

Grassland-type ecosystem stability in China differs under the influence of drought and wet events (Postprint)

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Abstract

Ecological stability is a core issue in ecological research and holds significant implications for humanity. The increased frequency and intensity of drought and wet climate events resulting from climate change pose a major threat to global ecological stability. Variations in stability among different ecosystems have been confirmed, but it remains unclear whether there are differences in stability within the same terrestrial vegetation ecosystem under the influence of climate events in different directions and intensities. China's grassland ecosystem includes most grassland types and is a good choice for studying this issue. This study used the Standardized Precipitation Evapotranspiration Index-12 (SPEI-12) to identify the directions and intensities of different types of climate events, and based on Normalized Difference Vegetation Index (NDVI), calculated the resistance and resilience of different grassland types for 30 consecutive years from 1990 to 2019 (resistance and resilience are important indicators to measure stability). Based on a traditional regression model, standardized methods were integrated to analyze the impacts of the intensity and duration of drought and wet events on vegetation stability. The results showed that meadow steppe exhibited the highest stability, while alpine steppe and desert steppe had the lowest overall stability. The stability of typical steppe, alpine meadow, temperate meadow was at an intermediate level. Regarding the impact of the duration and intensity of climate events on vegetation ecosystem stability for the same grassland type, the resilience of desert steppe during drought was mainly affected by the duration. In contrast, the impact of intensity was not significant. However, alpine steppe was mainly affected by intensity in wet environments, and duration had no significant impact. Our conclusions can provide decision support for the future grassland ecosystem governance.

Full Text

Preamble

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Grassland-type ecosystem stability in China differs under the influence of drought and wet events

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Abstract

Ecological stability is a core issue in ecological research with significant implications for humanity. Climate change has increased the frequency and intensity of drought and wet climate events, posing major threats to global ecological stability. While variations in stability among different ecosystems have been confirmed, it remains unclear whether stability differs within the same terrestrial vegetation ecosystem when subjected to climate events of different directions and intensities. China's grassland ecosystem, which includes most grassland types, provides an ideal system for investigating this question.

This study used the Standardized Precipitation Evapotranspiration Index-12 (SPEI-12) to identify the direction and intensity of climate events, and calculated the resistance and resilience of different grassland types over 30 consecutive years from 1990 to 2019 based on the Normalized Difference Vegetation Index (NDVI). Resistance and resilience are important indicators for measuring stability. Building upon a traditional regression model, we integrated standardized methods to analyze the impacts of drought and wet event intensity and duration on vegetation stability. The results showed that meadow steppe exhibited the highest stability, while alpine steppe and desert steppe had the lowest overall stability. The stability of typical steppe, alpine meadow, and temperate meadow fell at intermediate levels. Regarding the impact of climate event duration and intensity on vegetation ecosystem stability within the same grassland type, the resilience of desert steppe during drought was mainly affected by duration, whereas intensity had no significant effect. In contrast, alpine steppe in wet environments was primarily affected by intensity, with duration having no significant impact. These conclusions can provide decision support for future grassland ecosystem governance.

Keywords: grassland ecosystem; stability; resistance; resilience; different cli-

mate types; drought climate event; wet climate event

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1 Introduction

Global warming from climate change has led to increasing frequency and intensity of drought and wet events (Easterling et al., 2000; King et al., 2015; Stott, 2016), significantly impacting terrestrial ecosystem stability (Hansen et al., 2019; Fan et al., 2021; Xu and di Vittorio, 2021; Creedy et al., 2022). Ecosystem stability refers to the ability of an ecosystem to maintain or restore its structure and function to maintain relative stability, typically described through resistance and resilience (Hu et al., 2022). Resistance is the ability of vegetation to maintain its original productivity level when experiencing climate events (Li et al., 2020a), while resilience is the rate at which the ecosystem recovers to normal productivity after climate events (Liu et al., 2021). Highly resistant and resilient ecosystems are more stable, exhibiting lower variability and stronger buffering capacity when exposed to climate events (Ives and Carpenter, 2007; Chen et al., 2021). Understanding terrestrial ecosystem stability in response to climate disturbances provides scientific references for ecological barrier protection, management, and services.

