diagnostics were conducted using `car`; residual diagnostics were performed using `DHARMa`; and data wrangling and visualization were conducted using `dplyr`, `tidyr`, and `ggplot2`.

3. Results

3.1. Overall Characteristics of Ecological Indicator Spatial Patterns

Prior to covariate adjustment, NPP, FVC, and EII showed distinct spatial patterns across the conservation gradient (Figures A1–A3). Notably, EII exhibited a “boundary collapse” pattern—sharp decline in Zone 2 (0–5 km) followed by recovery—whereas NPP and FVC showed gradual changes. EII also displayed contrasting trends, with mean val-

ues highest in Zone 1, yet over 50% of grids showed declining trends. NPP stability was anomalously lower in Zone 1 than surrounding buffers, suggesting high productivity co-occurred with high variability. These descriptive patterns indicated potential conservation effects but required LMM analysis to disentangle them from the confounding effects of topography, climate, and neighboring protected areas.

3.2. Linear Mixed-Effects Model Fitting Performance

(1) Assessment of Model Explanatory Power

LMMs showed satisfactory explanatory power, though performance varied by indicator and dimension (Table 2). State-dimension models outperformed trend and stability models. NPP achieved the best fit ($R^2_m = 0.465$, $R^2_c = 0.856$), followed by EII ($R^2_m = 0.457$, $R^2_c = 0.643$), while FVC showed weaker explanatory power ($R^2_m = 0.297$, $R^2_c = 0.487$). Notably, NPP stability was primarily driven by spatial random effects ($R^2_m = 0.281$ vs. $R^2_c = 0.713$), whereas FVC trend and stability variances mainly reflected random error rather than spatial structure (Appendix B.1).

Net conservation effects and spillover patterns differed markedly across indicators in the state dimension (Figure 2). NPP showed strong net protection ($\beta = 0.99$, 95% CI: 0.25–1.73, $p < 0.001$) with continuous positive spillover to all buffer zones (Zone 2–Zone 5: $\beta = 0.58$ –0.87, all $p < 0.001$). EII also demonstrated significant net protection ($\beta = 1.23$, 95% CI: 0.44–2.02, $p < 0.001$) but exhibited the distinctive “boundary collapse” pattern, with sharp decline in Zone 2 ($\beta = -1.84$) and Zone 3 ($\beta = -0.38$). FVC showed no net protection in Zone 1 ($p = 0.738$) but unexpected positive spillover in peripheral buffers (Zone 3–Zone 5: $\beta = 0.25$ –0.31, $p < 0.05$) (Appendix B.2).

Table 2. Model fitting results of linear mixed-effects models for ecological indicators across state, trend, and stability dimensions.

Indicator	Dimension	R^2_m	R^2_c	ICC	AIC	σ^2_{Block}	σ^2_{Res}
NPP	State	0.465	0.856	0.730	45,817	0.478	0.177
NPP	Trend	0.320	0.552	0.340	73,380	0.209	0.406
NPP	Stability	0.281	0.713	0.600	77,220	0.650	0.434
FVC	State	0.297	0.487	0.271	83,562	0.203	0.546
FVC	Trend	0.138	0.217	0.092	94,921	0.079	0.782
FVC	Stability	0.105	0.210	0.118	96,013	0.107	0.799
EII	State	0.457	0.643	0.344	68,958	0.188	0.359
EII	Trend	0.113	0.385	0.306	86,337	0.259	0.586
EII	Stability	0.213	0.494	0.357	82,554	0.290	0.523

R^2_m = marginal R -squared (proportion of variance explained by fixed effects); R^2_c = conditional R -squared (proportion of variance explained by fixed + random effects); ICC = intra-class correlation coefficient; σ^2_{block} = random intercept variance; σ^2_{res} = residual variance. All models converged without singular fit warnings.

In the trend dimension, NPP showed limited negative spillover in Zone 2–Zone 3 ($\beta = -0.41$ to -0.31 , $p < 0.05$), while FVC showed no significant effects and EII improved in Zone 2 but deteriorated in Zone 3, followed by recovery in Zone 4–Zone 5. In the stability dimension, NPP buffer zones (Zone 2–Zone 3) exceeded Zone 6 ($\beta = 0.85$ –1.69, $p < 0.001$), whereas EII showed higher stability in Zone 1 ($\beta = 1.69$, $p < 0.001$) but collapse in Zone 2 ($\beta = -1.91$, $p < 0.001$). FVC stability was lower in Zone 3–Zone 4 ($\beta = -0.29$ to -0.30 , $p < 0.05$) (Figure 2; Appendix B.2).

3.3. Moderating Effects of Elevation on Conservation Effects

Elevation significantly moderated conservation effects, with contrasting patterns across indicators in the state dimension (Figure 3). Most notably, EII exhibited a spatial reversal—negative elevation effects in Zone 1–Zone 3 ($\beta = -1.04$ to -0.39 , all $p < 0.001$) shifted to positive effects in Zone 5 ($\beta = 0.18$, $p < 0.001$)—suggesting elevation benefits ecological integrity primarily in peripheral areas. In contrast, NPP and FVC showed consistently positive elevation effects (NPP: $\beta = 0.43$ – 0.68 ; FVC: $\beta = 0.36$ – 0.58 ; all $p < 0.01$), indicating stronger protection effectiveness at high elevations across all zones.

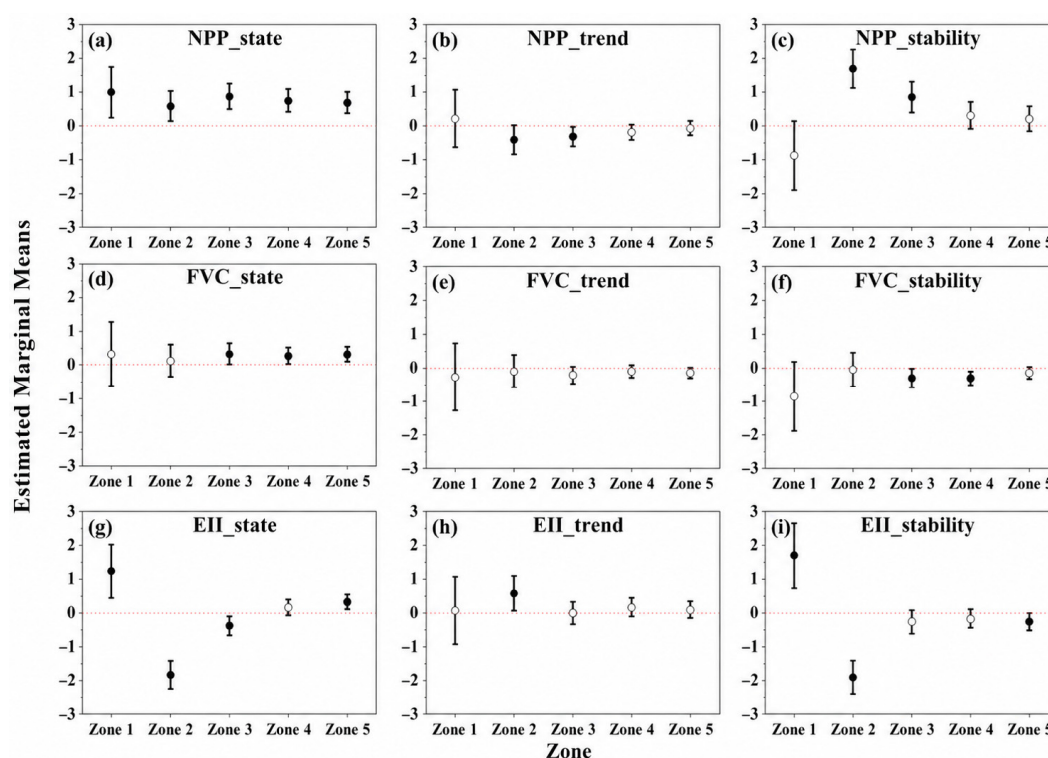


Figure 2. (a) NPP state; (b) NPP trend; (c) NPP stability; (d) FVC state; (e) FVC trend; (f) FVC stability; (g) EII state; (h) EII trend; and (i) EII stability. Gradient responses of NPP, FVC, and EII across state, trend, and stability dimensions in Daxiangling Nature Reserve. Estimated Marginal Means (EMMs) based on linear mixed-effects models (including $zone \times DEM$ and $zone \times dnat$ interaction terms). Points represent marginal means (solid circles indicate significant difference from the peripheral reference area at $p < 0.05$; open circles indicate non-significance at $p > 0.05$), with error bars showing 95% confidence intervals. The horizontal dashed line at $y = 0$ indicates the reference level of the peripheral reference area (Zone 6). Zone labels: Zone 1 = protected area interior; Zone 2 to Zone 5 = buffer zones at 0–5 km, 5–10 km, 10–15 km, and 15–20 km.

For trend, EII showed a gradient from negative (Zone 1–Zone 2: $\beta = -0.35$ to -0.31 , $p < 0.05$) to positive (Zone 4–Zone 5: $\beta = 0.15$ to 0.62 , $p < 0.05$), while NPP and FVC exhibited mixed or non-significant patterns. For stability, all three indicators showed predominantly negative elevation effects (EII: $\beta = -1.33$ to -0.16 ; FVC: $\beta = -0.83$ to -0.45 ; NPP: $\beta = -0.36$ to -0.22 ; $p < 0.05$), except NPP in Zone 1 ($\beta = 0.73$, $p < 0.001$), indicating that high-elevation areas generally experienced greater interannual variability (Figure 3).

