Effects of Simulated Drought on Soil Moisture and Community Structure in Temperate Grasslands on the Northeastern Margin of the Qinghai-Tibet Plateau

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Abstract

Soil moisture is a key factor regulating the structure and function of grassland ecosystems. To elucidate the response of fragile ecosystems in the Qinghai-Tibet Plateau–Loess Plateau transition zone to drought, this study selected a typical temperate steppe area on the northeastern margin of the Qinghai-Tibet Plateau as the research object. A continuous 6 a (2019—2024) rainfall-reduction simulation experiment with different gradients was conducted to analyze the effects of six treatments—natural precipitation and 20%, 30%, 40%, 60%, and 90% rainfall reduction—on soil moisture, community structure, species diversity, and niches in this region. The results showed that: (1) shallow soil moisture was the most sensitive to drought, with soil moisture decreasing markedly and drought severity increasing as the degree of rainfall reduction increased; (2) plant community responses exhibited a nonlinear threshold pattern, with species diversity increasing under mild to moderate drought, whereas extreme drought led to species loss and community simplification; (3) the drought-resistant advantage of Poaceae species (such as Agropyron cristatum) continued to strengthen with intensified drought stress; under the 90% rainfall-reduction treatment, the importance value of Agropyron cristatum reached 37.8%, showing clear dominance, whereas Cyperaceae and Fabaceae species gradually declined; (4) five key plant species, Kobresia humilis, Stipa sareptana var. krylovii, Agropyron cristatum, Medicago ruthenica, and Potentilla bifurca, all had niche breadths greater than 0.9 and niche overlap values higher than 0.8, forming a competitively dominant group under drought stress and serving as an important basis for maintaining community stability. This study indicates that intensified drought driven by reduced precipitation is a key factor constraining the stability of temperate steppe ecosystems on the Qinghai-Tibet Plateau, and that extreme drought events will accelerate the process of grassland desertification.

Full Text

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Effects of Simulated Drought on Soil Moisture and Community Structure in Temperate Grasslands on the Northeastern Margin of the Qinghai-Tibet Plateau

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Abstract: Soil moisture is a key factor regulating the structure and function of grassland ecosystems. To clarify the response of the fragile ecosystem in the Qinghai-Tibet Plateau-Loess Plateau transition zone to drought, a typical temperate grassland area on the northeastern margin of the Qinghai-Tibet Plateau was selected as the study site. A rainfall-reduction simulation experiment with different gradients was conducted continuously for 6 years (2019-2024), and the effects of six treatments—natural precipitation and rainfall reductions of 20%, 30%, 40%, 60%, and 90%—on soil moisture, community structure, species diversity, and ecological niches in the region were analyzed. The results showed that: (1) shallow soil moisture was the most sensitive to drought; as the degree of rainfall reduction increased, soil moisture decreased markedly and the drought level became more severe; (2) the response of the plant community exhibited a nonlinear turning point: species diversity increased under mild to moderate drought, whereas extreme drought led to species loss and community simplification; (3) the drought-resistance advantage of Poaceae plants, such as crested wheatgrass, continuously strengthened as drought stress intensified. Under the 90% rainfall-reduction treatment, the importance value of crested wheatgrass reached 37.8%, indicating a clear dominance, while Cyperaceae and Fabaceae plants gradually declined; (4) the niche breadths of five key plants—dwarf *Kobresia*, northwestern needlegrass, crested wheatgrass, Ruthenian medic, and bifurcate cinquefoil—were all greater than 0.9, and their overlap values were all higher than 0.8. Under drought stress, these species formed a competitively advantaged assemblage and became an important basis for maintaining community stability. The study indicates that drought intensification driven by reduced precipitation is a key factor constraining the stability of temperate grassland ecosystems on the Qinghai-Tibet Plateau, and that extreme drought events will accelerate the process of grassland desertification.

Keywords: northeastern margin of the Qinghai-Tibet Plateau; temperate grassland; drought; soil moisture; community structure

Against the background of global change, alterations in precipitation patterns have become a key factor affecting the structure and function of terrestrial ecosystems[1]. The IPCC Sixth Assessment Report 指出 that global warming will strengthen the atmosphere’ s water-holding capacity, leading to increased precipitation variability and frequent extreme drought events. As an “amplifier” of climate change, the Qinghai-Tibet Plateau is warming at a rate 2-3 times the global average, and uncertainty in precipitation has increased significantly[2-5]. The complex ecosystems of the Qinghai-Tibet Plateau provide multiple functions, including water conservation, carbon sequestration, and support for pastoral production, and are of strategic significance for regional ecological security[6-8]. Temperate grasslands on the Qinghai-Tibet Plateau occur in high-altitude, low-temperature environments and are located in the ecological transition zone between the Qinghai-Tibet Plateau and the Loess Plateau.