Existing literature shows that terrestrial ecosystem stability varies among different vegetation communities and ecological regions. For example, gymnosperms and angiosperms exhibit different drought resistance and spatial patterns (Li et al., 2020b). According to de Keersmaecker et al. (2015), semi-arid locations have limited drought resilience, while high latitudes have weak resistance to negative temperature anomalies. Van Ruijven and Berendse (2010) confirmed variable resistance and resilience among different vegetation communities under drought conditions by studying experimental vegetation responses to natural droughts. However, most current research focuses on forest ecosystems (Li et al., 2020b), particularly their response to drought, while ignoring other climate conditions. Wet climate conditions also affect vegetation, and if too severe, may cause irreversible changes (Jiao et al., 2022). For instance, Hossain et al. (2022) confirmed that cold grasslands and wet temperate ecosystems typically have higher resistance but lower resilience after wet climate events. However, little research has examined ecosystem stability in wet environments, making the resistance and resilience of vegetation in these conditions an important area of attention.

In grassland ecosystems, Liu et al. (2021) computed overall system stability in response to dry conditions but did not analyze stability variations among different grassland types. Although Huang et al. (2021) confirmed stability dif-

ferences among grassland types in drought environments, they did not explore how grassland ecosystems respond to wet climates. Additionally, it remains questionable whether grassland ecosystems can remain stable during climate events of varying intensities. Therefore, thoroughly comprehending how different grassland types survive and recover after harsh climatic impacts of various intensities (mild to moderate or severe) and orientations (drought or wet) is crucial.

China's grassland ecosystem covers almost all grassland types including meadow steppe, typical steppe, desert steppe, alpine steppe, temperate meadow, and alpine meadow (Yuan et al., 2004). The distribution of different grassland ecosystems spans large latitudinal and longitudinal ranges with varying geographical environments, making it an ideal research subject for addressing stability variation among grassland types. This study used Standardized Precipitation Evapotranspiration Index-12 (SPEI-12) annual average data to identify climate events of different orientations and intensities from 1990 to 2019. We then utilized Normalized Difference Vegetation Index (NDVI) data to characterize grassland health status and calculate the resistance and resilience of six grassland types in China. While most previous studies focused only on quantifying vegetation stability with little discussion of climate event intensity and duration, this study explored these impacts on grassland ecosystem stability. The novelty of this article includes: (1) further subdividing different grassland types and considering differences in vegetation stability when exposed to climate environments of different orientations (drought or wet) and intensities (mild to moderate, or severe); and (2) integrating standardization to provide explanatory contribution rates of climate event factors (duration and intensity) on stability based on traditional regression models.

This study aimed to identify stability differences among six Chinese grassland types—meadow steppe, typical steppe, desert steppe, alpine steppe, temperate meadow, and alpine meadow—under drought and wet climate events from 1990 to 2019. It also explored differences in how drought and wet event intensity and duration impact grassland ecosystems and provided suggestions for grassland management and protection. To achieve these goals, the three research objectives were: (1) identify the years and durations of drought and wet climate events for each grassland type in China from 1990 to 2019; (2) calculate the resistance and resilience of different grassland types over the past 30 years and analyze their stability differences under climate events of different intensities and orientations; and (3) for the grassland types with the worst stability, compare the degree of impact from climate event intensity and duration on stability over the past 30 years.

2.1 Study Area

The research object of this study was Chinese grassland, characterized by hydrothermal synchronism. We classified Chinese grassland into six types based on various water and wet conditions from the 1:1,000,000 Chinese Vegetation Atlas published by the Chinese Academy of Sciences (Editorial Board of Vegetation Map of China, 2007; Huang et al., 2021): meadow steppe (4.5% of total grassland area), typical steppe (19.5%), desert steppe (9.4%), alpine steppe (25.0%), temperate meadow (14.8%), and alpine meadow (26.8%). Alpine steppe and alpine meadow are collectively referred to as alpine grasslands, mainly distributed in the Xizang Autonomous Region, Qinghai Province, and Gansu Province—unique grassland types in China (Fig. 1 [Figure 1: see original paper]). Meadow steppe, typical steppe, desert steppe, and temperate meadow are collectively referred to as temperate grasslands, primarily distributed in the Inner Mongolia Autonomous Region, Heilongjiang Province, Xinjiang Uygur Autonomous Region, and Qinghai Province, representing the main grassland types in China. These data were derived from the Resources and Environmental Science Data Center of the Chinese Academy of Sciences (<https://www.resdc.cn/>) at 1 km resolution, which has higher classification accuracy than International Geosphere-Biosphere Programme (IGBP) classification data (Liu et al., 2022).