3.4. Moderating Effects of Distance to Neighboring Protected Areas on Conservation Effects

Distance to neighboring national protected areas significantly moderated conservation effects, with EII showing the strongest connectivity dependence (Figure 4). For EII state, increasing distance strongly reduced ecological integrity across all buffer zones

(Zone 2–Zone 5: $\beta = -3.29$ to -0.27 , all $p < 0.001$), indicating that proximity to neighboring protected areas enhances conservation outcomes. This pattern extended to trend (Zone 3–Zone 5: $\beta = -0.63$ to -0.23 , $p < 0.001$) and stability, where a “core positive, periphery negative” pattern emerged—Zone 1 showed a positive distance effect ($\beta = 1.24$, $p = 0.011$), whereas peripheral zones were negative (Zone 2–Zone 5: $\beta = -2.89$ to -0.12 , $p < 0.05$).

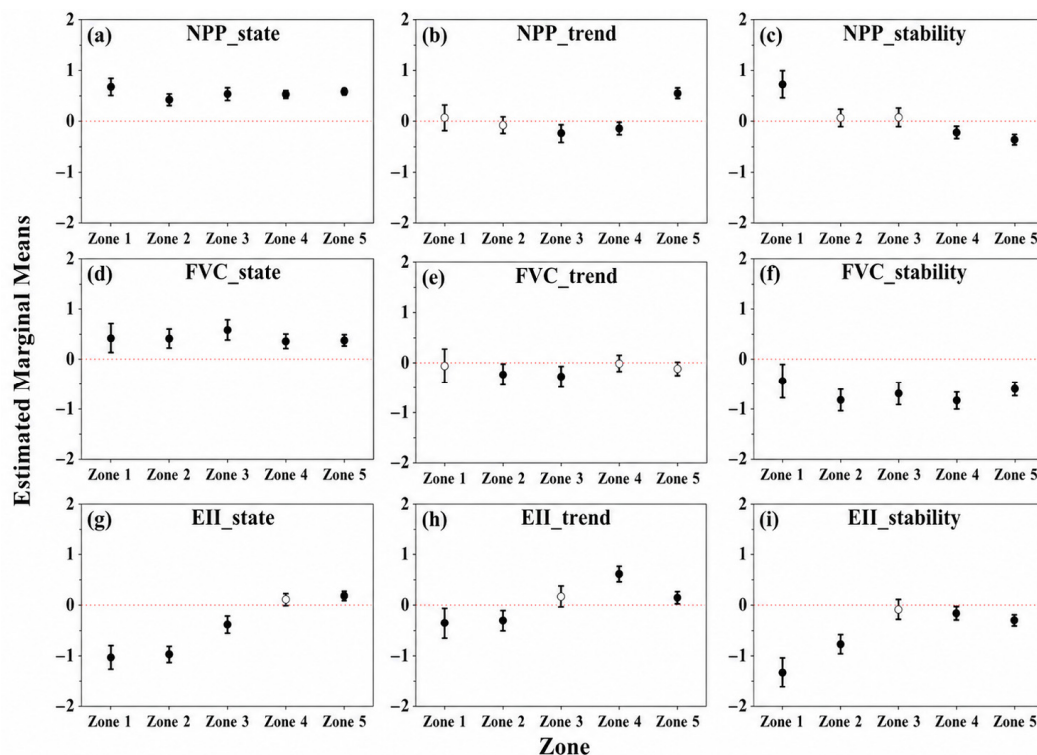


Figure 3. (a) NPP state; (b) NPP trend; (c) NPP stability; (d) FVC state; (e) FVC trend; (f) FVC stability; (g) EII state; (h) EII trend; and (i) EII stability. Moderating effects of elevation on conservation effects. Estimated Marginal Means (EMMs) based on linear mixed-effects models (zone $\times$ DEM interaction term). Points represent marginal means (solid circles indicate significant difference from the peripheral reference area at $p < 0.05$; open circles indicate non-significance at $p > 0.05$), with error bars showing 95% confidence intervals. The horizontal dashed line at $y = 0$ indicates the reference level of the peripheral reference area (Zone 6). Zone labels: Zone 1 = protected area interior; Zone 2 to Zone 5 = buffer zones at 0–5 km, 5–10 km, 10–15 km, and 15–20 km.

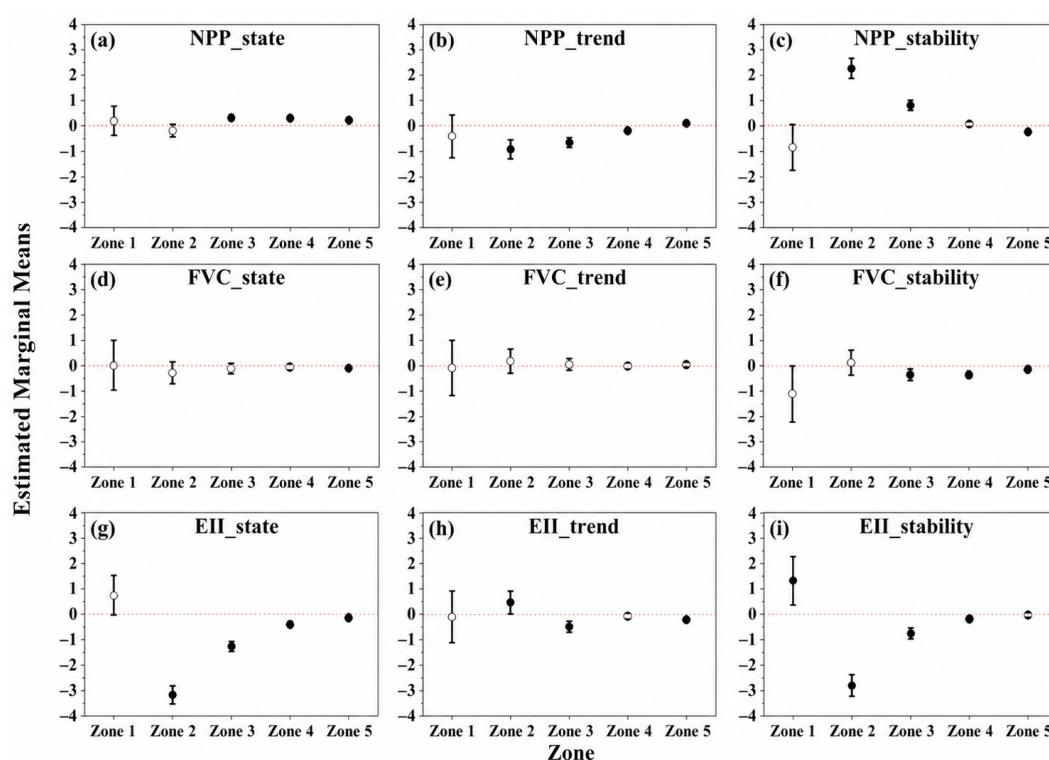


Figure 4. (a) NPP state; (b) NPP trend; (c) NPP stability; (d) FVC state; (e) FVC trend; (f) FVC stability; (g) EII state; (h) EII trend; and (i) EII stability. Moderating effects of distance to neighboring national protected areas on conservation effects. Estimated Marginal Means (EMMs) based on linear mixed-effects models ($zone \times dnat$ interaction term). Points represent marginal means (solid circles indicate significant difference from the peripheral reference area at $p < 0.05$; open circles indicate non-significance at $p > 0.05$), with error bars showing 95% confidence intervals. The horizontal dashed line at $y = 0$ indicates the reference level of the peripheral reference area (Zone 6). Zone labels: Zone 1 = protected area interior; Zone 2 to Zone 5 = buffer zones at 0–5 km, 5–10 km, 10–15 km, and 15–20 km. $dnat$ = distance to the nearest national protected area.

In contrast, NPP showed weaker and spatially variable distance effects, with positive effects on state in outer buffers (Zone 3–Zone 5: $\beta = 0.20$ – 0.29 , $p < 0.001$) but directionally reversed effects on trend and stability. FVC showed minimal distance sensitivity, with only scattered significant effects on state (Zone 4–Zone 5: $\beta = -0.13$ to -0.16 , $p < 0.05$) and stability (predominantly negative, $p < 0.05$) (Figure 4).

3.5. Independent Effects of Climate Factors

Climate factors showed significant independent effects after controlling for zoning, topography, and neighboring protected area effects (Table 3), enabling distinction between conservation and climate drivers. Precipitation stability consistently enhanced ecosystem state across all indicators (NPP: $\beta = 0.245$; EII: $\beta = 0.106$; FVC: $\beta = 0.071$; all $p < 0.001$). In contrast, precipitation trend effects diverged, positive for EII (state: $\beta = 0.334$; trend: $\beta = 0.104$; stability: $\beta = 0.167$; $p < 0.001$) but negative for NPP stability ($\beta = -0.361$, $p < 0.001$) and FVC across all dimensions ($\beta = -0.055$ to -0.144 , $p < 0.05$).

Temperature effects were generally weaker. Temperature trend negatively affected NPP state and trend ($\beta = -0.030$ to -0.029 , $p < 0.001$) but positively affected stability (NPP: $\beta = 0.065$; FVC: $\beta = 0.047$; $p < 0.001$). Temperature stability showed mixed effects, positive for EII across dimensions ($\beta = 0.016$ – 0.032 , $p < 0.001$) and FVC trend ($\beta = 0.020$, $p < 0.01$), but negative for FVC state ($\beta = -0.062$, $p < 0.001$).

Table 3. Fixed-effects coefficients of climate indicators.

