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Spatiotemporal Patterns of Ecological Resilience in the Northern Fukang Desert under Alternative Stable States: Postprint

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Abstract

The ecological resilience of desert ecosystems under alternative stable states reflects the system' s capacity to recover following environmental disturbances, which holds important theoretical significance for understanding desert ecosystem processes. Current research has primarily focused on lake and forest ecosystems, whereas studies on desert ecosystem resilience generally neglect alternative stable states and seldom consider temporal variations in resilience. This study examines a transect from the southern margin to the hinterland of the Gurbantünggüt Desert north of Fukang as a case study, utilizing MODIS global vegetation index remote sensing data from January 2001 to December 2020. Data processing and extraction were conducted using BFAST (Breaks for Additive Season and Trend) and state-space modeling. Ecological resilience under alternative stable state conditions across different periods was quantified based on exit times from different states, and the spatiotemporal evolution characteristics of ecological resilience in the region and their influencing mechanisms were analyzed according to the calculation results. The research findings indicate: (1) Resilience+ and Resilience- in the study area exhibit an overall trend of initial decline followed by increase, with significant spatial differentiation from the desert edge to the hinterland. (2) Ecological resilience shows a lagged response to precipitation changes. (3) Differences in seasonal precipitation variation reduce the correlation between precipitation amount and ecological resilience. In summary, the spatial distribution of ecological resilience is overall controlled by precipitation patterns; however, vegetation spatial heterogeneity resulting from site conditions increases the complexity of this distribution. The relationship between ecological resilience and precipitation changes depends on vegetation community composition, plant responses to precipitation variation, precipitation amount trends, and seasonal distribution. This study holds important theoretical and practical significance for understanding the maintenance mechanisms of

functional stability in desert ecosystems and for desert ecological conservation and restoration.

Full Text

Spatial and Temporal Patterns of Ecological Resilience under Alternative Stable States in the Desert of the Northern Fukang Region

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Abstract

The ecological resilience of desert ecosystems under alternative stable states reflects the system’ s capacity to recover from environmental disturbances, which holds important theoretical significance for understanding desert ecosystem processes. Current research has primarily focused on lake and forest ecosystems, while studies on desert ecosystem resilience generally neglect alternative stable states and rarely consider temporal changes in resilience. This study examines a transect from the southern edge to the hinterland of the Gurbantunggut Desert in northern Fukang, using global vegetation index remote sensing data. We processed and extracted the data using state-space modeling and Breaks for Additive Season and Trend (BFAST) to quantify ecological resilience under alternative stable states across different periods through exit times. The results reveal that: (1) Resilience+ and Resilience− exhibited an overall trend of initial decline followed by increase, though spatial differences between the desert edge and hinterland were significant. (2) Ecological resilience showed a lagged response to precipitation changes. (3) Differences in seasonal precipitation patterns reduced the correlation between precipitation and ecological resilience. In summary, the spatial distribution of ecological resilience is generally controlled by precipitation patterns, but spatial heterogeneity in vegetation resulting from site conditions increases the complexity of resilience distribution. The relationship between ecological resilience and precipitation depends on vegetation community composition, plant responses to precipitation changes, and both the trend and seasonal distribution of precipitation. This study provides important theoretical and practical implications for understanding the mechanisms maintaining functional stability in desert ecosystems and for desert ecological conservation and restoration.

Keywords: alternative stable states; ecological resilience; exit time; Gurbantunggut Desert

Ecological resilience is a crucial indicator for measuring ecosystem stability, defined as the magnitude of disturbance a system can withstand before transitioning to an alternative stable state with different structures and functions [1]. Based on the trend of system variables, ecological resilience can be assessed by the duration that system variables deviate from their trend—the longer the deviation, the weaker the resilience. System variables can deviate from trends in multiple ways, exhibiting stability that constitutes alternative stable states. When system variables are disturbed by positive environmental factors and remain above the trend, this is termed a positive stable state (Resilience+), whereas deviation below the trend represents a negative stable state (Resilience−) [2]. Ecosystems demonstrate different resilience under different alternative stable states, with distinct fluctuation ranges for system variables. This phenomenon is widespread across lakes, forests, deserts, and other ecosystems [3-5]. In changing environments, ecological resilience is an important mechanism for ecosystems to maintain functional stability. Using temporal sequences of vegetation function as an entry point, investigating the spatiotemporal characteristics of ecological resilience and its underlying mechanisms under different alternative stable states in the desert ecosystem of northern Fukang holds both theoretical and practical significance for understanding desert ecosystem processes and for regional ecological conservation and restoration.