2.2 Data

SPEI is a drought index based on precipitation and potential evapotranspiration (PET) that combines the sensitivity of Palmer Drought Severity Index (PDSI) to evaporative demand changes with the multi-scale characteristics of Standardized Precipitation Index (SPI) (Vicente-Serrano et al., 2010; Beguería et al., 2014). We used SPEI to identify specific climate event years (this study categorized climate events annually) (Isbell et al., 2015; Li et al., 2020b; Hossain et al., 2022). SPEI data were obtained from the National Earth System Science Data Center of National Science & Technology Infrastructure (<http://www.geodata.cn>), which used Global Land Data Assimilation System (GLDAS) data as input. We combined GLDAS data with the Penman-Monteith Equation to calculate PET, then combined this with precipitation data to calculate SPEI. The synthesized SPEI data has a resolution of 0.25°. We downloaded SPEI monthly interval data from 1990 to 2019, which was resampled to 5 km resolution. SPEI-12 data reflect dry or wet conditions during the grassland growing season.

NDVI is a key metric for measuring vegetation growth and nutritional condition. We used NDVI to characterize grassland health status in this study (Hossain et al., 2022). NDVI data were obtained from the Earth Engine Data Catalog (https://developers.google.com/earth-engine/datasets/catalog/NOAA_{{CDR}}_{{AVHRR}}_{{NDVI}}_{{V5}}). We utilized RStudio (Public Benefit Corporation, Boston, Massachusetts, USA) to call the Google Earth Engine server for monthly synthesis at 5 km resolution

for the period 1990–2019.

The key to calculating grassland ecosystem resistance and resilience lies in vegetation growth data, specifically NDVI. Therefore, we converted these data into a format compatible with software such as MATLAB (Mathworks, Boston, Massachusetts, USA) and used ArcGIS (Environmental Systems Research Institute, Redlands, California, USA) with bilinear interpolation for resampling to unify the resolution with the original NDVI data at 5 km resolution for further analysis.

Fig. 1 Distribution of six grassland types in China. Note that this map is based on the standard map (No. GS(2020)4619) of the Map Service System (<http://bzdt.ch.mnr.gov.cn/>) marked by the Ministry of Natural Resources of the People's Republic of China, and the base map has not been modified.

2.3.1 Identification of Climate Event Years

To indicate the intensity and orientation of climate events, this study categorized climate events on an annual basis, referred to as “climate event year,” defined as starting one month after the end of the grassland growing season and continuing until the end of the next year's growing season month. We categorized SPEI-12 values into five groups: severe wet, mild to moderate wet, normal, mild to moderate drought, and severe drought (Table 1). This study focused solely on the impact of drought and wet climate events on grasslands, thus normal years were only categorized without analysis. Specifically, this study was conducted at an interannual scale; for each grid cell, when the annual average SPEI-12 value fell within different categorized intervals, we defined that grid cell as experiencing severe drought, mild to moderate drought, normal, mild to moderate wet, or severe wet event years (Isbell et al., 2015; Huang and Xia, 2019). The duration of drought and wet events was measured on a monthly basis. When SPEI-12 value was less than or greater than a certain threshold for three consecutive months (Schwalm et al., 2017), it was defined as a climate event in that year.

Using the above method, we calculated the climate event types for each year in the study area from 1990 to 2019 and determined the duration of climate events each year.

Table 1 Category of climate event types of grassland ecosystem based on Standardized Precipitation Evapotranspiration Index-12 (SPEI-12) value

| Climate event type | SPEI-12 value |
|--------------------------|--------------------|
| Severe drought | < -1.28 |
| Mild to moderate drought | -1.28 to -0.52 |
| Normal | -0.52 to 0.52 |
| Mild to moderate wet | 0.52 to 1.28 |

| Climate event type | SPEI-12 value |
|--------------------|---------------|
| Severe wet | ≥ 1.28 |

To observe spatio-temporal changes in climate events across different grassland types over the past 30 years, we quantified the proportion of drought or wet exposure events on different grassland types and compared climate event durations each year across grassland types.