Indicator	Temp_Trend	Temp_Sta	Prcp_Trend	Prcp_Sta
NPP_mean	−0.030 ***	0.013 ***	−0.001	0.245 ***
NPP_trend	−0.029 ***	0.041 ***	0.079 ***	−0.155 ***
NPP_sta	0.065 ***	0.017 ***	−0.361 ***	0.117 ***
FVC_mean	0.003	−0.062 ***	−0.055 ***	0.071 ***
FVC_trend	0.009	0.020 **	−0.048 ***	−0.117 ***
FVC_sta	0.047 ***	0.011	−0.144 ***	0.083 ***
EII_mean	0.002	0.016 ***	0.334 ***	0.106 ***
EII_trend	−0.006	0.028 ***	0.104 ***	0.046 **
EII_sta	0.008	0.032 ***	0.167 ***	−0.163 ***

Temp_trend = temperature trend; Temp_sta = temperature stability; Prcp_trend = precipitation trend; Prcp_sta = precipitation stability. Coefficients are standardized estimates. ** $p < 0.01$, *** $p < 0.001$.

3.6. Environmental-Comparability Diagnostic for the Peripheral Reference Area

To avoid treating the 20–100 km zone as a perfect no-treatment counterfactual, we added a concise zoning-diagnostic table (Table 4). The table summarizes sample size, the distribution of HFI-derived EII values as an indicator of ecosystem condition, and the role of each zone in interpreting distance-gradient responses. *DEM*, *slope*, *dnat*, and *dloc* were controlled in the LMM, so the table should be read as a descriptive diagnostic rather than a full zoning sensitivity analysis.

Table 4. Zoning-diagnostic summary for interpreting the peripheral reference area and potential confounding sources.

Zone	EII State (Unadjusted)	Diagnostic Implication
Zone 1	0.834	PA interior reference; terrain controlled by <i>DEM</i> and <i>slope</i> .
Zone 2	0.366	Near-boundary zone; used to diagnose edge/leakage disturbance.
Zone 3	0.045	Tests whether the boundary signal persists beyond 5 km.
Zone 4	0.031	Intermediate buffer for distance-decay or recovery patterns.
Zone 5	0.115	Outer buffer used to evaluate direct spillover range.
Zone 6	−0.020	Distant peripheral reference; network effects controlled by <i>dnat/dloc</i> .

EII values are unadjusted standardized means from the final analysis dataset and are used here only as a human-footprint-based proxy. Zone 6 is therefore interpreted as a distant peripheral reference area rather than a strictly untreated control area.

4. Discussion

This study demonstrates that integrating the spatial gradient dose–response framework with linear mixed-effects models (LMMs) provides a viable pathway for assessing conservation-associated ecological gradients in network-embedded mountainous protected areas, particularly where traditional counterfactual approaches face practical constraints. We therefore position this framework as complementary to PSM and DID: it is useful when strict spatial controls, pre-intervention baselines, or parallel trends are unavailable, but it does not provide the same level of causal identification as a well-designed counterfactual study.

Compared with PSM, the gradient LMM framework does not require a binary protected-unprotected contrast or the exclusion of all areas potentially affected by spillover. This is advantageous in Daxiangling because neighboring protected areas and continuous elevation gradients make it difficult to identify uncontaminated matched controls. Compared with DID, the framework does not require pre-establishment time series or the par-

allel-trends assumption, which is important because the reserve was established in 2003 and the available remote sensing time series also begins in 2003. However, LMM relies on model specification, observed covariates, and spatial blocking; it cannot eliminate unobserved confounding or fully prove that observed ecological improvements were caused by the reserve. Future studies with longer pre-intervention data should compare this framework with PSM, spatial DID, synthetic control, or Bayesian spatial hierarchical models.

In practical terms, PSM is strongest when suitable control samples with comparable environmental backgrounds exist; DID is strongest when long and reliable pre- and post-intervention data are available; and the present LMM gradient framework is most suitable for diagnosing spatial gradients, spillover, and interaction effects under data-limited and network-embedded conditions. Therefore, the framework is better described as a baseline-independent diagnostic approach rather than a definitive causal attribution method.

4.1. Spatial Gradient Characteristics and Environmental Dependencies of Conservation Effects

4.1.1. Overall Effects and Indicator Divergence

This study confirms that Daxiangling Nature Reserve was associated with significant positive adjusted differences in NPP and EII after controlling for topography, climate dynamics, and neighboring protected area effects—consistent with global assessments that conservation interventions generally maintain ecosystem functions [1,2,17]. However, because the study period begins in the same year as reserve establishment and lacks a pre-establishment baseline, these results should be interpreted as conservation-associated spatial gradients rather than strict causal effects. The absence of significant FVC effects echoes findings that structural indicators often lag behind functional indicators in capturing conservation signals [8,14], potentially attributable to phenological rhythms, high forest-cover saturation, topographic shadow effects, and resolution limitations that reduce FVC sensitivity.

4.1.2. Spillover Effects and Boundary Dynamics

Spillover effects exhibited marked indicator divergence. NPP showed sustained positive spillover extending to 15–20 km (Zone 5), aligning with previous evidence that protected area effects may extend beyond administrative boundaries [35,41]. In contrast, EII displayed a distinctive boundary-degradation pattern—sharp declines in Zone 2 (0–5 km) and Zone 3 (5–10 km) followed by recovery in Zone 5 (15–20 km). Because EII is derived from HFI, this pattern primarily indicates a concentration of human-footprint pressure near the reserve boundary. Nevertheless, it should not be attributed exclusively to any single activity such as tourism or grazing. Possible mechanisms include road accessibility, settlement distribution, land-use transition, management-boundary discontinuity, edge effects, leakage of resource-use pressure, and terrain-mediated accessibility [5–8,42,43]. Direct field data on tourism intensity, grazing pressure, and resource collection would be needed to separate these mechanisms quantitatively.

These findings carry direct management implications. Zone 2 (0–5 km) should not be treated merely as a zone of decreasing conservation effect, but rather requires differentiated control strategies—strengthened patrols, disturbance regulation, and strict limits on tourism development [9,11]. Zone 3–Zone 4 (5–15 km) can serve as sustainable use areas with moderate community participation, while Zone 5 (15–20 km) should prioritize ecological compensation and alternative livelihood development, forming a gradient-management framework of core protection–buffer control–peripheral use [44,45].

The zoning scheme itself also introduces uncertainty. A 20 km threshold cannot fully eliminate spillover contamination from Daxiangling or from neighboring protected areas. If Zone 6 is still positively influenced by conservation spillover, the estimated Zone 1–

Zone 6 difference would be conservative and may underestimate Daxiangling-specific conservation-associated differences. Conversely, if Zone 6 is environmentally less favorable than the reserve because of lower elevation, gentler terrain, stronger accessibility, or higher human pressure, the contrast may be inflated and may overestimate the reserve-specific contribution. Therefore, Zone 6 should be interpreted as a distant peripheral reference area after covariate adjustment, rather than as a strict counterfactual control. In the present framework, potential bias was reduced by excluding other protected areas from Zone 6 and by controlling DEM, slope, climate dynamics, $Zone \times DEM$, $dnat$, and $Zone \times dnat$. Full robustness testing using alternative buffer widths, alternative reference-zone ranges, and topography-matched control subsets remains an important next step.

4.1.3. Moderating Effects of Elevation

Elevation significantly moderated conservation effects. NPP effects strengthened at high elevations across all zones ($\beta = 0.43\text{--}0.68$), supporting conclusions that high-elevation protected areas are more effective and that wilderness quality increases with topographic gradients [2,46]. This likely reflects both reduced anthropogenic disturbance and greater productivity responsiveness to habitat improvements in temperature/precipitation-limited high-elevation ecosystems [3]. However, NPP stability decreased in high-elevation peripheral zones, likely reflecting enhanced climatic harshness and environmental stochasticity at high elevations [3] rather than measurement artifacts from remote sensing resolution limitations. This interpretation requires validation via field surveys and climate reanalysis data.

EII exhibited spatially reversed elevation effects—negative in Zone 1–Zone 3 ($\beta = -1.04$ to -0.39) shifting to positive in Zone 5 ($\beta = 0.18$). We hypothesize that high-elevation areas in the core zone may concentrate alpine roads, pastoral activities, or tourism infrastructure, where human footprint (HFI) effects on EII outweigh elevation-related ecological gains; conversely, in peripheral zones, elevation benefits ecological integrity primarily by reducing human accessibility. This hypothesis requires testing with high-resolution human footprint data. Overall, areas above 2000 m should be prioritized for core zone designation, coupled with strengthened stability monitoring and climate adaptation planning [2].

4.1.4. Moderating Effects of Protected Area Network Connectivity

Evaluating the net effect of an individual protected area requires addressing spatial spillovers from neighboring conservation units—a well-documented methodological challenge [11]. Prior studies have largely relied on spatial exclusion strategies to isolate focal-PA effects, such as removing buffer zones overlapping with other protected areas [10,47], discarding control samples contaminated by nearby-park spillovers [43], applying independent subregional matching to avoid cross-boundary contamination [48], or combining threshold regression with propensity score matching to delineate and exclude spillover ranges [49]. Rather than excluding spillover zones a priori, the present LMM framework treats network connectivity—distance to the nearest neighboring protected area—as a continuous covariate, enabling the simultaneous quantification of net conservation effects and spatial interdependencies within a dose–response architecture. This design is particularly suited to Daxiangling, which is embedded within a dense protected area network surrounded by Erlangshan, Labahe, and other national reserves.