Advances in Earth big data technologies have created possibilities for quantifying ecosystem resilience using remote sensing time series. BFAST (Breaks for Additive Season and Trend) is one of the most important methods for distinguishing inherent seasonal changes from environmental disturbances [6]. This method has been widely applied to detect vegetation function trends and can quantify ecosystem resilience [7-9]. Representative methods for quantifying ecological resilience through time series fall into two categories: autocorrelation coefficient methods and autoregressive coefficient methods. The former quantifies resilience by calculating temporal autocorrelation of system variables [10-11], while the latter uses autoregressive coefficients [12-13]. Both methods assume a single stable state in ecosystems and thus cannot quantify resilience under alternative stable states. Recently, the time required for ecosystems to exit different stable states has solved the quantification problem for resilience under alternative stable states and has been applied to quantify resilience in lake ecosystem algal biomass [14], though it has not yet been applied to spatial-scale ecological resilience research.

Some studies have used Landsat time series to quantify the ecological resilience of the Xiangjiang River basin and preliminarily explored its spatiotemporal changes [15], but they lacked in-depth discussion of differences in resilience under alternative stable states and their driving factors. To better understand the spatiotemporal evolution of ecological resilience in the desert ecosystem of northern Fukang, this study selected a transect from the southern edge to the hinterland of the Gurbantunggut Desert. Using MODIS global vegetation index remote sensing data products, we divided the time series into four periods, processed and extracted the data using BFAST and state-space modeling, and calculated ecological resilience under alternative stable states through exit times. We further analyzed the spatiotemporal evolution characteristics of ecological resilience and their influencing mechanisms. This study provides methodological and technical support for quantifying ecological resilience under alternative stable states.

1.1 Study Area and Transect Selection

The study transect extends from the southern edge of the Gurbantunggut Desert in northern Fukang to the desert hinterland, geographically located at 87°42 ~88°12 E, 44°21 ~45°21 N, covering a total area of approximately 4.47$×10^{3}$ km^{2}. The transect measures 111.3 km from north to south and 40.1 km from east to west. Fixed and semi-fixed dunes oriented north-south develop within the transect, with relative heights of 10-30 m. Dunes and interdune lowlands alternate, creating undulating terrain. Precipitation decreases from south to north, with a regional average annual precipitation of 250 mm. Spring snowmelt is an important supplement to soil moisture [16] and a crucial water source for desert plants [17]. The area develops typical temperate desert vegetation with *Haloxylon ammodendron* and *H. persicum* as constructive species. Common shrubs include *Calligonum leucocladum*, which is a major factor maintaining the fixed and semi-fixed state of dunes in this region [18]. Herbaceous plants are sparsely distributed, with common annuals such as *Salsola* spp. and *Ceratocarpus arenarius* [19]. Biodiversity indices show a decreasing trend from south to north along the transect [20], and desert plant species composition varies. Therefore, we divided the transect into three equal parts along the north-south direction (Fig. 1) to further analyze the spatiotemporal evolution of precipitation and ecological resilience.

1.2.1 Quantification of Ecological Resilience

The workflow for quantifying ecological resilience is shown in Fig. 2. Data were obtained from MODIS MOD13Q1 vegetation index products with a temporal resolution of 16 days and spatial resolution of 250 m. The geographic coordinate system is WGS84. Since the product data began in February 2000, to ensure time series completeness, the study period was set from January 2001 to December 2020. We used Google Earth Engine to extract maximum NDVI values for each month, creating monthly NDVI time series data. The main processing steps are shown in Fig. 2. First, we extracted different time series and used BFAST to detect trend changes, obtaining trend and remainder components.