2.3.2 Quantification of Vegetation Stability

We used resistance and resilience to measure grassland stability under climate events. Resistance refers to the ability of an ecosystem to maintain normal growth levels when resisting climate events (Li et al., 2020a), while resilience refers to the rate at which an ecosystem recovers to normal growth levels after climate event disturbances (Liu et al., 2021). If climate events reduce or increase vegetation growth levels, the higher the rate at which biomass returns to normal during the recovery period, the stronger the resilience—until the speed is fast enough to restore normal growth levels in the following year. Stronger resistance and resilience after climate disturbances indicate more stable ecosystems. The specific calculation methods are as follows (Isbell et al., 2015; Huang and Xia, 2019):

Resistance:

$$\Omega = \frac{Y_e}{Y_n}$$

Resilience:

$$\Delta = \frac{Y_{e+1}}{Y_n}$$

where Ω is the resistance value; Δ is the resilience value; Y_n is the normal growth level in normal years; Y_e is the vegetation growth level in years experiencing climate events; and Y_{e+1} is the vegetation growth level in a normal year after experiencing a climate event in the previous year. Ω and Δ gauge the magnitude of fluctuations in vegetation growth level in climate event years and recovery years compared with normal years. Smaller fluctuations indicate greater stability, while larger Ω and Δ values correspond to more favorable outcomes. These calculations are based on the identification of climate types and intensities for climate event years and are conducted on a grid-by-grid basis. These formulas indicate that: (1) since the calculated values for resistance and resilience are dimensionless, they can be compared across vegetation productivity categories and research areas; and (2) the results are symmetrical, which can express grassland type responses to climate events in different orientations (Isbell et al., 2015).

2.3.3 Regression Analysis

To explore the impact of climate events on grassland stability, we extracted grids from identified climate event years and eliminated outliers. Using different climate event durations and intensities as explanatory factors and grassland stability indicators as response variables, we constructed a multiple regression model. We calculated regression coefficients for each explanatory factor. Building upon the traditional regression model, we employed a standardization method to obtain average parameter estimates for model factors, yielding standardized regression coefficients along with their corresponding 95% confidence intervals and the relative importance of each influencing factor, expressed as a percentage to explain the degree of impact (Sirami et al., 2019). The relative influence of factors and their interactions can be straightforwardly calculated as the ratio between parameter estimates of influencing factors, represented in percentages.

In the model building process, raw data were first preprocessed. Due to positive skew in the distribution of resistance and resilience indicators, values less than and greater than the 5.0% thresholds were removed according to the kernel density distribution map (Yoo et al., 2013). For explanatory factors, we set the standardized mean to 0 and standard deviation (SD) to 1. The influence of an explanatory factor on the response variable was measured as the change in the response variable when the explanatory factor changed by one SD unit. This method eliminated dimensions, making regression coefficients for different explanatory factors directly comparable. Second, we used the vif function of RStudio to rule out multicollinearity among explanatory factors. When the variance inflation factor (VIF) exceeds 10, strong multicollinearity is considered to exist among explanatory factors (Lavery et al., 2019). Third, we used the Performance Analytics package of RStudio to explore distribution, scatter plots, and correlation coefficients among these explanatory factors. Diagnostic tools were run to validate residuals, and results were ultimately obtained and visualized. All analyses were conducted using RStudio software.

While considering non-uniformity of units and magnitudes among factors, this method allows direct comparison of obtained coefficients and effectively addresses issues such as overfitting in random forest models (Scornet, 2016).

