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ORIGINAL RESEARCH

Effect of landscape diversity on temporal stability of Normalized Difference Vegetation Index across spatial scales

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Abstract

Understanding how landscape diversity (i.e., land-cover heterogeneity) influences ecosystem stability across spatial scales is critical for predicting ecosystem responses to environmental change and for designing effective landscape-level conservation strategies. This study aims to quantify the scale dependence (ranging from 0.0625 km^2 to 2500 km^2) of landscape diversity effects on multiple dimensions of ecosystem temporal stability, resistance, and resilience in response to climatic events using satellite-derived Normalized Difference Vegetation Index (NDVI) time series from 2000 to 2020 across four major vegetation types (meadows, shrubs, wetlands, and coniferous forests) on the Qinghai-Xizang Plateau. We also calculated temporal stability of growing season temperature and precipitation at matching spatial scales. We found that both landscape diversity and temporal stability of NDVI increased with spatial scales, whereas resistance and resilience showed no consistent scale dependence. The effects of landscape diversity on temporal stability of NDVI varied significantly across spatial scales in all four vegetation types. In alpine wetlands and shrubs, higher landscape diversity was associated with lower precipitation stability, which in turn was linked to reduced temporal stability of NDVI; however, this indirect relationship was reversed in meadows. Our findings demonstrate that precipitation stability modulates the effect of landscape diversity on NDVI temporal stability across spatial scales. This work not only extends diversity-stability theory by incorporating scale-dependent mechanisms and climatic mediators, but also provides novel guidance for landscape-scale conservation and ecosystem management under changing environmental conditions.

Keywords Diversity-stability relationship · Landscape diversity · Ecosystem stability · Scale dependence · Qinghai-Xizang Plateau

Introduction

Global climate change and anthropogenic activities are posing serious risks to ecosystem stability, functioning and biodiversity (Hautier et al. 2015). These stability and functionality are fundamentally influenced by biodiversity (Craven et al. 2018; Tilman et al. 2006). Most previous biodiversity experiments have demonstrated that local taxonomic diversity (species richness) (Tilman et al. 2006), functional diversity (Bello et al. 2021; Hallett et al. 2017), and phylogenetic diversity (Cadotte and Marc 2012) can enhance temporal stability of productivity, defined as the ratio of the mean to the standard deviation of productivity over time (Tilman et al. 2006). However, these studies have largely focused on relatively small spatial scales.

In recent decades, some studies have expanded to explore biodiversity-ecosystem stability relationships across multiple spatial scales. For example, studies have shown that

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biodiversity at various scales can reduce variance in ecosystem functioning (Burley et al. 2016; Pasari et al. 2013; Zavaleta et al. 2010) and enhance ecosystem stability at larger spatial scales (Delsol et al. 2018; Li et al. 2023a; Wang and Loreau 2016; Wisnoski et al. 2023). Despite these advances, a critical gap remains in understanding how landscape diversity, defined as the variation of ecosystem types within a given spatial area (Li et al. 2023b), is distinct from biological diversity but can influence it by providing a variety of habitats, thereby affects ecosystem stability across spatial scales. Landscape diversity is a key driver of ecosystem functioning and services (Gao et al. 2023; Oehri et al. 2020a; Zirbel et al. 2019), as more diverse landscapes often support higher species diversity (O'Farrell et al. 2010; Poggio et al. 2010) and greater ecosystem stability (Nelson et al. 2022; Oehri et al. 2020b). However, whether the effects of landscape diversity on stability are scale-dependent remains controversial (Oehri et al. 2020b; Wang et al. 2017). Understanding this scale dependence is critical for ecosystem management, which often operates at landscape levels beyond local scales.

In addition to biodiversity, abiotic factors such as climate factors, soil type, slope, and aspect also contribute significantly to stability by influencing resource availability, environmental heterogeneity, and disturbance regimes (García-Palacios et al. 2018; White et al. 2022; Wang et al.2025). Climate change is the most important mediator at landscape levels, which modulates ecosystem stability through both direct and indirect pathways (Bai et al. 2004; García-Palacios et al. 2018; Ren et al. 2023; Zhang et al. 2018). For instance, climate stability, particularly precipitation stability, is a direct determinant of vegetation productivity (Craine et al. 2012; Cuo et al. 2021; Sloat et al. 2018) and ecosystem stability (Bai et al. 2004; Gao et al. 2023; Gherardi and Sala 2015). Variability in growing-season precipitation and temperature can reduce ecosystem stability by diminishing species richness and asynchrony (Bai et al. 2004; Zhang et al. 2018). Research has also demonstrated that on the Qinghai-Xizang Plateau, temperature serves as the primary driver of grassland ecosystem stability, whereas precipitation acts as the dominant factor governing the stability of forest and shrub ecosystems (Wang et al. 2020). Yet, it remains unclear how climate variability interacts with landscape diversity to influence ecosystem stability among vegetation types across spatial scales.

Ecological stability is a multi-faceted concept that includes temporal stability (constancy of ecosystem function over time), resistance (ability to withstand disturbance) (Lloret et al. 2007; Van Ruijven and Berendse 2010; Vogel et al. 2012), resilience (speed of recovery after disturbance) (Dakos et al. 2012; Telesca and Lasaponara 2006; Telesca et al. 2008; Zaccarelli et al. 2013), and other dimensions (Donohue et al. 2016; Grimm and Wissel 1997; Pimm 1984). However, most studies have focused on temporal stability at small scales. Furthermore, trade-offs between stability components (e.g. resistance vs. resilience) mean that no single metric fully captures ecosystem stability (Chen et al. 2023; Clark et al. 2021; Donohue et al. 2013; Hillebrand et al. 2018). Remote sensing provides a powerful tool to quantify multidimensional stability at landscape scales (De Keersmaecker et al. 2014; Kang et al. 2022; White et al. 2020), but whether these stability metrics are scale-dependent remains largely unexplored.