The seasonality component was fitted using the default harmonic model. We then used the remainder component to divide stable states (Et>0 for positive stable state, Et<0 for negative stable state), further eliminating environmental interference [27]. Finally, state-space modeling was performed using the trend and remainder components. This modeling approach effectively reflects the true state of nature [28], with specific methods implemented using the MARSS package in R [29].

Ecological resilience, as a stability indicator obtained from long-term observations, requires lengthy time series for quantification. The highest vegetation index values in this region occur in August. Given significant differences in trend changes compared to earlier periods, we divided the 20-year data into four periods of equal length for resilience quantification. To compare resilience changes across periods, the time series data for quantification needed to be equal in length. Combining Earth surface system analysis methods [30], we divided the data into cycles of 5 years, resulting in four periods: 2001-2005 (t_1), 2006-2010 (t_2), 2011-2015 (t_3), and 2016-2020 (t_4). Each grid cell within the transect has a specific time series Y , which comprises several components in the following formula:

$$Y_t = S_t + T_t + R_t + E_t$$

where S_t is the seasonal component, representing seasonal variation; T_t is the trend component, representing long-term change; R_t is the remainder component, representing changes from environmental pressure disturbances beyond seasonal variation; and E_t is the residual component, representing changes from pulse disturbances. This study used BFAST to extract these components.

After converting the data into time series objects and completing state-space modeling, BFAST was used again to separate trend and remainder components. The remainder component was then used to identify stable states (Et>0 for positive stable state, Et<0 for negative stable state). Finally, exit times were calculated from the remainder component to obtain ecological resilience.

Exit time calculates the average time required for environmental disturbances to cause an ecosystem state to exit its current stable state [14]. Since state-space modeling restores the continuity of data changes, this approach can accurately calculate the "exit time (EXITTIME)" for system transitions between different alternative stable states. Here, we used statistical methods to treat EXITTIME from different periods as sample data and calculated the average for each stage as follows:

$$EXITTIME_T = \frac{\sum_{i=1}^{n} month_i}{n}$$

where n represents the frequency of continuous changes in the system variable within the same stable state during the study period, and $month_i$ is the number of months included in the i-th continuous run. T represents the specific time period.

When $month_i$ has $E_t < 0$ (below the expected stable state), the ecosystem is in a negative stable state during that period, and the calculated result is $EXITTIME_{low}$, representing Resilience−. When $month_i$ has $E_t > 0$ (above the expected stable state), the ecosystem is in a positive stable state, and the calculated result is $EXITTIME_{high}$, representing Resilience+. The longer the calculated $EXITTIME$, the lower the resilience.

1.2.2 Methods for Analyzing Resilience Trends and Precipitation Factors

To understand the relationship between resilience and precipitation fluctuations, we selected multi-year average annual precipitation data and daily precipitation data from CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) with 0.05° spatial resolution. After zonal statistics to extract average values for different resilience zones, we used regular grid sampling to extract multi-year average annual precipitation data and ecological resilience data, then calculated Spearman correlation coefficients [32]. Resilience trends were obtained by subtracting earlier period data from later period data (e.g., the trend for period t_3 equals resilience in t_3 minus resilience in t_2). Precipitation trends were calculated similarly.

2.1 Spatiotemporal Distribution of Ecological Resilience

The spatiotemporal patterns of resilience values and trends are shown in Fig. 3. Resilience+ ranged from 0.075 to 0.500. Resilience+ in period t_1 was relatively high overall, while in t_2 it was relatively low, suggesting that precipitation trends during different periods may have affected regional resilience. High Resilience+ values were concentrated in the southern part of the transect, primarily influenced by the south-to-north precipitation gradient. Resilience− ranged from 0.085 to 0.500, with values in period t_2 higher than other periods. High values in period t_3 showed patchy, mixed distributions, indicating that resilience changes were strongly influenced by local habitat conditions.

Resilience trends showed that Resilience+ in the southern transect declined sharply during t_1-t_2, while the overall transect resilience increased during t_2-t_3, with substantial increases in Resilience+ in the southern transect. Different trends in Resilience+ and Resilience− across periods suggest that regional vegetation may have differential adaptive responses to different types of environmental disturbances.