Distance to neighboring national protected areas ($dnat$) significantly moderated conservation outcomes. For EII state, increasing distance from national reserves reduced ecological integrity across all buffer zones (Zone 2–Zone 5: $\beta = -3.29$ to -0.27 , all $p < 0.001$), indicating that proximity to national reserves enhances conservation outcomes and underscoring the ecological value of network connectivity [8,50]. Zone 1 exhibited a margin-

ally positive distance effect ($\beta = 1.24, p = 0.011$), suggesting that the relatively isolated core zone—characterized by high elevation and steep terrain—may experience attenuated direct management spillover from neighboring reserves while maintaining lower disturbance regimes. Notably, model selection showed that *dnat* strongly outperformed distance to local protected areas (*dloc*). This management-level differential reveals that connectivity within the national protected area network is the dominant driver of spatial variation in conservation effectiveness, whereas proximity to local-level protected areas exerts limited influence—a pattern consistent with systematic disparities in conservation investment, enforcement capacity, and corridor functionality across governance levels.

These findings carry direct management implications. Given Daxiangling's embedding within a cluster of national- and local-level protected areas, surrounding reserves may simultaneously enhance connectivity and complicate attribution of Daxiangling-specific effects. Cross-protected area information sharing, joint patrol mechanisms, and ecological corridors should be established to reduce management vacuums in the 0–5 km buffer zone and enhance network-wide collaborative conservation [8,51]. Importantly, the pronounced dependence of conservation-associated responses on national network connectivity, combined with the limited explanatory power of local-level protected area proximity, highlights the need for integrated governance frameworks that transcend administrative boundaries. Future research should explicitly model Daxiangling, Wawushan, Erlangshan, Labahe, and other neighboring protected areas as interacting network nodes rather than treating them only as covariates.

4.2. Differential Response Mechanisms Across Ecosystem Dimensions

This study reveals significant divergence in conservation effectiveness across three dimensions—state, trend, and temporal stability—confirming the prevalence of multidimensional decoupling in landscape-scale ecological assessments. Specifically, NPP in the core zone (Zone 1) exhibits high state values with a multi-year mean 1.99 times that of the control zone, yet its temporal stability (represented by $1/CV$) decreases relative to the near-boundary buffer zones (Zones 2–3), displaying a “high-state, low-stability” spatial pattern. This spatial decoupling of state and stability is not coincidental; rather, it reflects that while the Daxiangling Nature Reserve ecosystem possesses greater productivity response potential (state advantage), it simultaneously faces greater climatic harshness and inter-annual environmental stochasticity at high altitudes, leading to amplified interannual fluctuations in ecosystem function [3].

EII presents a paradox of “mean advantage coexisting with boundary collapse.” Mean values within Zone 1 are significantly higher than those in the control zone ($\beta = 1.23$), yet integrity in Zones 2–3 declines sharply ($\beta = -1.84$ to -0.38), while trends in the buffer zones actually improve. This cross-dimensional response divergence indicates that single time-slice state assessments may obscure the true spatial heterogeneity of conservation effects [27], thereby highlighting the necessity of a multidimensional monitoring framework [25]. More importantly, the inconsistency between NPP and EII in dimensional divergence patterns—NPP showing a state-stability trade-off, EII showing a state-trend contrast—suggests that different ecological indicators follow distinct stability dimension laws in their responses to conservation gradients, further confirming that landscape-scale stability assessments must adopt multidimensional rather than single-indicator approaches [52].

The above dimensional divergence carries direct implications for adaptive management. Relying solely on state assessment may lead to the conclusion that “the core zone is in good ecological condition”, yet incorporating temporal stability analysis—similar to the variability component proposed by White et al. [52]—can reveal that high-altitude core zones face greater interannual fluctuation risks. Meanwhile, incorporating trend

analysis (reflecting the directionality of recovery rates) can identify early degradation signals in boundary zones, despite their currently high state values. Such multidimensional information integration can avoid systematic biases in single-dimension assessments [25] and trigger preventive management adjustments, such as intensifying stability monitoring in core zones and strengthening trend early warning in boundary zones. Long-term monitoring systems should incorporate three-dimensional “state–trend–stability” data to enable dynamic assessment of conservation effectiveness and adaptive management cycles.

Indicator sensitivity analysis shows that NPP and EII both exhibit relatively high model explanatory power across dimensions (state dimension R^2_m of 0.465 and 0.457, respectively), whereas FVC shows substantially weaker explanatory power, particularly for trend and stability ($R^2_m < 0.14$). This weak performance likely reflects several limitations of FVC in densely forested mountainous landscapes: saturation under high vegetation cover, sensitivity to cloud contamination and terrain shadow, phenological variability, and limited ability to represent vertical forest structure. FVC captures fractional canopy cover but not canopy height, forest age, understory complexity, LAI, or habitat fragmentation. Therefore, FVC should be treated as an auxiliary structural indicator rather than a core indicator of conservation effectiveness. Future applications should incorporate additional structural metrics such as LAI, canopy height from GEDI/ICESat-2 or other LiDAR products, forest age, patch fragmentation, and landscape connectivity to improve the structure-function integrity assessment framework.

Therefore, monitoring system optimization should follow the principle of “functional priority, composite supplementation, and structural complementarity” [20,21], incorporating NPP and EII as core functional indicators in routine monitoring, with FVC serving as an auxiliary structural indicator for specific objectives such as forest coverage assessment. An adaptive management decision support system based on the three-dimensional framework can transform conservation effectiveness assessment from single-indicator static snapshots to multidimensional dynamic diagnosis, thereby providing more ecologically robust management foundations for mountain protected area networks [9,11].

4.3. Limitations and Future Directions

This study has five main limitations. First, remote sensing resolution (250 m to 1 km) may smooth local-scale effects, and cloud interference and topographic shadow may affect high-elevation accuracy [18,23]. Second, stability based on the reciprocal coefficient of variation reflects temporal variability or engineering resilience rather than full ecological resilience; high stability may mask functional degradation [27,37]. Third, the EII used here is an HFI-derived proxy and does not directly represent biodiversity, species composition, habitat fragmentation, trophic interactions, or ecological processes. Fourth, the 20–100 km peripheral reference-zone design reduces—but does not eliminate—uncertainty associated with residual spillover and environmental mismatch. Although DEM, slope, climate variables, dnat, and interaction terms were included to reduce these biases, a full model-refitting sensitivity analysis using alternative buffer widths, alternative peripheral reference ranges, and topography-matched control subsets should be conducted in future work or supplementary robustness testing. Fifth, because the reserve was established in 2003 and the available time series also begins in 2003, this study cannot provide a strict before–after causal attribution of reserve establishment effects.

Future research should: methodologically, apply Bayesian hierarchical models, spatial GLMMs, spatial DID, or synthetic control approaches where suitable pre-establishment data exist [28,30]; for data accumulation, extend time series beyond 30 years to capture fuller recovery dynamics [26]; for mechanism validation, conduct field surveys coupling remote sensing with biodiversity, habitat fragmentation, grazing, tourism, road-ac-

cessibility, patrol, and community-use data [9,14]; for indicator improvement, integrate LAI, canopy height, forest age, and landscape connectivity metrics; and for policy application, promote three-dimensional assessment framework standardization to support the UN Decade on Ecosystem Restoration [1,11].

5. Conclusions

This study develops a spatial gradient dose–response framework using linear mixed-effects models to assess conservation-associated ecological responses in mountainous protected areas where traditional counterfactuals are difficult to establish. We find significant positive adjusted differences for NPP and the HFI-derived EII, but divergent spatial profiles: NPP spillover extended continuously to 15–20 km, while EII exhibited a boundary collapse pattern—sharp decline near boundaries (0–5 km) followed by distal recovery—demonstrating that conservation-associated boundaries are indicator-specific and that near-boundary zones require differentiated management. Because the study lacks pre-establishment data, these findings should be interpreted as robust spatial associations after covariate adjustment rather than as definitive causal proof of reserve establishment effects.

Elevation amplified protection effects but reduced temporal stability in peripheral zones, revealing a productivity–variability trade-off, while proximity to neighboring national protected areas enhanced EII outcomes, underscoring network connectivity as a critical moderator. Three-dimensional assessment further showed that conservation outcomes diverge across state, trend, and stability dimensions: NPP displayed high productivity with high variability in the core zone, whereas EII showed decoupled state and trend responses in buffers. These findings confirm that single-dimension, single-indicator assessments risk mischaracterizing conservation performance.

Our results support three priority actions: (1) manage near-boundary zones (0–5 km) as active intervention areas to mitigate edge effects and leakage; (2) prioritize high-elevation areas for core zone designation with stability monitoring; and (3) establish cross-protected area collaborative mechanisms to leverage connectivity effects. This framework offers a replicable, baseline-independent pathway for conservation assessment in data-limited mountain systems. Future research should validate the framework across diverse mountain contexts, extend time series for decadal dynamics, and couple remote sensing with field data to strengthen mechanistic interpretation.