This study aims to address these gaps by integrating remote sensing and climate data to investigate the scale dependence of landscape diversity effects on ecosystem stability. We quantified landscape diversity, temporal stability, resistance, and resilience of NDVI across 10 spatial scales (0.0625–2500 km^2) in four vegetation types on the Qinghai-Xizang Plateau. We hypothesized that: (1) Metrics of landscape diversity and ecosystem stability are scale-dependent; (2) Relationships between landscape diversity and ecosystem stability strengthen with spatial scale; (3) Climate stability (precipitation and temperature) modulates the diversity-stability relationship across scales. Our findings provide novel insights into scale-dependent stability mechanisms and practical guidance for landscape-scale conservation under climate change.

Methods and materials

Overview of the study area

The study area is located in the Qinghai-Xizang Plateau, in China, which stretches from the Pamir Plateau in the west to the Hengduan Mountains in the east (Fig. 1). Its total area is approximately 2.5 million square kilometers, and it is bordered to the north by the Kunlun, the Altun and the Qilian Mountains, and to the south by the Himalayas. The region is characterized by strong solar radiation, low temperature, and shorter growing season, while also has species-rich vegetation types, such as alpine wetlands, meadows and forests. In alpine meadows, dominant species include grasses and sedges such as *Kobresia humilis, K. pygmaea, and K. capillifolia*. In alpine wetlands, dominant species are sedges and reeds including *Carex multensis, Phragmites australis*, and *Carex miyabei*. Alpine shrubs are dominated by deciduous shrubs such as *Salix vaccinioides, Sibiraea angustata, and Rhododendron fastigiatum*. Coniferous forests are dominated by evergreen conifers including *Tsuga dumosa, Pinus densata,* and *Abies delavayi* (Table S1).

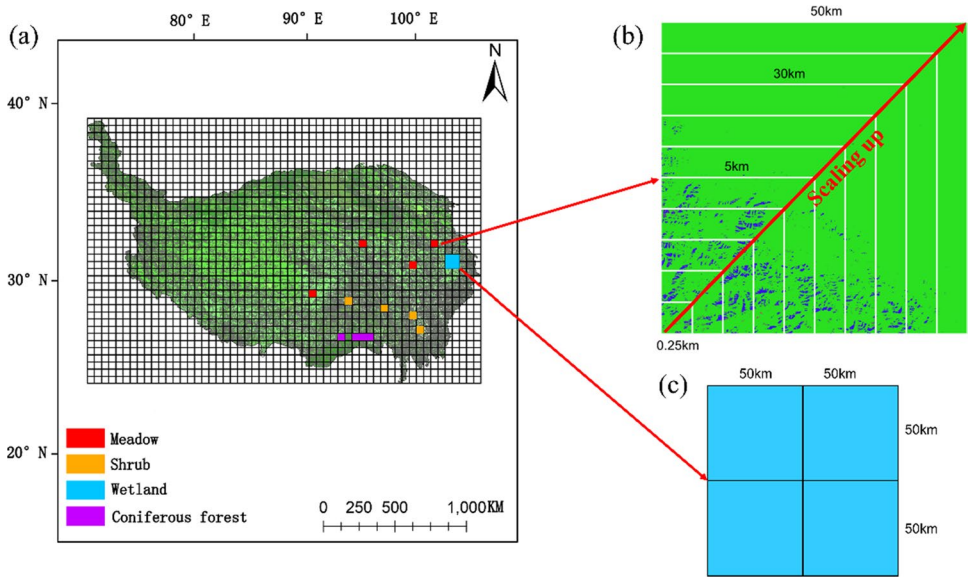

Fig. 1 Location of the study area and experimental design. **a** Location of the study area (Red represents meadow plots, yellow represents shrub plots, blue represents wetland plots, and purple represents coniferous forest plots. Total number of plots = 4*4); **b** Sampling plots with increasing scale (Area: 0.0625 km^2 ~ 2500 km^2); **c** Enlarged view of the 4 wetland plots

Experimental design

According to the vegetation map of the People's Republic of China (1:1 000 000), four typical dominant vegetation types on the Qinghai-Xizang Plateau were selected: meadow, shrub, wetland and coniferous forest. The environmental conditions of each vegetation type are shown in Table S1. Four 50 *50 km plots were established in each vegetation type, with a total of 16 plots. Each plot was firstly divided into 40,000 squares of 250 m*250 m; and then divided into 10 nested scales from the lower left corner of the plot, denoted as scale 1- scale 10. Scale1 contains 1 square, scale 2 contains 4 squares, scale 3 contains 16 squares and so on. Area of scale 1-scale 10 ranged from 0.0625 km^2 to 2500 km^2 (Fig. 1).

Data acquisition

The land use type maps were cropped by ArcGIS software (https://www.esri.com) to obtain raster maps at each scale (10 scales) for each plot (16 plots) in the study area. The 30 m land use data from 2000–2020 were obtained from the dataset developed by Wuhan University (https://zenodo.org/record/5210928#.Y2dDTctByUk).