Overall, resilience was significantly correlated with precipitation (Table 1). Resilience was correlated not only with precipitation in the same period but also with precipitation in previous periods. For example, overall Resilience+ in period t_3 showed high correlation with precipitation in period t_2 (r=0.701,

$p<0.001$). However, this correlation showed local variation. Based on precipitation data resolution, we constructed vector grids (Fig. 4) and extracted precipitation and ecological resilience data for 100 sample points across different periods, ultimately calculating spatiotemporal changes in the correlation between precipitation and resilience. The southern transect maintained significant positive correlation with precipitation, while the central and northern parts showed significant negative correlation with precipitation in period t_3. Moreover, correlations differed substantially between alternative stable states. In the southern transect, Resilience+ correlations with precipitation across periods ranged from 0.701 to 0.851 ($p<0.001$), while Resilience− correlations were below 0.5.

2.2 Spatial Differences in the Relationship Between Ecological Resilience and Precipitation

The overall multi-year average annual precipitation in the transect showed a substantial increase from t_1 to t_4 (Fig. 4). Dividing the transect into three equal parts from south to north, Table 1 shows average annual precipitation changes for each zone. The southern and central parts showed trends of initial increase followed by decrease, while the northern part maintained an increasing trend. Precipitation trends varied significantly across the transect, which was the main reason for spatial differences in resilience under different alternative stable states during period t_3. Results showed that resilience trends were significantly correlated with precipitation trends. For example, the correlation between overall Resilience+ trends and precipitation trends during t_2-t_3 was 0.701 ($p<0.001$), indicating that Resilience+ increased with precipitation.

2.3 Relationship Between Ecological Resilience and Seasonal Precipitation Distribution

The overall resilience trend showed low correlation with precipitation trend (Table 2), while local resilience trends showed more significant correlation with precipitation trends. Overall, correlations between Resilience+/Resilience− and precipitation varied complexly across time and space, possibly due to differential vegetation adaptation to precipitation trends and complex seasonal precipitation patterns.

Fig. 5 shows the frequency of positive stable states and negative stable states across months, with frequency differences reflecting ecosystem stability patterns. The ecosystem was more likely to be in a negative stable state during March-May and September-November, and in a positive stable state during June-August and December-February. When precipitation changes promoted vegetation growth (Fig. 5), the ecosystem spent more time in a positive stable state and less time in a negative stable state, potentially even transitioning to alternative stable states. Consequently, average exit time from positive stable state increased, decreasing Resilience+ values, while Resilience− values increased. Conversely, when spring-summer precipitation changes differentially affected stable states

(Fig. 5), average exit times became more complex, reducing correlation with precipitation in some periods. This may explain why resilience under alternative stable states showed low correlation with precipitation in certain periods.

3 Discussion

This study quantified and explored spatiotemporal changes in ecological resilience under different alternative stable states for a desert vegetation transect in northern Fukang. Results show that regional ecological resilience initially decreased then increased, with significant spatial distribution differences in resilience values from the southern edge to the hinterland of the Gurbantunggut Desert under different alternative stable states. Resilience values showed lagged responses to precipitation fluctuations, with spatial differences in precipitation patterns, heterogeneous vegetation distribution, and differential vegetation responses to precipitation likely being the main causes of these differences.

Ecological resilience calculated under alternative stable states indicates the time required for ecosystem function to recover after positive or negative environmental disturbances. Longer recovery times indicate lower resilience and reduced capacity to withstand and recover from disturbances. For desert ecosystems, precipitation is the primary limiting factor for ecosystem productivity. Previous studies on ecosystem resilience across Central Asia found that desert ecosystem resilience in the Gurbantunggut Desert of northern Fukang is greater at the southern edge than in the hinterland [33], consistent with our finding of lower resilience in the north than south during period t_2.