Their ecosystem resilience threshold is relatively low, and they are extremely sensitive to climate change and human activities, showing pronounced vulnerability[9–11]. In this context, an in-depth investigation of how reduced precipitation drives vegetation-community restructuring and the redistribution of dominant-species niches by altering soil moisture has important scientific value and practical significance for predicting degradation risks in temperate grasslands on the Qinghai–Tibet Plateau and for formulating adaptive management strategies.

Reduced precipitation not only directly affects plant physiological processes, but also alters species composition and community characteristics through cascading effects, thereby reshaping the sensitivity and stability of communities under drought. Specifically, reduced precipitation causes soil-water deficits, which in turn trigger distinct responses among different plant functional groups: deep-rooted plants can absorb deep soil water and thereby maintain relatively stable productivity, whereas shallow-rooted plants experience significantly reduced survival rates under long-term drought stress[12–13]. This asymmetric response changes the balance of interspecific competition and drives community composition toward drought-tolerant species by increasing leaf thickness, reducing specific leaf area, and decreasing the richness of plant functional groups[14–15]. At the same time, the reduction of species diversity exacerbates the instability of the entire grassland ecosystem, thereby increasing the risk of functional degradation and significantly weakening its ability to resist external disturbances[16–18]. Therefore, when grassland plant communities face water stress induced by reduced precipitation, they undergo "physiological stress → dominant-species filtering → community-structure simplification ⋯"

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⋯ization → weakened stability," thereby systematically reducing the drought-sensitivity threshold of grasslands.

Although the above mechanisms have been widely recognized at the theoretical level, current research in China and abroad has mainly focused on the statistical relationships between plant diversity and precipitation at large spatial scales, as well as the interactions between changes in meteorological factors and various elements of ecosystems. These studies are also affected by spatial heterogeneity and regional complexity, leading to substantial differences in conclusions[19-23]. For the temperate grassland ecosystem of the Qinghai-Tibet Plateau-Loess Plateau transition zone under different gradients of precipitation reduction, further research is still needed on how soil moisture, as a core factor, drives the coordinated evolution of dominant species composition and community species diversity. At present, studies on the impacts of reduced precipitation on temperate grassland ecosystems of the Qinghai-Tibet Plateau remain relatively limited, especially because systematic controlled-experiment evidence is lacking, and mechanistic analyses of the continuous process of "soil-moisture dynamics—dominant-species functional strategies—community stability" are insufficient. This study was conducted at the Haibei Animal Husbandry Meteorological Experimental Station on the northeastern margin of the Qinghai-Tibet Plateau-Loess Plateau transition zone, taking temperate grassland as the research object. By establishing controlled experiments with multiple gradients of precipitation reduction, combined with enclosure-management measures, the study simulated the distribution characteristics of soil moisture under drought conditions and their effects on vegetation community diversity and dominant-species composition. The results can provide a scientific basis for predicting dynamic changes in Qinghai-Tibet Plateau grassland ecosystems under future climate-change scenarios, and offer decision support for formulating effective grassland adaptive-management strategies and ecological-restoration measures. They are of great significance for maintaining ecological security on the Qinghai-Tibet Plateau and promoting sustainable regional development.

1 Materials and Methods

1.1 Overview of the Study Area

The study area is located in Xihai Town, Haiyan County, Haibei Tibetan Autonomous Prefecture, Qinghai Province, in the northeastern part of the Qinghai-Tibet Plateau (Fig. 1). It lies on the northeastern margin of the Qinghai-Tibet Plateau and belongs to the Qinghai-Tibet Plateau-Loess Plateau ecological transition zone. Specifically, it is located in the grassland observation field of the Haibei Animal Husbandry Meteorological Experimental Station ($36°57'\mathrm{N}, 100°51'\mathrm{E}$), at an elevation of 3140 m, and has a typical plateau continental climate[24]. The diurnal temperature range is large. Over the past 5 years, the mean annual temperature has been 1.4 °C, and annual precipitation has been 435.8 mm. Precipitation is unevenly distributed seasonally, with approximately 85% concentrated in the plant growing season from April to September, exerting an important influence on vegetation growth[25]. The study area is temperate grassland[26]. The main dominant species are *Kobresia humilis* and *Agropyron cristatum*, both of which are co-edificator species. *Astragalus adsurgens* and *Stipa krylovii* are key companion species; the community also includes common companion species such as *Medicago ruthenica* and *Koeleria cristata*. Together, these species form a complex and stable community structure, playing an irreplaceable role in maintaining regional ecological balance.