NDVI was selected over EVI due to its longer historical record, wider application in stability studies (De Keersmaecker et al. 2014; Wang et al. 2017), and better performance in capturing vegetation dynamics in alpine ecosystems where vegetation cover is often sparse or moderate (Huete et al. 2002). We used the MOD13Q1 NDVI product, which includes a quality assurance (QA) band to filter out low-quality pixels (e.g. those affected by clouds, aerosols, or snow). We applied the QA band to mask out unreliable pixels and used a Savitzky–Golay filter to smooth the time series and further reduce noise (Chen et al. 2004). Only high-quality pixels were retained for analysis. NDVI data was obtained through Google Earth Engine (GEE) (https://code.earthengine.google.com). By uploading the vector maps of each scale of each parcel to GEE, selecting the MODIS satellite dataset (https://doi.org/10.5067/MODIS/MOD13Q1.061), then calculating the NDVI data of each scale of each parcel from 2000 to 2020, and the NDVI data at each scale for each parcel were obtained from the MOD13Q1 product with a spatial resolution of 250 m × 250 m and a temporal resolution of 16 days (23 times per year). For each spatial scale, we averaged NDVI values across all pixels within the scale-defined area for each time point (16-day intervals). This produced one NDVI value per scale per time step, which was then used to compute temporal stability, resistance, and resilience.

The 1 km-resolution monthly precipitation and temperature datasets from 2000 to 2020 were obtained from the National Tibetan Plateau Data Center (https://www.tpdc.ac.cn) (Peng 2019, 2020). The datasets were obtained with a spatial resolution of 0.0083333° (about 1 km). All time series data covered the period 2000–2020 (Peng 2019, 2020).

Landscape diversity and stability calculation

Landscape diversity calculation

We used the Shannon Wiener Index (SHDI) to quantify landscape diversity based on land-cover types (e.g. forest, grassland, wetland) derived from 30 m resolution land-use data (Li et al. 2023b). SHDI was calculated using FragStats software with the following formula.

$$SHDI = -\sum_{i=1}^{n} P_i lnP_i$$

where p_i is the proportion of the landscape occupied by land-cover type i derived from 30 m resolution land-use maps. We used annual land-cover compositions (not NDVI values) aggregated at each spatial scale. This metric captures the heterogeneity of ecosystem types within a landscape. In summary, after obtaining the raster maps, FragStats software was used to calculate the landscape diversity index of each plot at each scale. SHDI is sensitive to the non-equilibrium distribution status of patchwork types in the landscape and reflects the heterogeneity of the landscape, i.e., it emphasizes the contribution of rare patchwork types to information, which is different from other diversity indices. The richer the land use and the higher the degree of fragmentation in a landscape system, the greater information content of its characterization and the higher the calculated SHDI value.

Temporal stability of NDVI

For each spatial scale, we calculated mean NDVI values by averaging all high-quality pixels within the scale-defined area for each time step. This produced one NDVI value per scale per time point, which was then used to compute stability metrics. Temporal stability of NDVI was calculated as the ratio of the mean to the standard deviation of NDVI across years (2000–2020), representing interannual variability.

Resistance and resilience calculation

The specific formula for calculating resistance and resilience is as follows (Isbell et al. 2015):

$$\text{Resistance}: \Omega = \frac{\overline{Yn}}{\left|Ye - \overline{Yn}\right|},$$

$$\text{Resilience}: \Delta = \left|\frac{Ye - \overline{Yn}}{Y_{e+1} - \overline{Yn}}\right|,$$

We used NDVI as a proxy for productivity, thus, $\overline{Y_n}$ represents mean NDVI in non-event years, Y_e is NDVI during a climate event, and Y_{e+1} is NDVI in the year following the event.

As suggested by Isbell et al. (2015), the Standardized Precipitation-Evapotranspiration Index (SPEI-12) was calculated monthly based on the local monthly meteorological data from January 2000 to December 2020, and the climatic events in our experimental area were classified into seven types: extremely dry, severely dry, moderately dry, normal, moderately wet, severely wet, and extremely wet. SPEI is calculated in the R package SPEI (http://cran.r-project.org/web/packages/SPEI). We used SPEI-12 values in August of each year to identify climatic events during the growing season (June–August). The SPEI-12 value in August integrates moisture conditions over the preceding 12 months, including the current growing season, providing a robust indicator of accumulated water deficit/surplus that can impact vegetation, particularly in the critical late growing season on the Qinghai-Xizang Plateau. The SPEI data had a spatial resolution of 0.5° (approximately 50 km at the equator), obtained from the Global SPEI database (Vicente-Serrano et al. 2010).

The SPEI classification is shown in Table 1.

Temporal stability of temperature and precipitation

By using the ArcGIS software "Multi-value Extraction to Points" function, we extracted all available data points (center point) within each spatial unit (0.25*0.25 km) in each scale, then calculated an average value in each scale. For example, Scale 1 contains a 0.25*0.25 km square, Scale 2 contains 4 squares of 0.25*0.25 km, and so on, up to the largest scale of 50*50 km, which contains 40,000 squares of 0.25*0.25 km. We extracted climate data for the center of each 0.25*0.25 km square, and then obtained the average meteorological data for each scale by averaging the climate data of all the 0.25*0.25 km square centers. This method is common in landscape ecology studies to capture full spatial variability (Li et al. 2023b), and it aligns with our goal of examining scale-dependent effects. We then derived average annual growing season temperature and annual growing season precipitation, and then assessed growing season precipitation stability (P stability) and temperature stability (T stability) as the inverse of the coefficient of variation (CV) of precipitation and temperature at growing season, over the study period, respectively.