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Abbreviations

The following abbreviations are used in this manuscript:

Zone 1	Protected area
Zone 2	Buffer zone outside the protected area boundary at 0–5 km
Zone 3	Buffer zone outside the protected area boundary at 5–10 km
Zone 4	Buffer zone outside the protected area boundary at 10–15 km
Zone 5	Buffer zone outside the protected area boundary at 15–20 km
Zone 6	Peripheral reference area
NPP	Net Primary Productivity
FVC	Fractional Vegetation Cover
HFI	Human Footprint Index
DEM	Digital Elevation Model
EII	Human-footprint-derived Ecosystem Integrity Index
EMMs	Estimated marginal means
LMM	Linear Mixed-Effects Model
R^2_m	Marginal R^2
R^2_c	Conditional R^2
REML	Restricted Maximum Likelihood
<i>dnat</i>	Distance to nearest national protected areas
<i>dloc</i>	Distance to nearest local protected areas
DID	Difference-in-differences

Appendix A

Appendix A.1

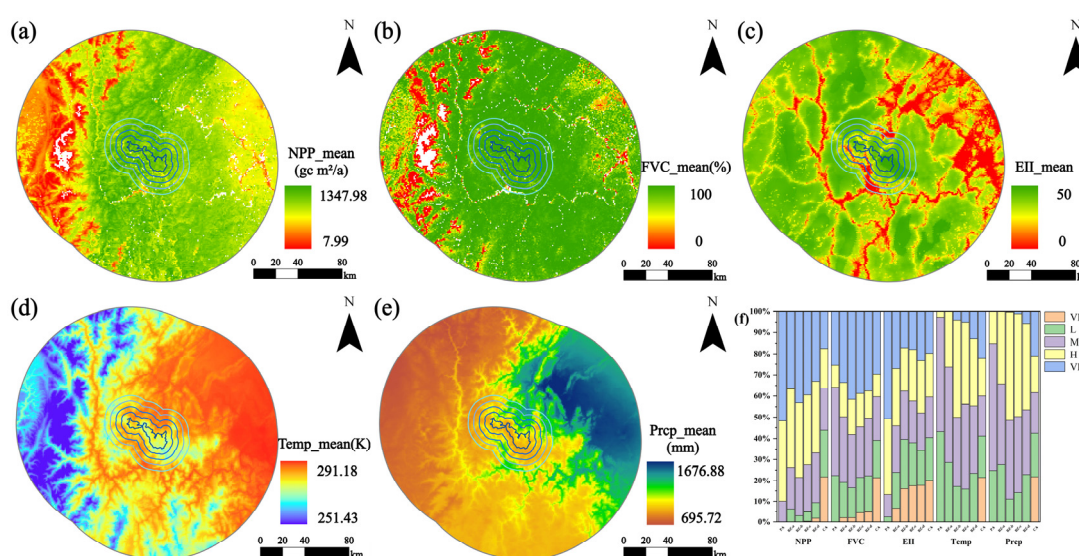


Figure A1. Spatial distributions and zonal compositions of mean ecological and climatic indicators in Daxiangling Nature Reserve and its surrounding areas during 2003–2022. (a) Mean net primary productivity (NPP; g C m⁻² year⁻¹); (b) mean fractional vegetation cover (FVC; %); (c) mean Ecosystem Integrity Index (EII); (d) mean annual temperature (K); (e) mean annual precipitation (mm); and (f) percentage composition of five classes—very low (VL), low (L), moderate (M), high (H), and very high (VH)—for NPP, FVC, EII, temperature, and precipitation across Zones 1–6. The nested outlines in panels (a)–(e) represent the boundaries of Zones 1–6, and the colors indicate the values of the corresponding indicators according to the color bars.

Appendix A.2

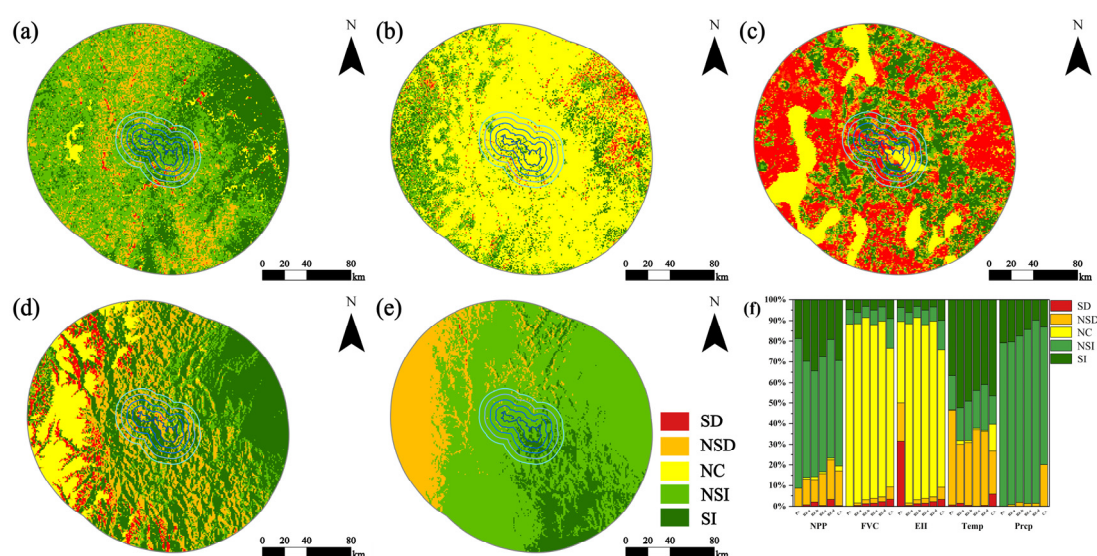


Figure A2. Spatial trend maps of vegetation, EII, and climate indicators, and area proportion of spatial trends for each indicator across different zones (2003–2022). ((a): NPP, (b): FVC, (c): EII, (d): mean annual temperature, (e): mean annual precipitation, (f): percentage composition of trend classes for NPP, FVC, EII, temperature, and precipitation across Zones 1–6; Zone 1: protected area, Zone 2: buffer zone (a), Zone 3: buffer zone (b), Zone 4: buffer zone (c), Zone 5: buffer zone (d), Zone 6: peripheral reference area; SI: significant increase, NSI: non-significant increase, NC: no change; NSD: non-significant decrease, SD: significant decrease).

Appendix A.3

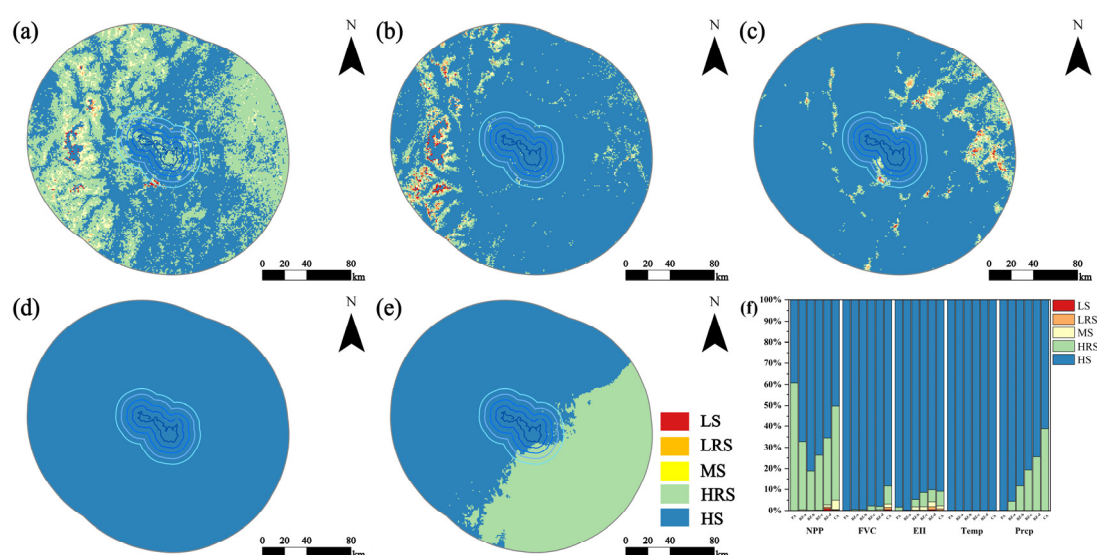


Figure A3. Spatial distribution maps of stability for vegetation, EII, and climate indicators, and area proportion of stability for each indicator across different zones (2003–2022). ((a): NPP, (b): FVC, (c): EII, (d): mean annual temperature, (e): mean annual precipitation, (f): percentage composition of stability classes for NPP, FVC, EII, temperature, and precipitation across Zones 1–6; Zone 1: protected area, Zone 2: buffer zone (a), Zone 3: buffer zone (b), Zone 4: buffer zone (c), Zone 5: buffer zone (d), Zone 6: peripheral reference area; HS: high stability; HRS: relatively high stability, MS: moderate stability, LRS: relatively low stability, LS: low stability). The color legend shown beside panel (e) applies to panels (a)–(e).

Appendix B

Appendix B.1

Table A1. Complete fixed-effects coefficients for nine linear mixed-effects models (with standard errors and *p*-values).