Ecosystems maintain their original function, structure, characteristics, and capacity for resistance and reorganization during changes. Thus, species richness within ecosystems helps increase ecological resilience [34]. Studies show that desert vegetation community resilience is significantly affected by species richness [35], and areas with higher precipitation have significantly greater plant species richness than low-precipitation areas [20]. The complex changes in plant species abundance from the desert edge to hinterland caused by precipitation gradients [20] form the natural basis for higher ecological resilience at the southern edge of the Gurbantunggut Desert. Additionally, site conditions such as slope aspect and gradient affect ecological resilience [36]. In the northern Fukang desert ecosystem, dunes rise and fall with sparse vegetation distribution, mainly concentrated at dune bases and interdune lowlands [37]. Terrain undulation creates better moisture conditions in interdune lowlands, leading to higher species richness and affecting resilience spatial distribution. Different dune types (fixed, semi-fixed, and mobile) also create different moisture conditions, causing desert vegetation population stable states to differ under various geomorphic conditions [38]. Therefore, under the combined effects of precipitation patterns and local site conditions, the spatial distribution of ecological resilience in northern Fukang shows both north-south trending differences and local patchy mixed distributions.

Previous studies showed that Gurbantunggut Desert precipitation and NDVI have lagged responses [39], and this study further demonstrates that such lagged responses are reflected in NDVI-based ecological resilience calculations. For example, Resilience+ in the southern transect correlated with precipitation in period t_2 ($r=0.701$, $p<0.001$). This occurs because precipitation effects on vegetation species richness proceed slowly, with long time lags before changes in vegetation community structure are reflected in ecological resilience.

Not all desert plant cover correlates significantly with precipitation [40]. For example, the density and cover of *Haloxylon persicum*, *Calligonum leucocladum*, and others decrease with increasing precipitation, while *Haloxylon ammodendron* shows no correlation with precipitation. This may relate to different survival strategies formed during adaptation to temperate desert climates [41]. Our results show negative correlations between resilience and precipitation in some areas (Table 1). For instance, in the northern transect during t_2-t_3, the correlation between resilience trends and precipitation trends was -0.701 ($p<0.001$). Combined with the relationship between resilience and seasonal precipitation distribution, when vegetation cover in the central and northern transect negatively correlates with precipitation, resilience decreases with increasing precipitation. Due to diverse seasonal precipitation patterns and complex effects on resilience, the correlation between desert ecosystem resilience and precipitation is complex and varied. Overall, the relationship between ecological resilience and precipitation depends on vegetation community composition, plant responses to precipitation changes, precipitation trends, and seasonal distribution.

To address quantification of ecological resilience under different alternative stable states, this study combined BFAST trend detection and state-space modeling to identify different alternative stable states (positive stable state and negative stable state), then used exit time methods to quantify ecological resilience. Application to the Gurbantunggut Desert ecosystem in northern Fukang confirmed that alternative stable states are widespread in desert ecosystems [11] and that ecological resilience differs under different alternative stable states. Compared with previous studies [33,35], this study better explains spatiotemporal patterns of desert ecosystem resilience by dividing different alternative stable states and time periods, providing new insights for understanding long-term dynamics of desert ecological stability and its relationship with environmental disturbances. The stability of the Gurbantunggut Desert in northern Fukang is crucial for regional ecological security and sustainable development [41], and our resilience research results help deepen understanding of mechanisms maintaining functional stability in desert ecosystems under environmental disturbances, providing important theoretical guidance for desert ecosystem conservation and restoration.

4 Conclusion

This study used BFAST and state-space modeling to process remote sensing time series data in stages, extracting ecological resilience under alternative stable states across different periods, quantifying the spatial distribution of ecological resilience in the desert ecosystem of northern Fukang, and exploring the relationship between ecological resilience and precipitation changes across different zones.

The spatial distribution of resilience is generally controlled by precipitation patterns, but spatial heterogeneity in vegetation due to site conditions increases the complexity of resilience distribution. Temporally, ecological resilience showed a decreasing then increasing trend during the study period, with a lagged response to precipitation changes. The correlation between ecological resilience and precipitation depends on vegetation community composition, plant responses to precipitation changes, precipitation trends, and seasonal distribution. This study provides methodological and technical support for quantifying ecological resilience under alternative stable states and offers important theoretical and practical significance for understanding mechanisms maintaining functional stability in desert ecosystems and for desert ecosystem conservation and restoration.

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