Statistical analysis

We performed linear regression to explore the effects of spatial scales on landscape diversity (SHDI) and ecosystem

Table 1 Drought classification standard based on SPEI

Classification standard of drought based on Standardized Precipitation-Evapotranspiration Index (SPEI)							
Drought level	Extremely dry	Severely dry	Moderately dry	Normal	Moderately wet	Severely wet	Extremely wet
SPEI	SPEI < − 2.0	− 2.0 ≤ SPEI < − 1.5	− 1.5 ≤ SPEI < − 1	− 1 ≤ SPEI ≤ 1	1 < SPEI ≤ 1.5	1.5 < SPEI ≤ 2	SPEI > 2

stability (Fig. S2-4 and Table S4, 7–9). We also used linear regression models to assess how ecosystem stability changes with landscape diversity, P stability and T stability at different spatial scales (Fig. S5-9 and Table S5-6, 10–13), and we extracted the slopes of these regression models to examine the potential influence of spatial scales on the landscape diversity-stability and climate-NDVI stability. Next, for each vegetation type, we fitted linear regression models and quadratic regression models between the slopes and spatial scales of these models, selecting the optimal model based on the lowest AIC (Akaike information criterion) value using the R package "ggtrendline" (Greenwell and Schubert Kabban 2014; Ritz and Streibig 2008).We also assessed ordinary least squares (OLS) assumptions including multicollinearity (VIF < 3), normality of residuals (Shapiro–Wilk test), and homoscedasticity (Breusch-Pagan test). Where assumptions were violated, we applied log transformations or used robust regression techniques. Spatial autocorrelation was tested using Moran's I (all $p > 0.05$), which was calculated and found to be absent ($p > 0.05$, see Appendix, Table S14-15).

Finally, we employed piecewise structural equation modeling (SEM) (Lefcheck 2016) to evaluate the direct and indirect effects of SHDI, climate stability (precipitation and temperature), resistance and resilience on NDVI stability. We built an initial theoretical model (Fig. S1 and Table S3) and then followed the model simplification process, in which non-significant paths were iteratively removed until only significant paths remained and/or the model fit (i.e., minimization of AIC) was optimal. All analyses were performed using R 4.2.1 (Team 2021).

Results

Landscape diversity, stability of NDVI, resistance and resilience across spatial scales

Landscape diversity significantly increased with sampling spatial scales in three vegetation types (Wetland: $p < 0.001$, $R^2 = 0.49$; Coniferous forest: $p < 0.001$, $R^2 = 0.43$; Shrub: < 0.01, $R^2 = 0.14$), but not in meadows (Fig. 2a). Temporal stability of NDVI showed strong positive scaling relationships across all four vegetation types ($p < 0.05$), with the strongest effect in wetlands ($R^2 = 0.15$) and weakest in coniferous forest ($R^2 = 0.08$) (Fig. 2b). In contrast, neither resistance nor resilience exhibited consistent scale dependence across vegetation types ($p > 0.05$) (Fig. 2c, d).

Landscape diversity-NDVI stability relationships across spatial scales

The strength of diversity-stability relationships varied systematically with spatial scale depending on both vegetation type and stability metric. In meadows, regression slopes

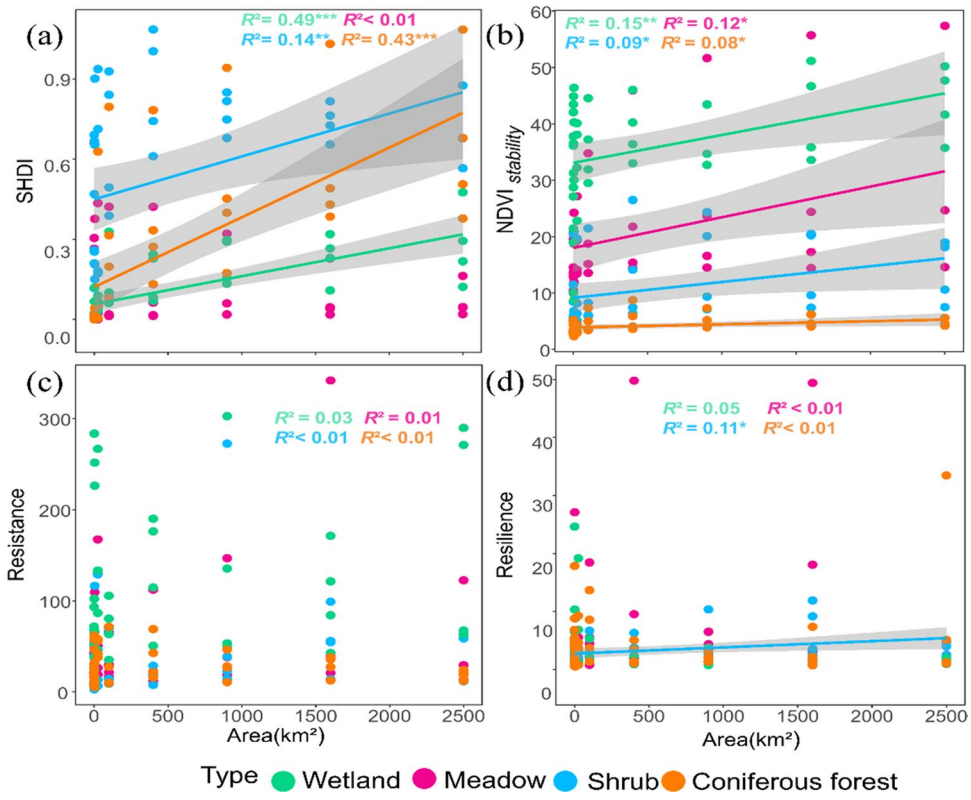

Fig. 2 Landscape diversity (SHDI) (**a**), NDVI temporal stability (**b**), resistance (**c**), and resilience (**d**) in four vegetation types, in relation to sampling area. Note, the Shannon Wiener Index as a measure of landscape diversity (abbreviated as SHDI) in our study. The solid lines are significant, gray areas are 95% confidence intervals. The significance levels for each predictor (figure R-squared is adjusted R-squared) are $*p < 0.05$, $**p < 0.01$, $***p < 0.001$, respectively