Model	Term	Estimate	SE	<i>p</i> -Value	Sig.
NPP (State)	Intercept	−0.055	0.019	0.0044	**
NPP (State)	Zone 1 (PA)	0.990	0.276	0.0003	***
NPP (State)	Zone 2 (0–5 km)	0.584	0.163	0.0003	***
NPP (State)	Zone 3 (5–10 km)	0.869	0.139	<0.0001	***
NPP (State)	Zone 4 (10–15 km)	0.744	0.122	<0.0001	***
NPP (State)	Zone 5 (15–20 km)	0.686	0.115	<0.0001	***
NPP (State)	ln(Distance to national PA + 1)	−0.039	0.005	<0.0001	***
NPP (State)	ln(Distance to local PA + 1)	0.013	0.005	0.0077	**
NPP (State)	DEM	−0.821	0.006	<0.0001	***
NPP (State)	Slope	0.067	0.003	<0.0001	***
NPP (State)	Temperature trend	−0.030	0.003	<0.0001	***
NPP (State)	Temperature stability	0.013	0.003	<0.0001	***
NPP (State)	Precipitation trend	−0.001	0.007	0.9272	ns
NPP (State)	Precipitation stability	0.245	0.013	<0.0001	***
NPP (State)	Zone 1 × DEM	0.680	0.083	<0.0001	***
NPP (State)	Zone 2 × DEM	0.429	0.056	<0.0001	***
NPP (State)	Zone 3 × DEM	0.536	0.060	<0.0001	***
NPP (State)	Zone 4 × DEM	0.532	0.040	<0.0001	***
NPP (State)	Zone 5 × DEM	0.586	0.032	<0.0001	***
NPP (State)	Zone 1 × <i>dnat</i>	0.211	0.289	0.4646	ns
NPP (State)	Zone 2 × <i>dnat</i>	−0.172	0.126	0.1731	ns
NPP (State)	Zone 3 × <i>dnat</i>	0.334	0.065	<0.0001	***
NPP (State)	Zone 4 × <i>dnat</i>	0.315	0.034	<0.0001	***
NPP (State)	Zone 5 × <i>dnat</i>	0.238	0.023	<0.0001	***
NPP (Trend)	Intercept	0.001	0.013	0.9668	ns
NPP (Trend)	Zone1 (PA)	0.215	0.311	0.4891	ns
NPP (Trend)	Zone 2 (0–5 km)	−0.409	0.158	0.0097	**
NPP (Trend)	Zone 3 (5–10 km)	−0.313	0.109	0.0040	**
NPP (Trend)	Zone 4 (10–15 km)	−0.187	0.086	0.0301	*
NPP (Trend)	Zone 5 (15–20 km)	−0.065	0.079	0.4146	ns
NPP (Trend)	ln(Distance to national PA + 1)	0.172	0.007	<0.0001	***
NPP (Trend)	ln(Distance to local PA + 1)	0.009	0.007	0.1606	ns
NPP (Trend)	DEM	−0.260	0.008	<0.0001	***
NPP (Trend)	Slope	−0.024	0.005	<0.0001	***
NPP (Trend)	Temperature trend	−0.029	0.004	<0.0001	***
NPP (Trend)	Temperature stability	0.041	0.005	<0.0001	***
NPP (Trend)	Precipitation trend	0.079	0.010	<0.0001	***
NPP (Trend)	Precipitation stability	−0.155	0.013	<0.0001	***
NPP (Trend)	Zone 1 × DEM	0.068	0.125	0.5846	ns
NPP (Trend)	Zone 2 × DEM	−0.082	0.082	0.3222	ns
NPP (Trend)	Zone 3 × DEM	−0.239	0.087	0.0059	**
NPP (Trend)	Zone 4 × DEM	−0.144	0.060	0.0164	*
NPP (Trend)	Zone 5 × DEM	0.551	0.048	<0.0001	***
NPP (Trend)	Zone 1 × <i>dnat</i>	−0.400	0.427	0.3497	ns

NPP (Trend)	Zone 2 × <i>dnat</i>	−0.900	0.187	<0.0001	***
NPP (Trend)	Zone 3 × <i>dnat</i>	−0.646	0.095	<0.0001	***
NPP (Trend)	Zone 4 × <i>dnat</i>	−0.178	0.051	0.0005	***
NPP (Trend)	Zone 5 × <i>dnat</i>	0.110	0.034	0.0014	**
NPP (Stability)	Intercept	−0.028	0.023	0.2252	ns
NPP (Stability)	Zone 1 (PA)	−0.878	0.378	0.0202	*
NPP (Stability)	Zone 2 (0–5 km)	1.688	0.210	<0.0001	***
NPP (Stability)	Zone 3 (5–10 km)	0.849	0.169	<0.0001	***
NPP (Stability)	Zone 4 (10–15 km)	0.305	0.144	0.0347	*
NPP (Stability)	Zone 5 (15–20 km)	0.206	0.135	0.1281	ns
NPP (Stability)	ln(Distance to national PA + 1)	−0.075	0.008	<0.0001	***
NPP (Stability)	ln(Distance to local PA + 1)	0.235	0.007	<0.0001	***
NPP (Stability)	DEM	−0.857	0.009	<0.0001	***
NPP (Stability)	Slope	−0.015	0.005	0.0018	**
NPP (Stability)	Temperature trend	0.065	0.004	<0.0001	***
NPP (Stability)	Temperature stability	0.017	0.005	0.0004	***
NPP (Stability)	Precipitation trend	−0.361	0.011	<0.0001	***
NPP (Stability)	Precipitation stability	0.117	0.019	<0.0001	***
NPP (Stability)	Zone 1 × <i>DEM</i>	0.731	0.130	<0.0001	***
NPP (Stability)	Zone 2 × <i>DEM</i>	0.058	0.087	0.5062	ns
NPP (Stability)	Zone 3 × <i>DEM</i>	0.072	0.093	0.4376	ns
NPP (Stability)	Zone 4 × <i>DEM</i>	−0.222	0.063	0.0004	***
NPP (Stability)	Zone 5 × <i>DEM</i>	−0.357	0.050	<0.0001	***
NPP (Stability)	Zone 1 × <i>dnat</i>	−0.815	0.451	0.0705	ns
NPP (Stability)	Zone 2 × <i>dnat</i>	2.270	0.197	<0.0001	***
NPP (Stability)	Zone 3 × <i>dnat</i>	0.820	0.101	<0.0001	***
NPP (Stability)	Zone 4 × <i>dnat</i>	0.103	0.054	0.0552	ns
NPP (Stability)	Zone 5 × <i>dnat</i>	−0.231	0.036	<0.0001	***
FVC (State)	Intercept	−0.019	0.013	0.1539	ns
FVC (State)	Zone 1 (PA)	0.313	0.348	0.3691	ns
FVC (State)	Zone 2 (0–5 km)	0.112	0.174	0.5199	ns
FVC (State)	Zone 3 (5–10 km)	0.308	0.113	0.0065	**
FVC (State)	Zone 4 (10–15 km)	0.255	0.087	0.0035	**
FVC (State)	Zone 5 (15–20 km)	0.302	0.080	0.0002	***
FVC (State)	ln(Distance to national PA + 1)	−0.070	0.008	<0.0001	***
FVC (State)	ln(Distance to local PA + 1)	0.066	0.008	<0.0001	***
FVC (State)	DEM	−0.719	0.010	<0.0001	***
FVC (State)	Slope	0.082	0.005	<0.0001	***
FVC (State)	Temperature trend	0.003	0.004	0.5006	ns
FVC (State)	Temperature stability	−0.062	0.005	<0.0001	***
FVC (State)	Precipitation trend	−0.055	0.011	<0.0001	***
FVC (State)	Precipitation stability	0.071	0.014	<0.0001	***
FVC (State)	Zone 1 × <i>DEM</i>	0.419	0.145	0.0038	**
FVC (State)	Zone 2 × <i>DEM</i>	0.413	0.094	<0.0001	***
FVC (State)	Zone 3 × <i>DEM</i>	0.580	0.099	<0.0001	***
FVC (State)	Zone 4 × <i>DEM</i>	0.357	0.069	<0.0001	***
FVC (State)	Zone 5 × <i>DEM</i>	0.371	0.056	<0.0001	***
FVC (State)	Zone 1 × <i>dnat</i>	0.012	0.490	0.9801	ns
FVC (State)	Zone 2 × <i>dnat</i>	−0.280	0.215	0.1918	ns
FVC (State)	Zone 3 × <i>dnat</i>	−0.111	0.108	0.3027	ns
FVC (State)	Zone 4 × <i>dnat</i>	−0.059	0.058	0.3146	ns