1.2 Experimental Design

Experimental plots were established beginning in 2019, and fencing was installed around the plots to protect the experiment from human and animal disturbance. A rainfall-reduction simulation system and a natural-precipitation treatment were constructed to simulate changes in natural precipitation gradients. This study adopted a single-factor completely randomized experimental design, with six treatments: natural precipitation, 20% rainfall reduction, 30% rainfall reduction, 40% rainfall reduction, 60% rainfall reduction, and 90% rainfall reduction. Each treatment had three replicates, for a total of 18 experimental plots. The rainfall-reduction simulation system consisted of two parts: a steel-frame structure and different numbers of U-shaped transparent rigid-plastic rain-collection gutters. To prevent water diffusion from affecting the experimental results, two types of water-isolation devices were also used: first, a 1 m-wide isolation buffer zone was established in the middle of each experimental plot; second, galvanized iron sheets were used around each water-control plot for water isolation. At the center of each experimental plot, an SMEC300 automatic soil-moisture measuring instrument or an SMR1400 automatic soil-moisture measuring instrument, together with a tipping-bucket rain gauge, was buried/installed. During the pasture growing seasons from 2023 to 2025 (*April–September*), soil moisture was measured hourly at 10 cm, 20 cm,

Visible map labels: Study area; Qinghai–Tibet Plateau; Haibei Tibetan Autonomous Prefecture; Elevation/m; 5281; 2298; 0; 420 km; 0; 50 km; N.

Note: The base map was produced using the standard map from the National Platform for Common Geospatial Information Services; the map approval number is GS(2024)0650, and the boundaries of the base map were not modified.

Fig. 1 Geographic information map of the study area

30 cm soil volumetric water content, precipitation, and other data. The experimental facilities are shown in Fig. 2.

1.3 Plant Community Survey

Aboveground biomass and community diversity data were investigated in July or August of 2023-2025. In each experimental plot, one standard quadrat of 50 cm × 50 cm was randomly selected near the center. The names of all pasture species in the quadrat were recorded, and five individuals of the same species were randomly selected within the quadrat to measure their height and coverage. According to species classification, the herbage within the quadrat was clipped flush with the ground and brought back to the laboratory. It was oven-dried at 65 °C to constant weight, and dry weight was measured.

1.4 Research Methods

Community diversity was evaluated using species richness (SR), the Shannon-Wiener diversity index (SH), and the Pielou evenness index (SP) [27]. The formulas for calculating community species diversity indices are as follows:

Species richness (SR):

$$SR = S \tag{1}$$

Shannon-Wiener diversity index (SH):

$$SH = -\sum_{i=1}^{S} p_i \ln p_i \tag{2}$$

Pielou evenness index (SP):

$$SP = \frac{SH}{\ln S} \tag{3}$$

where S is the total number of species appearing in a 1 m^2 quadrat; $p_i = n_i/N$, where n_i is the number of individuals of species i, and N is the sum of all species in the quadrat.

Combined with field survey records, the importance value (IV) of each species in the sample-plot community was calculated as follows:

$$IV = (CR + HR + BR)/3 \tag{4}$$

where IV is the importance value; CR is relative coverage; HR is relative height; and BR is relative biomass.

The interaction relationships among species and between species and the environment were evaluated using niche breadth (B_s) and niche overlap (O_{ik}) [28]. Niche breadth was calculated using the Shannon–Wiener index, and niche overlap was calculated using the Pianka overlap index. The formulas are as follows:

$$B_s = -\sum_{j=1}^{r} \left(p_{ij} \ln p_{ij}\right) \tag{5}$$

$$O_{ik} = \frac{\sum_{j=1}^{r} p_{ij} p_{kj}}{\sqrt{\sum_{j=1}^{r} p_{ij}^2 \sum_{j=1}^{r} p_{kj}^2}} \tag{6}$$

where p_{ij} and p_{kj} are the utilization proportions of species i and species k, respectively, in treatment j; j is the simulated rainfall-gradient treatment; and r is the number of levels of the simulated rainfall-gradient treatments. There were 6 treatments in total, i.e., $r = 6$.

Fig. 2 Diagram of experimental facilities

Panel annotations:
(a) Rainfall-reduction experimental simulation system; control experiment. Steel-frame structure: length 2.4 m, width 2.4 m. Galvanized iron sheet: length 2 m, width 2 m.
(b) Field view of the experimental facilities.
(c) Aerial view of the experimental plots.

1.5 Data Processing

Meteorological data were taken from the Haiyan National Meteorological Station for the corresponding period, including daily precipitation, maximum temperature, minimum temperature, mean temperature, and sunshine duration. Strict quality control was applied to the meteorological data: abnormal data were removed, and missing data were supplemented using methods such as moving-average interpolation.