between SHDI and both NDVI temporal stability ($R^2 = 0.99$, $p < 0.05$) and resistance ($R^2 = 0.76$, $p < 0.05$) increased with spatial scale (Fig. 3b, f). Shrub communities exhibited non-linear patterns, with SHDI-NDVI stability relationships following a concave curve ($p < 0.05$) while SHDI-resistance and SHDI-resilience relationships showed unimodal patterns across scales (Fig. 3g, k). Wetlands and coniferous forests demonstrated relatively scale-invariant diversity-stability relationships (Fig. 3).

Climate-NDVI stability relationships across spatial scales

Precipitation stability (P stability) exerted stronger impacts on NDVI temporal stability than temperature stability (T stability) across most vegetation types. The strength of P stability-NDVI stability relationships decreased with increasing spatial scale in wetlands ($R^2 = 0.67$, $p < 0.01$), meadows ($R^2 = 0.83$, $p < 0.05$), and shrubs ($R^2 = 0.44$, $p < 0.05$), but remained scale-invariant in coniferous forests (Fig. 4a–c). Temperature stability showed no significant relationships with NDVI stability at any scale or vegetation type.

Direct and indirect drivers of NDVI temporal stability

Structural equation modeling revealed complex pathways of spatial scale's influence on NDVI stability (Fig. 5). Spatial scales directly increased landscape diversity in wetlands (standardized path coefficient = 0.71, $p < 0.001$), shrubs (0.41, $p = 0.009$), and coniferous forests (0.67, $p < 0.001$). Landscape diversity then indirectly affected NDVI stability through precipitation-mediated pathways, but with opposite directions in different vegetation types. Landscape diversity had negative indirect effects on NDVI stability in wetlands and shrubs via reduced precipitation stability, but positive indirect effects in meadows through enhanced precipitation stability.

Resistance consistently emerged as the strongest direct predictor of NDVI temporal stability across vegetation