FVC (State)	Zone 5 × <i>dnat</i>	−0.094	0.040	0.0171	*
FVC (Trend)	Intercept	0.012	0.009	0.1958	ns
FVC (Trend)	Zone 1 (PA)	−0.265	0.369	0.4731	ns
FVC (Trend)	Zone 2 (0–5 km)	−0.087	0.176	0.6219	ns
FVC (Trend)	Zone 3 (5–10 km)	−0.199	0.095	0.0366	*
FVC (Trend)	Zone 4 (10–15 km)	−0.087	0.066	0.1914	ns
FVC (Trend)	Zone 5 (15–20 km)	−0.138	0.058	0.0165	*
FVC (Trend)	ln(Distance to national PA + 1)	−0.041	0.008	<0.0001	***
FVC (Trend)	ln(Distance to local PA + 1)	0.035	0.008	<0.0001	***
FVC (Trend)	DEM	0.332	0.010	<0.0001	***
FVC (Trend)	Slope	0.028	0.006	<0.0001	***
FVC (Trend)	Temperature trend	0.009	0.005	0.0851	ns
FVC (Trend)	Temperature stability	0.020	0.006	0.0020	**
FVC (Trend)	Precipitation trend	−0.048	0.012	<0.0001	***
FVC (Trend)	Precipitation stability	−0.117	0.011	<0.0001	***
FVC (Trend)	Zone 1 × <i>DEM</i>	−0.062	0.169	0.7119	ns
FVC (Trend)	Zone 2 × <i>DEM</i>	−0.233	0.104	0.0252	*
FVC (Trend)	Zone 3 × <i>DEM</i>	−0.275	0.106	0.0097	**
FVC (Trend)	Zone 4 × <i>DEM</i>	−0.016	0.080	0.8383	ns
FVC (Trend)	Zone 5 × <i>DEM</i>	−0.117	0.065	0.0736	ns
FVC (Trend)	Zone 1 × <i>dnat</i>	−0.085	0.547	0.8761	ns
FVC (Trend)	Zone 2 × <i>dnat</i>	0.173	0.242	0.4744	ns
FVC (Trend)	Zone 3 × <i>dnat</i>	0.065	0.116	0.5730	ns
FVC (Trend)	Zone 4 × <i>dnat</i>	0.008	0.066	0.9056	ns
FVC (Trend)	Zone 5 × <i>dnat</i>	0.063	0.045	0.1593	ns
FVC (Stability)	Intercept	−0.003	0.010	0.8050	ns
FVC (Stability)	Zone1 (PA)	−0.845	0.383	0.0273	*
FVC (Stability)	Zone 2 (0–5 km)	−0.051	0.183	0.7829	ns
FVC (Stability)	Zone 3 (5–10 km)	−0.290	0.103	0.0049	**
FVC (Stability)	Zone 4 (10–15 km)	−0.298	0.073	<0.0001	***
FVC (Stability)	Zone 5 (15–20 km)	−0.140	0.064	0.0293	*
FVC (Stability)	ln(Distance to national PA + 1)	−0.084	0.008	<0.0001	***
FVC (Stability)	ln(Distance to local PA + 1)	−0.037	0.008	<0.0001	***
FVC (Stability)	<i>DEM</i>	−0.368	0.011	<0.0001	***
FVC (Stability)	Slope	0.018	0.006	0.0032	**
FVC (Stability)	Temperature trend	0.047	0.005	<0.0001	***
FVC (Stability)	Temperature stability	0.011	0.007	0.1068	ns
FVC (Stability)	Precipitation trend	−0.144	0.012	<0.0001	***
FVC (Stability)	Precipitation stability	0.083	0.012	<0.0001	***
FVC (Stability)	Zone 1 × <i>DEM</i>	−0.448	0.172	0.0092	**
FVC (Stability)	Zone 2 × <i>DEM</i>	−0.832	0.108	<0.0001	***
FVC (Stability)	Zone 3 × <i>DEM</i>	−0.701	0.111	<0.0001	***
FVC (Stability)	Zone 4 × <i>DEM</i>	−0.839	0.082	<0.0001	***
FVC (Stability)	Zone 5 × <i>DEM</i>	−0.606	0.066	<0.0001	***
FVC (Stability)	Zone 1 × <i>dnat</i>	−1.096	0.564	0.0517	ns
FVC (Stability)	Zone 2 × <i>dnat</i>	0.119	0.248	0.6321	ns
FVC (Stability)	Zone 3 × <i>dnat</i>	−0.343	0.120	0.0044	**
FVC (Stability)	Zone 4 × <i>dnat</i>	−0.361	0.067	<0.0001	***
FVC (Stability)	Zone 5 × <i>dnat</i>	−0.133	0.046	0.0040	**
EII (State)	Intercept	−0.030	0.012	0.0150	*
EII (State)	Zone 1 (PA)	1.232	0.293	<0.0001	***

EII (State)	Zone 2 (0–5 km)	−1.836	0.149	<0.0001	***
EII (State)	Zone 3 (5–10 km)	−0.378	0.103	0.0002	***
EII (State)	Zone 4 (10–15 km)	0.167	0.082	0.0410	*
EII (State)	Zone 5 (15–20 km)	0.329	0.075	<0.0001	***
EII (State)	ln(Distance to national PA + 1)	−0.129	0.007	<0.0001	***
EII (State)	ln(Distance to local PA + 1)	−0.097	0.006	<0.0001	***
EII (State)	DEM	0.717	0.008	<0.0001	***
EII (State)	Slope	0.148	0.004	<0.0001	***
EII (State)	Temperature trend	0.002	0.004	0.5153	ns
EII (State)	Temperature stability	0.016	0.004	0.0005	***
EII (State)	Precipitation trend	0.334	0.009	<0.0001	***
EII (State)	Precipitation stability	0.106	0.013	<0.0001	***
EII (State)	Zone 1 × DEM	−1.036	0.118	<0.0001	***
EII (State)	Zone 2 × DEM	−0.975	0.078	<0.0001	***
EII (State)	Zone 3 × DEM	−0.386	0.082	<0.0001	***
EII (State)	Zone 4 × DEM	0.110	0.056	0.0513	ns
EII (State)	Zone 5 × DEM	0.181	0.045	<0.0001	***
EII (State)	Zone 1 × dnat	0.746	0.402	0.0633	ns
EII (State)	Zone 2 × dnat	−3.165	0.176	<0.0001	***
EII (State)	Zone 3 × dnat	−1.256	0.089	<0.0001	***
EII (State)	Zone 4 × dnat	−0.401	0.048	<0.0001	***
EII (State)	Zone 5 × dnat	−0.142	0.032	<0.0001	***
EII (Trend)	Intercept	−0.011	0.015	0.4548	ns
EII (Trend)	Zone 1 (PA)	0.066	0.367	0.8571	ns
EII (Trend)	Zone 2 (0–5 km)	0.574	0.185	0.0019	**
EII (Trend)	Zone 3 (5–10 km)	−0.003	0.124	0.9822	ns
EII (Trend)	Zone 4 (10–15 km)	0.170	0.097	0.0794	ns
EII (Trend)	Zone 5 (15–20 km)	0.097	0.089	0.2778	ns
EII (Trend)	ln(Distance to national PA + 1)	−0.152	0.008	<0.0001	***
EII (Trend)	ln(Distance to local PA + 1)	−0.027	0.008	0.0006	***
EII (Trend)	DEM	0.195	0.010	<0.0001	***
EII (Trend)	Slope	0.131	0.005	<0.0001	***
EII (Trend)	Temperature trend	−0.006	0.005	0.1691	ns
EII (Trend)	Temperature stability	0.028	0.006	<0.0001	***
EII (Trend)	Precipitation trend	0.104	0.012	<0.0001	***
EII (Trend)	Precipitation stability	0.046	0.015	0.0026	**
EII (Trend)	Zone 1 × DEM	−0.354	0.150	0.0184	*
EII (Trend)	Zone 2 × DEM	−0.305	0.099	0.0020	**
EII (Trend)	Zone 3 × DEM	0.173	0.104	0.0960	ns
EII (Trend)	Zone 4 × DEM	0.622	0.072	<0.0001	***
EII (Trend)	Zone 5 × DEM	0.149	0.058	0.0099	**
EII (Trend)	Zone 1 × dnat	−0.083	0.511	0.8708	ns
EII (Trend)	Zone 2 × dnat	0.483	0.224	0.0311	*
EII (Trend)	Zone 3 × dnat	−0.482	0.113	<0.0001	***
EII (Trend)	Zone 4 × dnat	−0.081	0.061	0.1841	ns
EII (Trend)	Zone 5 × dnat	−0.209	0.041	<0.0001	***
EII (Stability)	Intercept	−0.003	0.015	0.8484	ns
EII (Stability)	Zone1 (PA)	1.690	0.356	<0.0001	***
EII (Stability)	Zone2 (0–5 km)	−1.913	0.182	<0.0001	***
EII (Stability)	Zone3 (5–10 km)	−0.266	0.127	0.0359	*
EII (Stability)	Zone4 (10–15 km)	−0.168	0.101	0.0958	ns

EII (Stability)	Zone5 (15–20 km)	−0.254	0.093	0.0064	**
EII (Stability)	ln(Distance to national PA + 1)	−0.086	0.008	<0.0001	***
EII (Stability)	ln(Distance to local PA + 1)	−0.138	0.008	<0.0001	***
EII (Stability)	DEM	0.578	0.010	<0.0001	***
EII (Stability)	Slope	−0.018	0.005	0.0006	***
EII (Stability)	Temperature trend	0.008	0.004	0.0695	ns
EII (Stability)	Temperature stability	0.032	0.005	<0.0001	***
EII (Stability)	Precipitation trend	0.167	0.011	<0.0001	***
EII (Stability)	Precipitation stability	−0.163	0.015	<0.0001	***
EII (Stability)	Zone 1 × DEM	−1.335	0.142	<0.0001	***
EII (Stability)	Zone 2 × DEM	−0.773	0.094	<0.0001	***
EII (Stability)	Zone 3 × DEM	−0.088	0.099	0.3735	ns
EII (Stability)	Zone 4 × DEM	−0.159	0.068	0.0199	*
EII (Stability)	Zone 5 × DEM	−0.299	0.055	<0.0001	***
EII (Stability)	Zone 1 × <i>dnat</i>	1.322	0.486	0.0065	**
EII (Stability)	Zone 2 × <i>dnat</i>	−2.804	0.213	<0.0001	***
EII (Stability)	Zone 3 × <i>dnat</i>	−0.757	0.108	<0.0001	***
EII (Stability)	Zone 4 × <i>dnat</i>	−0.188	0.058	0.0012	**
EII (Stability)	Zone 5 × <i>dnat</i>	−0.039	0.039	0.3226	ns

SE = standard error; Sig. = significance level (*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, ns = not significant).

Reference category for Zone is Zone 6 (peripheral reference area, 20–100 km).

Appendix B.2.

Table A2. Pairwise comparisons between Zone 1–Zone 5 and peripheral reference area Zone 6 (Holm-corrected *p*-values).