3.1.1 Identification of Climate Event Years

This study counted the proportions of different climate events in six Chinese grassland types over 30 consecutive years from 1990 to 2019. Proportion refers to the ratio of grassland grids affected by climate events in a given year to the total grid number of that grassland type. These results reflect annual climate

event exposure throughout the study period (Fig. 2 [Figure 2: see original paper]). Exposure varied significantly among grassland types from 1990 to 2019. Meadow steppe, typical steppe, desert steppe, and temperate meadow experienced extensive disruptions from drought events between 2006 and 2009. Notably, meadow steppe and typical steppe were primarily impacted by drought events, aligning with Liu et al. (2021) who studied major drought events in Inner Mongolia's grasslands in 2008 and 2009. Alpine steppe had a relatively large area affected by severe wet events in 1990, accounting for over 40.0% of all alpine steppe area. Alpine meadow encountered significant disruptions from substantial wet events during 2017–2019, with more than 70.0% of all alpine meadow area affected in 2019, predominantly characterized by wet climate conditions. Comparing these findings with the grassland type map (Fig. 1) reveals that grassland types more susceptible to drought events were primarily situated in northwestern and northeastern China, while those more exposed to wet years were mainly located in the southwestern region, showing an overall pattern of “more drought events in the north and more wet events in the south.”

Fig. 2 Percentage of area influenced by different climate event types in six grassland types in China from 1990 to 2019. (a) meadow steppe; (b) typical steppe; (c) desert steppe; (d) alpine steppe; (e) temperate meadow; (f) alpine meadow.

3.1.2 Duration of Climate Events

Using the aforementioned methodology, this study computed the annual duration of drought events for six grassland types throughout the study period (Fig. 3 [Figure 3: see original paper]). Drought event duration varied between 4 and 12 months across the six grassland types, with all showing a discernible upward trend over time. Meadow steppe, typical steppe, and temperate meadow displayed more pronounced upward trends. Interestingly, all grassland types except alpine meadow reached maximum drought event duration in 2008 or 2009, with meadow steppe enduring the longest drought period of more than 11 months.

Wet event duration for the six grassland types varied from 5 to 10 months, with all exhibiting a fluctuating upward trend over time that was generally balanced (Fig. 4 [Figure 4: see original paper]). Alpine steppe showed the least noticeable upward trend, with its global maximum occurring in 1995 at more than 11 months.

Fig. 3 Annual duration of drought events in six grassland types in China from 1990 to 2019. (a) meadow steppe; (b) typical steppe; (c) desert steppe; (d) alpine steppe; (e) temperate meadow; (f) alpine meadow. The dotted line indicates the trend of annual duration as years increase. Missing data points indicate no climate events were detected in that particular year.

Fig. 4 Annual duration of wet events in six grassland types in China from 1990 to 2019. (a) meadow steppe; (b) typical steppe; (c) desert steppe; (d) alpine steppe; (e) temperate meadow; (f) alpine meadow. The dotted line indicates the trend of annual duration as years increase. Missing data points indicate no climate events were detected in that particular year.

3.2 Stability Under the Influence of Climate Events

Vegetation ability to resist drought and wet events showed large spatial differences (Fig. 5a [Figure 5: see original paper]). Resistance values in northwestern and northeastern China were higher (50–55) than other areas. The Qinghai-Tibet Plateau in southwestern China had lower resistance values of less than 50. The spatial recovery rate of vegetation to normal levels under drought and wet climate disturbances also exhibited significant variation (Fig. 5b [Figure 5: see original paper]). The central part of the Inner Mongolia Autonomous Region in northeastern China displayed stronger resilience, with most resilience values falling between 2–3, and some small areas exceeding 3. In contrast, the eastern part of the Qinghai-Tibet Plateau in southwestern China exhibited weaker resilience, with most values ranging 1–2. This region was predominantly characterized by alpine meadows. Divided by the latitude line of the northern edge of the Qinghai-Tibet Plateau, overall resistance and resilience showed a pattern of high in the north and low in the south. Grassland stability consequently displayed a spatial pattern of high in the north and low in the south.