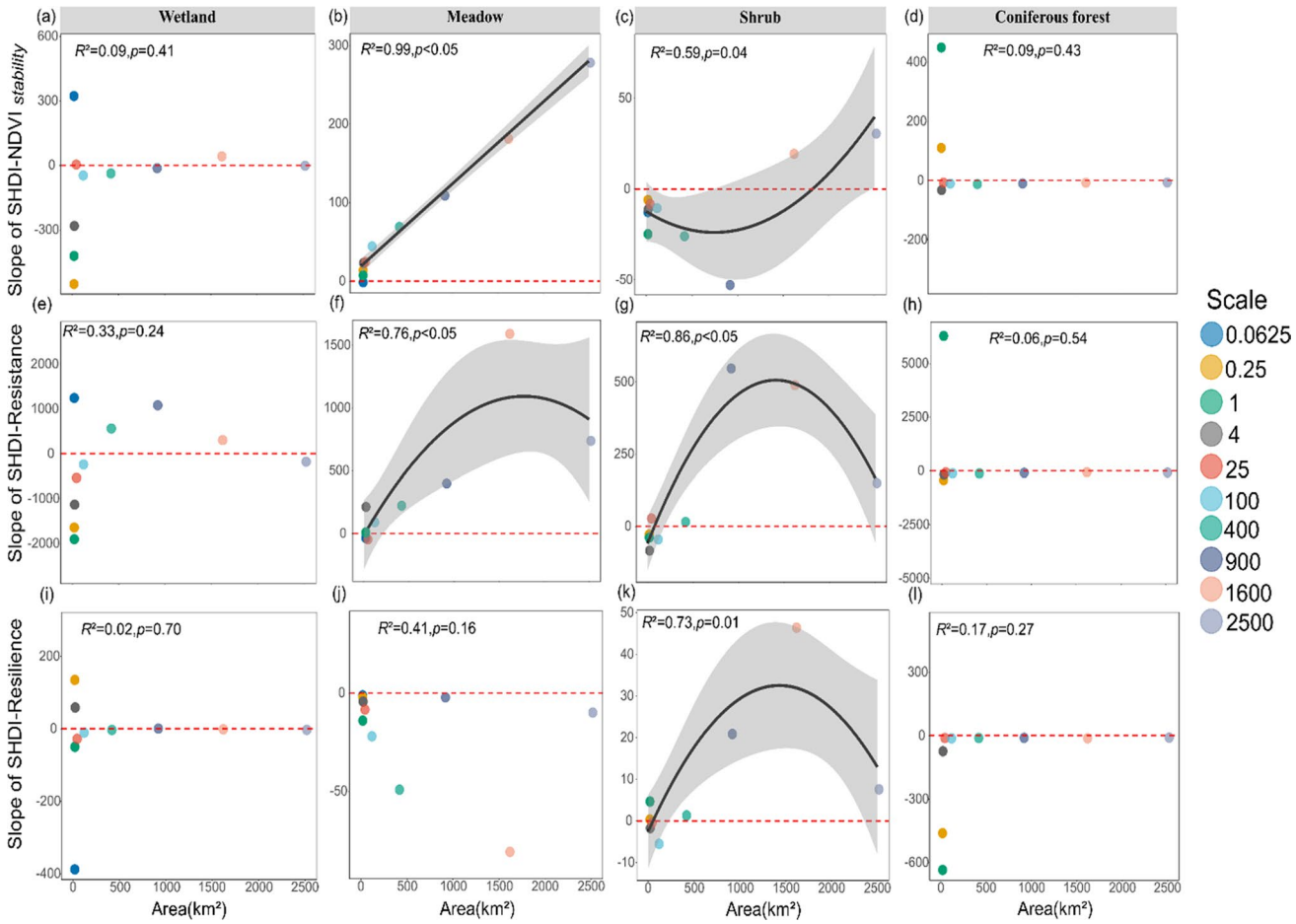

Fig. 3 Effects of SHDI on ecosystem temporal stability including NDVI, resistance and resilience across multiple spatial scales. **a** Meadows, **b** Shrubs, **c** Wetlands, and d Coniferous forests. The solid lines are significant, gray areas are 95% confidence intervals. The significance levels for each predictor are $*p < 0.05$, $**p < 0.01$, $***p < 0.001$, respectively

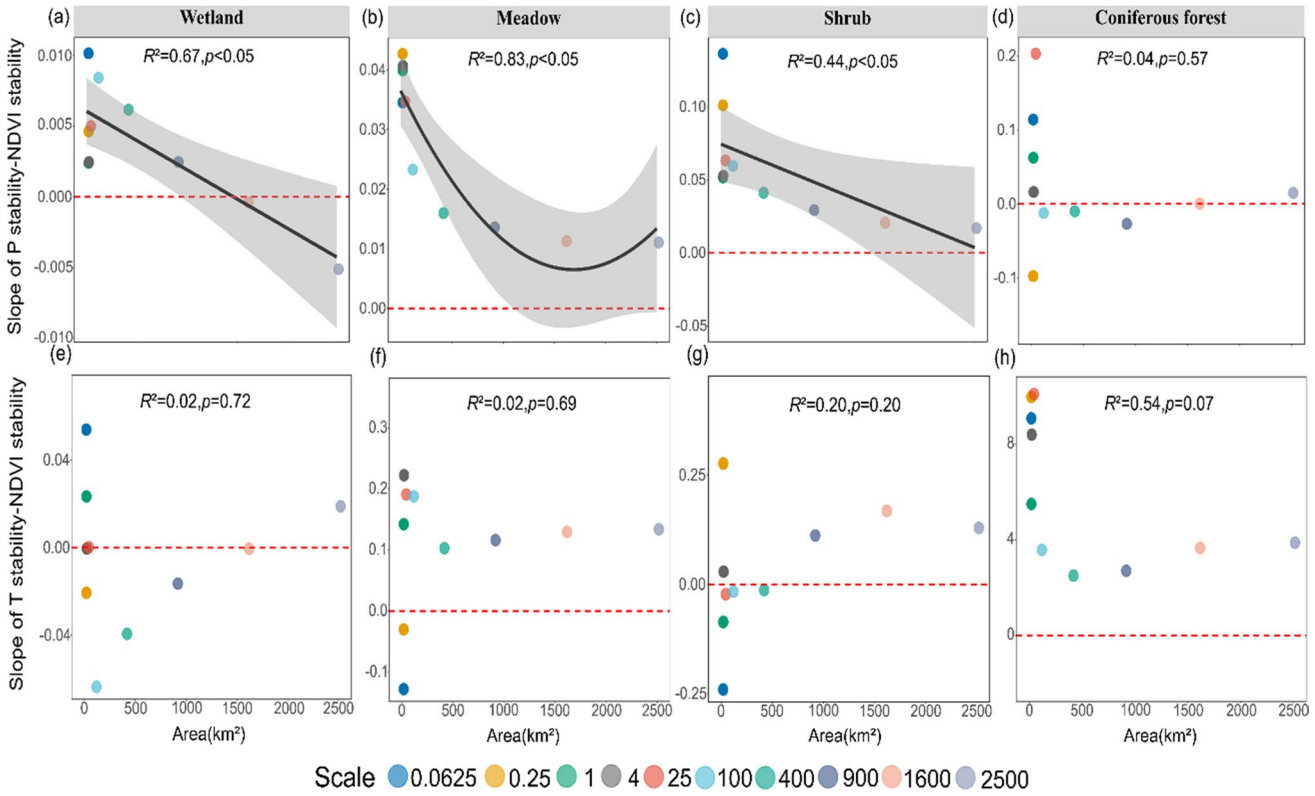

Fig. 4 Effects of growing season precipitation stability (P stability) and growing season average temperature stability (T stability) on NDVI temporal stability across multiple spatial scales. The solid lines are significant, gray areas are 95% confidence intervals. The significance levels for each predictor are $*p<0.05$, $**p<0.01$, $***p<0.001$, respectively

types (meadows: 0.57, $p<0.001$; wetlands: 0.38, $p=0.005$; shrubs: 0.44, $p=0.0002$). Resilience showed more complex associations, exhibiting direct negative effects on NDVI stability in wetlands but indirect positive effects in shrubs through mediation of diversity-climate relationships (Fig. 5).

Discussion

Our study demonstrates that landscape diversity and temporal stability of NDVI exhibit strong scale dependence across four vegetation types on the Qinghai-Xizang Plateau. The effects of landscape diversity on NDVI stability varied significantly across spatial scales and vegetation types. In meadows, diversity-stability slopes increased linearly with scale. NDVI stability in shrubs showed a concave relationship with spatial scale and these relationships in wetlands and forests were weak or non-significant. These differential responses across ecosystems can be attributed to a confluence of external drivers and intrinsic ecosystem attributes, such as variations in vegetation structure, sensitivity to climatic fluctuations and landscape configuration (Turner et al. 1993). For instance, herbaceous-dominated grasslands may exhibit pronounced scale dependence, potentially mediated by spatial insurance mechanisms that operate more effectively at broader scales (Loreau et al. 2003). In contrast, shrublands, characterized by deep-rooted woody plants, often demonstrate nonlinear responses due to complex interactions between water availability and biotic factors. Conversely, more structurally homogeneous or climate-buffered ecosystems like forests and wetlands may display weaker scale dependence in their stability.