Model	Zone	Estimate	SE	z-Ratio	<i>p</i> -Value (Holm)
NPP (State)	Zone 1 (PA)	0.990	0.276	−3.582	0.0040
NPP (State)	Zone 2 (0–5 km)	0.584	0.163	−3.589	0.0040
NPP (State)	Zone 3 (5–10 km)	0.869	0.139	−6.237	<0.0001
NPP (State)	Zone 4 (10–15 km)	0.744	0.122	−6.089	<0.0001
NPP (State)	Zone 5 (15–20 km)	0.686	0.115	−5.964	<0.0001
NPP (Trend)	Zone 1 (PA)	0.215	0.311	−0.692	1.0000
NPP (Trend)	Zone 2 (0–5 km)	−0.409	0.158	2.587	0.1356
NPP (Trend)	Zone 3 (5–10 km)	−0.313	0.109	2.883	0.0590
NPP (Trend)	Zone 4 (10–15 km)	−0.187	0.086	2.171	0.3895
NPP (Trend)	Zone 5 (15–20 km)	−0.065	0.079	0.816	1.0000
NPP (Stability)	Zone 1 (PA)	−0.878	0.378	2.323	0.0808
NPP (Stability)	Zone 2 (0–5 km)	1.688	0.210	−8.021	<0.0001
NPP (Stability)	Zone 3 (5–10 km)	0.849	0.169	−5.023	<0.0001
NPP (Stability)	Zone 4 (10–15 km)	0.305	0.144	−2.114	0.1035
NPP (Stability)	Zone 5 (15–20 km)	0.206	0.135	−1.523	0.2557
FVC (State)	Zone 1 (PA)	0.313	0.348	−0.898	1.0000
FVC (State)	Zone 2 (0–5 km)	0.112	0.174	−0.644	1.0000
FVC (State)	Zone 3 (5–10 km)	0.308	0.113	−2.723	0.0841
FVC (State)	Zone 4 (10–15 km)	0.255	0.087	−2.924	0.0484
FVC (State)	Zone 5 (15–20 km)	0.302	0.080	−3.799	0.0022
FVC (Trend)	Zone 1 (PA)	−0.265	0.369	0.717	1.0000
FVC (Trend)	Zone 2 (0–5 km)	−0.087	0.176	0.493	1.0000
FVC (Trend)	Zone 3 (5–10 km)	−0.199	0.095	2.091	0.5115
FVC (Trend)	Zone 4 (10–15 km)	−0.087	0.066	1.307	1.0000
FVC (Trend)	Zone 5 (15–20 km)	−0.138	0.058	2.401	0.2452
FVC (Stability)	Zone 1 (PA)	−0.845	0.383	2.207	0.3551
FVC (Stability)	Zone 2 (0–5 km)	−0.051	0.183	0.276	1.0000
FVC (Stability)	Zone 3 (5–10 km)	−0.290	0.103	2.818	0.0677
FVC (Stability)	Zone 4 (10–15 km)	−0.298	0.073	4.096	0.0006
FVC (Stability)	Zone 5 (15–20 km)	−0.140	0.064	2.181	0.3551
EII (State)	Zone 1 (PA)	1.232	0.293	−4.206	0.0002
EII (State)	Zone 2 (0–5 km)	−1.836	0.149	12.301	<0.0001
EII (State)	Zone 3 (5–10 km)	−0.378	0.103	3.684	0.0011
EII (State)	Zone 4 (10–15 km)	0.167	0.082	−2.045	0.0817
EII (State)	Zone 5 (15–20 km)	0.329	0.075	−4.385	<0.0001
EII (Trend)	Zone 1 (PA)	0.066	0.367	−0.180	1.0000
EII (Trend)	Zone 2 (0–5 km)	0.574	0.185	−3.100	0.0290
EII (Trend)	Zone 3 (5–10 km)	−0.003	0.124	0.022	1.0000
EII (Trend)	Zone 4 (10–15 km)	0.170	0.097	−1.755	0.8718
EII (Trend)	Zone 5 (15–20 km)	0.097	0.089	−1.086	1.0000
EII (Stability)	Zone 1 (PA)	1.690	0.356	−4.746	<0.0001
EII (Stability)	Zone 2 (0–5 km)	−1.913	0.182	10.499	<0.0001
EII (Stability)	Zone 3 (5–10 km)	−0.266	0.127	2.099	0.1789
EII (Stability)	Zone 4 (10–15 km)	−0.168	0.101	1.667	0.3823
EII (Stability)	Zone 5 (15–20 km)	−0.254	0.093	2.732	0.0377

SE = standard error; Holm correction applied for multiple comparisons. Reference category for Zone is Zone 6 (peripheral reference area, 20–100 km). Negative estimates indicate higher values in Zone 6 compared to the respective zone.

Appendix B.3

Table A3. Likelihood ratio test results comparing random slope models versus random intercept models.

Model	χ^2	df	<i>p</i> -Value	Convergence	Selected Model
NPP (State)	5.12	5	0.402	Converged	Random Intercept
NPP (Trend)	4.89	5	0.431	Converged	Random Intercept
NPP (Stability)	6.78	5	0.237	Converged	Random Intercept
FVC (State)	5.45	5	0.363	Singular fit	Random Intercept
FVC (Trend)	4.32	5	0.501	Singular fit	Random Intercept
FVC (Stability)	4.87	5	0.433	Singular fit	Random Intercept
EII (State)	5.67	5	0.341	Singular fit	Random Intercept
EII (Trend)	5.23	5	0.388	Singular fit	Random Intercept
EII (Stability)	6.15	5	0.291	Converged	Random Intercept

Random slope models included Zone|BlockID as random slopes. All *p*-values > 0.05 indicate no significant improvement in model fit when adding random slopes. “Singular fit” indicates Hessian non-positive definite, suggesting overparameterization. Based on these results, random intercept structure was adopted for all final models.

Appendix B.4

Among the candidate interaction terms, zone $\times$ DEM and zone $\times$ *dnat* yielded the lowest AICc values for five and three response variables, respectively, indicating that these two interactions exhibited relatively strong and consistent zone-specific moderating effects. In contrast, Zone $\times$ *dloc* was selected as the best-supported term for only one response variable, suggesting limited generality of its effect, whereas Zone $\times$ Slope was not supported as the optimal term for any response variable, indicating a relatively minor interactive contribution. Therefore, based on AICc support and the principle of model parsimony, Zone $\times$ DEM and Zone $\times$ *dnat* were retained as interaction terms in the final LMMs.

Table A4. Comparison of AICc values among candidate models for different response variables.

Response	Model	df	AICc	Delta
NPP (State)	DEM	21	45,883.8557	0
NPP (State)	<i>dloc</i>	21	45,959.0637	75.2079
NPP (State)	Slope	21	46,360.0984	476.2426
NPP (State)	<i>dnat</i>	21	46,361.3920	477.5363
NPP (State)	base	16	46,398.7294	514.8737
NPP (Trend)	<i>dloc</i>	21	73,327.5132	0
NPP (Trend)	DEM	21	73,344.9519	17.4387
NPP (Trend)	Slope	21	73,397.1478	69.6345
NPP (Trend)	<i>dnat</i>	21	73,397.5878	70.0745
NPP (Trend)	base	16	73,456.0418	128.5286
NPP (Stability)	<i>dnat</i>	21	77,196.5678	0
NPP (Stability)	DEM	21	77,350.4862	153.9184
NPP (Stability)	Slope	21	77,428.0303	231.4625
NPP (Stability)	base	16	77,456.0575	259.4897
NPP (Stability)	<i>dloc</i>	21	77,458.0458	261.4780

FVC (State)	DEM	21	83,446.8714	0
FVC (State)	<i>dnat</i>	21	83,565.6236	118.7522
FVC (State)	base	16	83,614.6411	167.7697
FVC (State)	Slope	21	83,615.9214	169.0410
FVC (State)	<i>dloc</i>	21	83,616.2087	169.3373
FVC (Trend)	DEM	21	94,798.5802	0
FVC (Trend)	base	16	94,809.0648	10.4847
FVC (Trend)	<i>dnat</i>	21	94,810.5155	11.9353
FVC (Trend)	<i>dloc</i>	21	94,812.6943	14.1141
FVC (Trend)	Slope	21	94,814.4585	15.8784
FVC (Stability)	DEM	21	95,937.632	0
FVC (Stability)	Slope	21	96,115.4616	177.8296
FVC (Stability)	<i>dloc</i>	21	96,129.0678	191.4358
FVC (Stability)	base	16	96,171.7756	234.1436
FVC (Stability)	<i>dnat</i>	21	96,174.8865	237.2545
EII (State)	<i>dnat</i>	21	69,102.9049	0
EII (State)	DEM	21	69,423.8147	320.9098
EII (State)	<i>dloc</i>	21	69,466.7867	363.8818
EII (State)	Slope	21	69,597.2647	494.3598
EII (State)	base	16	69,654.6422	551.7373
EII (Trend)	DEM	21	86,265.3598	0
EII (Trend)	<i>dnat</i>	21	86,315.1516	49.7918
EII (Trend)	<i>dloc</i>	21	86,324.2812	58.9214
EII (Trend)	Slope	21	86,363.4229	98.0631
EII (Trend)	base	16	86,419.5483	154.1885
EII (Stability)	<i>dnat</i>	21	82,619.2208	0
EII (Stability)	DEM	21	82,670.5237	51.3029
EII (Stability)	<i>dloc</i>	21	82,712.0327	92.8119
EII (Stability)	Slope	21	82,777.2168	157.9961
EII (Stability)	base	16	82,827.7878	208.5670

Response denotes the response variable. Model denotes the candidate model structure. All candidate models included zone as the main effect; environmental covariates included *dnat*, *dloc*, DEM, slope, Temp_trend, Temp_sta, Prcp_trend, and Prcp_sta. Preset interaction terms included *zone* × DEM, *Zone* × Slope, *Zone* × *dnat*, and *zone* × *dloc*. Models were compared using the corrected Akaike Information Criterion (AICc), where lower AICc values indicate better model support. ΔAICc represents the difference between the AICc value of a given model and that of the best-supported model for the same response variable.

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