This study also examined the relationship between resistance and resilience across different grassland types (Fig. 6 [Figure 6: see original paper]). Large differences existed in resistance and resilience among grassland types after drought and wet climate disturbances (Fig. 6). Meadow steppe exhibited the strongest resistance and resilience compared to other grassland types. Typical steppe ranked fourth in resistance and second in resilience among the six types. Temperate meadow and alpine meadow ranked second and third in resistance, respectively, but third-to-last and second-to-last in resilience. Desert steppe had the poorest resistance but average resilience. Alpine steppe ranked second-to-last in resistance and exhibited the poorest resilience. The rate at which grassland vegetation ecosystems recover to normal growth levels after climate events is particularly noteworthy. In an overall assessment of grassland stability levels, meadow steppe exhibited the highest comprehensive stability, while temperate meadow, typical steppe, and alpine meadow fell in an intermediate stability range. Desert steppe and alpine steppe had the poorest comprehensive stability and require more attention.

Furthermore, this study analyzed and compared the resistance and resilience of six grassland types under four climate intensities (severe drought, mild to moderate drought, mild to moderate wet, and severe wet). Vegetation resistance showed obvious differences under different climate event intensities (Fig. 7 [Fig-

ure 7: see original paper]). For meadow steppe, which exhibited the highest stability, both resistance and resilience were strongest under climate disturbances other than severe wet and severe drought conditions. Alpine meadow ranked low in resistance and resilience under drought events but had the strongest resistance yet worst resilience under severe wet conditions. In mild to moderate drought and wet conditions, temperate meadow ranked second in both resistance and resilience among the six grassland types. However, under severe drought and wet conditions, its resistance ranked higher than its resilience. Typical steppe showed intermediate resistance but the strongest resilience under severe drought and wet conditions. For desert steppe and alpine steppe, which require the most attention, they exhibited average resilience under wet climate conditions, ranking third and fourth respectively, but their resistance under wet conditions was weaker than other grassland types, indicating susceptibility to wet event disturbances with less-than-ideal recovery outcomes. Desert steppe showed the weakest resistance under mild to moderate drought, while alpine steppe showed the weakest resistance and resilience under severe drought, signifying the most significant impact of drought events on stability.

Fig. 5 Distribution of resistance value (a) and resilience value (b) of grassland in China from 1990 to 2019. Note that these maps are based on the standard map (No. GS(2020)4619) of the Map Service System (<http://bzdt.ch.mnr.gov.cn/>) marked by the Ministry of Natural Resources of the People's Republic of China, and the base map has not been modified.

Fig. 6 Resistance value (a) and resilience value (b) of six different grassland types in China from 1990 to 2019. Lines across boxes indicate median values, and points represent mean values. Lower and upper boxes show the interquartile range (25th and 75th percentiles). Whiskers correspond to the range within 1.5 times the interquartile range.

Fig. 7 Rank of resistance (a) and resilience (b) levels of six grassland types under different climate event types in China. SD, severe drought; MD, mild to moderate drought; MW, mild to moderate wet; SW, severe wet.

When drought event intensity increased, resistance and resilience of typical steppe, desert steppe, temperate meadow, and alpine meadow showed a coordinated trend. In contrast, when wet event intensity increased, resistance and resilience of typical steppe showed a trade-off, while meadow steppe showed a coordinated trend.

3.3 Impact of Climate Event Duration and Intensity on Stability

The above results indicated that desert steppe and alpine steppe had the lowest stability and require attention. This study employed a standardized regression model to investigate the impact of climate event duration and intensity on these two grassland types. VIF values obtained using RStudio for climate event dura-

tion and intensity were both less than 10. Standardized climate event duration and intensity factors were then input into the model, yielding the following results (Fig. 8 [Figure 8: see original paper]). The model was subjected to a t-test, with most grassland type results showing $P < 0.001$ for resistance and resilience, indicating significant relationships between variables (Table S1).

The results indicated that duration and intensity of different climate event types had varying effects on these grassland types. For desert steppe, climate event intensity had greater impact on resistance (75.1%) than duration under drought conditions, while intensity also had greater impact on resilience (66.3%) than duration under wet conditions. During drought, desert steppe resilience was primarily influenced by climate event duration (98.9%) rather than intensity. Conversely, alpine steppe was mainly influenced by climate event intensity in wet conditions for both resistance (97.8%) and resilience (53.7%) rather than duration.

Fig. 8 Effect of the duration and intensity of drought and wet climate events on desert steppe (a) and alpine steppe (b).