The relationship between resilience and NDVI stability exhibited context-dependent patterns reflecting ecosystem-specific recovery dynamics. In wetlands, the negative association suggests that rapid recovery following disturbance comes at the cost of reduced temporal stability, potentially reflecting trade-offs between fast resource acquisition and consistent performance (Donohue et al. 2013). In shrubs, positive indirect effects indicate that resilience enhances stability through improved maintenance of diversity and climate buffering. These contrasting patterns highlight that resilience contributes to overall stability through different mechanistic pathways depending on vegetation type and environmental context.

Our findings align with some prior studies but contrast with others. For example, Li et al. (2023b) reported a positive landscape diversity-stability relationship at 5–30 km

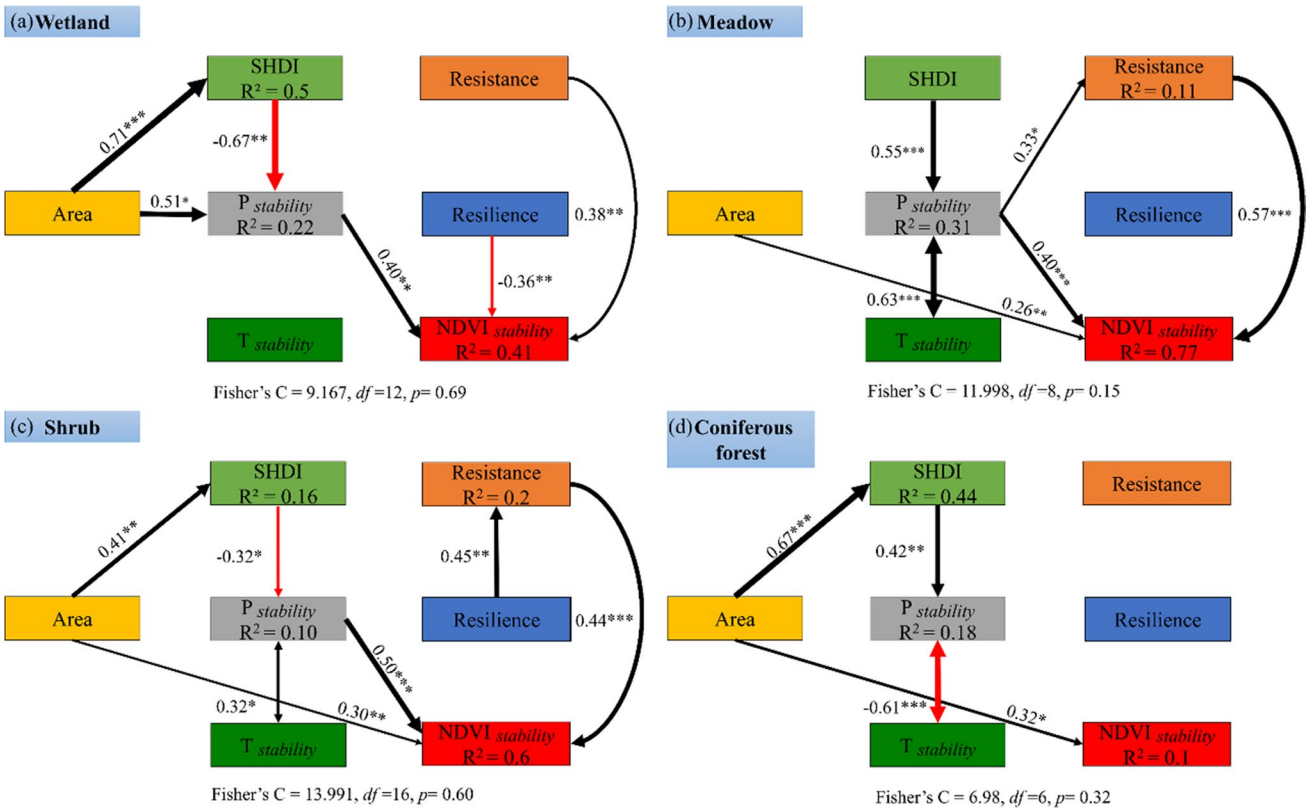

Fig. 5 Structural equation modeling (SEM) showing the effects of spatial scales on landscape diversity (SHDI), temporal stability of temperature and precipitation and ecosystem stability metrics and their relationships within the four vegetation types (a: wetland, b: meadow, c: shrub, d: coniferous forest). **a** Fisher's C = 9.167, p = 0.69, df = 12, AIC = 33.17. **b** Fisher's C = 11.998, p = 0.15, df = 8, AIC = 33.998 **c** Fisher's C = 13.991, p = 0.60, df = 16, AIC = 41.991 **d** Fisher's C = 6.98, p = 0.32, df = 6, AIC = 24.98. Black and red arrows indicate positive and negative effects, respectively. Solid lines represent significant paths, and all marked lines are significant effects (significance levels for each predictor are (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, respectively). The widths of each arrows are relative to the standardized path coefficients

scales in forest-grassland ecotones, which declined beyond 30 km, this pattern is inconsistent with our results. This discrepancy may stem from higher landscape heterogeneity in ecotones, which enhances β-diversity and spatial asynchrony at intermediate scales but not at larger ones (Loreau et al. 2003; Poggio et al. 2010). Conversely, our results support the theory that abiotic heterogeneity promotes β-diversity and stability at broad spatial scales (van der Plas et al. 2023; Wang and Loreau 2014, 2016). In our study, increased landscape diversity was associated with decreased precipitation stability in wetlands and shrubs, thereby indirectly lowering NDVI stability. This result contrasts with Li et al. (2023b), who observed positive diversity-temperature stability links in northern China. The negative association in our study may arise from the complex biophysical feedbacks in alpine ecosystems, where more heterogeneous landscapes could potentially modify local atmospheric processes and moisture redistribution, leading to greater precipitation variability at the scales we examined. This difference highlights the context-dependent nature of diversity-climate interactions, where vegetation type and regional climate modulate these relationships.