4.1 Differences in Stability

Meadow steppe demonstrated good stability against drought and wet climate events. Characterized by a semi-humid climate with moderate rainfall, it provides suitable conditions for vegetation growth. As Si et al. (2023) noted, meadow steppe exhibits favorable physiological and growth characteristics. Additionally, the good environment supports rich biodiversity and more complete ecosystem structure. Previous research showed that rich biodiversity can effectively improve ecosystem resistance stability (Isbell et al., 2015). These are the main reasons for meadow steppe's strong overall stability against climate event disturbances.

Regarding different climate types, meadow steppe exhibited remarkable resistance to drought and mild to moderate wet conditions. However, its resistance was generally lower under severe wet disturbance, indicating that excessive moisture can inhibit nutrient transport and reduce biodiversity and biomass (Zhou et al., 2023), which slows recovery rates and disrupts stability. Currently, few studies examine damage from wet climates to grasslands, representing an area for future research. Compared to other grassland types, meadow steppe showed stronger resilience after drought and wet disturbances, possibly attributed to lower productivity during periodic drought events caused by hydraulic depletion and carbon starvation, but more rapid recovery due to resource availability under normal climatic conditions (Zhang et al., 2019). Following droughts, precipitation along with sufficient moisture and effective photosynthesis provides conditions for growth state recovery.

Desert steppe and alpine steppe vegetation ecosystems had the worst stability

under climate events. Desert steppe is a grassland type transitioning from grassland to desert, with poor soil conditions and a harsh environment. Community species in this environment have simple structure and low biodiversity (Zhang et al., 2023). Vegetation coverage of desert steppe and alpine steppe was low (Fig. S1). Wang et al. (2023) suggested that vegetation types with lower coverage have lower recovery stability in response to disturbance events. Non-uniform ground temperature increases from global climate warming also reduce temporal stability during the alpine steppe growing season (Han et al., 2023). Additionally, human activities such as unreasonable grazing, reclamation, and mineral mining have directly led to grassland desertification. These factors are the main reasons for low stability in desert steppe and alpine steppe.

Grassland ecosystems respond to precipitation changes. The Qinghai-Tibet Plateau is becoming increasingly humid, and high mountain meadows in the northern plateau region show significantly increased NDVI due to increased precipitation, which may lead to increased grassland resilience stability in the future (Fu et al., 2018). Increased low-level precipitation contributes to increased species diversity in grasslands of the northern Qinghai-Tibet Plateau, thereby increasing grassland resistance (Xiao et al., 2023). These results are similar to Huang et al. (2021) regarding the rank of resistance and resilience levels among different grassland types. Differences between this study and previous research may be due to variations in study period, drought threshold classification methods, and SPEI data sources. The wet and drought threshold classification used in this study was proposed by Isbell et al. (2015), based on SPEI-12 values from more than 4000 sites worldwide over the past century and divided by percentile thresholds, thus being more unified and representative. Additionally, the SPEI-12 values used in this study were calculated using the Penman-Monteith Equation, which is universal and accurate given the rich data sources.

The standardized regression model used in this study has been widely applied in ecology and botany. Gross et al. (2017) used this method to study relationships between multiple biological traits and biodiversity. Grilli et al. (2017) and García-Palacios et al. (2018) also studied the impact of biodiversity on plant stability under extreme climate backgrounds. This method is simple and easy to implement, adding standardization and variance decomposition concepts to traditional regression models while maintaining research object independence. The results can more intuitively reflect independent effects of each factor. This study investigated the impact of climate event intensity and duration on grassland ecosystem stability and clearly provided the percentage contribution of duration versus intensity to vegetation ecosystem stability differences within the same grassland type. This study further clarified differences in response patterns of different grassland types to various climate events in terms of intensity and duration, providing insights and references for grassland ecosystem management.

4.2 Suggestions and Limitations

Global climate warming is an indisputable fact, and the increase and intensification of climate events has become a global trend. In recent years, many regions worldwide have experienced coexisting and frequent droughts and floods (Yang, 2019). Complex climate change has brought great uncertainty to grassland growth, potentially leading to varying degrees of degradation. Desert steppe and alpine steppe, being the least stable, urgently need attention. For these vulnerable grassland types, we should propose comprehensive management based on their characteristics in responding to climate events and implement diverse protection measures. For example, during the non-growing season, mechanical methods can improve soil properties and water use efficiency, creating favorable conditions for plant growth, enhancing productivity, and reducing vulnerability to climate events. During the growing season, excessive grazing and human-induced activities such as cultivation should be reduced. Additionally, establishing protected areas in key regions can mitigate human interference impacts. For grassland types more sensitive to climate event duration and intensity, monitoring climate factors such as precipitation and temperature can predict event occurrence, enabling early artificial intervention to help them recover as quickly as possible.

This article has certain limitations. This study considered the impact of long-term climate events on grassland vegetation at annual timescales. However, the stability of Chinese grasslands in response to short-term pulse events (such as sudden drought and extreme precipitation) remains unknown and requires future research. Moreover, regarding the impact of climate event duration and intensity on vegetation ecosystem stability within the same grassland type, this study only provided a comparative analysis of impact magnitude. Future curve fitting could clarify their relationship, offering more comprehensive recommendations for grassland management.

5 Conclusions

This study analyzed stability differences among six grassland types in China from 1990 to 2019 when disturbed by drought and wet climate events, using a standardized regression model to explore differences in how climate event duration and intensity impact grassland stability. We found that resistance and resilience differ significantly among grassland types. Meadow steppe had high-level resistance and resilience, indicating strong stability and better adaptation to environmental changes. The resistance and resilience of typical steppe, alpine meadow, and temperate meadow ranked at intermediate levels. In contrast, desert steppe exhibited the lowest resistance among the six types with no outstanding resilience performance, while alpine steppe showed the poorest resilience and lacked significant resistance—their management and protection should be strengthened.

Different grassland types exhibited varying responses to different climate event intensities. Alpine steppe showed the weakest resilience when facing mild to moderate and severe drought events. Once subjected to destructive drought disruptions, alpine steppe recovery may become challenging. Desert steppe had the poorest resistance to both mild to moderate drought and wet environments, but its resilience was better than alpine steppe. Regarding the impact of climate event duration and intensity on vegetation ecosystem stability within the same grassland type, desert steppe recovery during drought events was mainly influenced by duration, with intensity having less apparent effects. Conversely, for alpine steppe in wet environments, the primary influence was from intensity, while duration showed less noticeable effects. This study further clarified mechanisms through which wet and dry climate events affect grassland vegetation stability, laying groundwork for more in-depth research. The results can provide decisions and solutions for grassland ecosystem governance.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contributions

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Appendix

Fig. S1 Box plot of mean Normalized Difference Vegetation Index (NDVI) for different grassland types in China from 1990 to 2019. Lines across boxes indicate median values, and points represent mean values. Lower and upper boxes show the interquartile range (25th and 75th percentiles). Whiskers correspond to the range within 1.5 times the interquartile range.

Table S1 Results of the response model of the resistance and resilience of desert steppe and alpine steppe to the intensity and duration of climate events under drought and wet conditions

| Grassland type | Capability | Aspect | Estimate | SE | t-value | P (> |
|----------------|-----------------------------|-----------|----------|----|---------|----------|
| Desert steppe | Resistance to drought event | Intensity | | | | 0.000*** |
| | | Duration | | | | 0.000*** |
| | Resistance to wet event | Intensity | | | | 0.000*** |
| | | Duration | | | | 0.000*** |
| | Resilience to drought event | Intensity | | | | 0.000*** |
| | | Duration | | | | 0.000*** |
| Alpine steppe | Resistance to drought event | Intensity | | | | 0.000*** |
| | | Duration | | | | 0.000*** |
| | Resistance to wet event | Intensity | | | | 0.000*** |
| | | Duration | | | | 0.000*** |

| Grassland type | Capability | Aspect | Estimate | SE | t-value | P (> |
|----------------|-----------------------------|-----------|----------|----|---------|----------|
| | Resilience to drought event | Intensity | | | | 0.000*** |
| | | Duration | | | | 0.000*** |
| | Resilience to wet event | Intensity | | | | 0.000*** |
| | | Duration | | | | 0.000*** |

Note: SE, standard error; ***, significant at $P < 0.001$ level.

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

Source: ChinaXiv – Machine translation. Verify with original.