In our study, precipitation stability emerged as a stronger predictor of NDVI stability than temperature stability or landscape diversity in most vegetation types. This aligns with Zhang et al. (2018), who found that precipitation variability directly and indirectly reduces ecosystem stability via species asynchrony at local scale. The previous study from the Xizang Plateau using 40 years of environmental data, also found higher stability of production was associated with lower variability of precipitation (Ye et al. 2013). However, our results partially contradict studies like Hallett et al. (2017), which was conducted at the local, plot-level scale and found that precipitation variability enhanced stability through compensatory dynamics. This divergence highlights the scale-dependency of these relationships, where local compensatory effects may be overshadowed by different processes, such as spatial asynchrony or regional climate drivers, at the broader landscape scales examined in our study. At the same time,

a manipulating precipitation study at local scale in the Qinghai-Xizang Plateau found that precipitation alteration does not affect stability, but warming declines stability (Ma et al. 2017). This divergence may arise from the unique alpine conditions of the Qinghai-Xizang Plateau, where low temperatures limit productivity (Zhao et al. 2025), making precipitation stability more crucial (Ye et al. 2013), especially in landscape scale (Cuo et al. 2021; Körner and Paulsen 2004) and broad spatial scales (Wang et al. 2017; Liang et al. 2022). Additionally, landscape diversity influenced climate stability through biophysical feedbacks (Li et al. 2017, 2023b). Diverse landscapes can alter surface albedo, roughness, and evapotranspiration, thereby modifying local climate (Cao et al. 2015; Pielke 2005). For example, in meadows, landscape diversity increased precipitation stability, likely through enhanced vegetation cover and water retention, whereas in shrubs and wetlands, it reduced precipitation stability due to contrasting transpiration regimes or patch dynamics. These suggest that precipitation stability is a key driver for NDVI temporal stability in the Xizang Plateau, regardless of vegetation types. Definitely, more field and simulation experiments and models are needed in the future to reveal and verify these mechanisms.

Implications

From a conservation perspective, our study provides a novel guide for landscape-scale management. The scale dependence of diversity-stability relationships implies that conservation strategies should be tailored to spatial grain and vegetation type. For instance, in meadows and shrubs, where diversity-stability slopes strengthen with scale, protecting large and connected landscapes is crucial to maintain stability. In wetlands, where precipitation stability dominates, management should focus on water regulation and climate resilience. In forests, where scale effects are weak, local diversity conservation may suffice. Moreover, our findings underscore that precipitation stability, which is often overlooked in biodiversity-stability frameworks, is a key mediator of ecosystem responses to climate change. Land managers could use spatial scale-specific metrics (e.g. SHDI at 1–10 km scales) to prioritize areas for conservation, ensuring that landscape diversity enhances rather than diminishes climate resilience. This approach aligns with global efforts to integrate landscape heterogeneity into climate adaptation plans (Feddema et al. 2005; Oehri et al. 2017).

Limitations

In many studies, NDVI is widely used as a proxy for productivity and stability. However, we also recognize its limitations, including saturation in high-biomass areas and sensitivity to atmospheric conditions. Future studies could incorporate field-based productivity measures or alternative remote sensing indicators (e.g. solar-induced fluorescence, Enhanced Vegetation Index) to validate our findings. While our study used multi-year land use data, it did not explicitly model effects of temporal land use changes on stability. Furthermore, our study focuses on the stability of aboveground productivity (proxied by NDVI), which is one key dimension of ecosystem function. The stability of other processes or states (e.g., belowground productivity, nutrient cycling) may exhibit different scale dependencies and should be explored in future research. Future work could integrate dynamic land use change trajectories to uncover how shifts in landscape composition interact with scale-dependent stability mechanisms.

Conclusions

In summary, our results advance diversity-stability theory by revealing how scale, vegetation type, and climate interactions jointly govern ecosystem stability. Specifically, we show that maintaining landscape diversity can enhance ecosystem stability, but this effect is modulated by precipitation stability. Therefore, conservation strategies should consider both biotic and abiotic factors, e.g. protecting heterogeneous landscapes in regions with stable precipitation, or implementing water management practices in areas with high precipitation variability. These approaches may help buffer ecosystems against climate change impacts. Future studies should combine remote sensing with field experiments to further validate these mechanisms and explore nonlinearities across broader climatic gradients.

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Author contribution statement Zhiqiang Xiang, Junfeng Lu and Wenjin Li conceptualized the idea and designed the study; Zhiqiang Xiang, Junfeng Lu, Xi Zhou, Xuegang Xing and Jiahao Liang collected and analyzed the data; Zhiqiang Xiang, Junfeng Lu, Hannah J. White and Wenjin Li wrote the original draft; All authors contributed critically to editing and gave final approval of the submitted manuscript. The authors declare no conflicts of interest.

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Data availability The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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