After simple preprocessing of all data in Excel 2021, SPSS 21.0 was used to conduct one-way ANOVA, two-way ANOVA, and Duncan' s test for multiple comparisons to examine differences in soil water content among different precipitation scenarios and soil depths, as well as their interaction effects. Before data analysis, all types of data were tested for normal distribution using the one-sample K-S test; the results showed that all data conformed to a normal distribution. Figures were plotted using Origin 2021.

2 Results and Analysis

2.1 Changes in Soil Moisture in Temperate Grasslands of the Qinghai-Xizang Plateau under Different Precipitation-Reduction Treatments

Soil volumetric water content was used to characterize changes in soil moisture. As shown in Fig. 3, soil moisture in the 10 cm soil layer was the most sensitive to drought, and significant differences were observed among all precipitation-reduction treatments ($P < 0.05$). In particular, soil moisture under the 90% precipitation-reduction treatment was only 55.1% of that under natural precipitation. Soil moisture at 20 cm and 30 cm decreased significantly under 40% and 90% precipitation reduction, respectively ($P < 0.05$), and then increased markedly as the degree of precipitation reduction increased; under 90% precipitation reduction, soil moisture was 90.9% and 97.2% of that under natural precipitation at the same soil depths, respectively. In combination with the proportions of soil drought grades at the 10 cm soil depth under precipitation-reduction treatments (Table 1), it can be seen that drought stress intensified markedly with increasing precipitation reduction: the proportion of severe and extreme drought increased from 22.42% under natural precipitation to 100% under 90% precipitation reduction.

2.2 Effects of Precipitation-Reduction Treatments on Plant Community Diversity in Temperate Grasslands of the Qinghai-Xizang Plateau

In the temperate grassland plant communities of the Qinghai-Xizang Plateau, only the Pielou evenness index showed no significant difference ($P > 0.05$), whereas species richness and the Shannon–Wiener diversity index both differed significantly. The species richness index followed the order: 30% precipitation reduction > 20% precipitation reduction > 40% precipitation reduction > 60% precipitation reduction = natural precipitation > 90% precipitation reduction, and the value under 30% precipitation reduction was significantly higher than that under 90% precipitation reduction ($P < 0.05$). The Shannon–Wiener diversity index showed that 20% and 30% precipitation reduction were significantly higher than 90% precipitation reduction ($P < 0.05$); diversity levels gradually decreased from 20% and 30% precipitation reduction to 60% precipitation reduction, natural precipitation, 40% precipitation reduction, and 90% precipitation reduction (Fig. 4). Under 30% precipitation reduction, species were the richest, diversity was highest, and distribution was even; the 90% precipitation-reduction treatment performed poorly.

2.3 Effects of Precipitation-Reduction Treatments on Aboveground Biomass and Importance Values of Plant Functional Groups in Temperate Grasslands of the Qinghai-Xizang Plateau

The classification of functional groups is a core method in community ecology. By aggregating species according to function, it significantly reduces community complexity and simplifies ecosystem research through dimensionality reduction. At the same time, it is also an important means of revealing the internal mechanisms by which plants drive ecosystem processes, and of clarifying species distribution patterns and community-evolution dynamics[29-30].

2.3.1 Aboveground Biomass As shown in Fig. 5, the aboveground biomass of the community under 40%, 60%, and 90% precipitation reduction decreased significantly compared with natural precipitation and 20% precipitation reduction. Specifically, compared with natural precipitation, aboveground biomass decreased by 18.94%, 20.17%, and 30.22% under 40%, 60%, and 90% precipitation reduction, respectively. The aboveground biomass of Cyperaceae plants also showed a decreasing trend under precipitation-reduction treatments, but the decline was evident only under 90% precipitation reduction, decreasing by 65.12% compared with natural precipitation. The aboveground biomass of Poaceae plants, with increasing intensity of precipitation reduction, began to show a slight increase from 40% precipitation reduction onward.

Figure 3 labels: natural precipitation; 20% precipitation reduction; 30% precipitation reduction; 40% precipitation reduction; 60% precipitation reduction; 90% precipitation reduction.
Y-axis: soil volumetric water content / ($cm^3 \cdot cm^{-3}$).
X-axis: 10 cm; 20 cm; 30 cm.

Note: Different lowercase letters indicate significant differences according to Duncan' s multiple range test at the 5% level. The same below.

Fig. 3 Effects of different precipitation-reduction treatments on soil moisture in temperate grasslands on the Qinghai–Xizang Plateau.

Tab. 1 Proportion of soil drought levels in the 10 cm soil layer under different precipitation reduction treatments /%

Treatment	No drought	Light drought	Moderate drought	Severe drought	Extreme drought
Natural precipitation	43.10	21.84	12.64	14.37	8.05
Precipitation reduction 20%	40.80	12.07	23.56	23.56	0.00
Precipitation reduction 30%	16.09	13.79	31.61	16.67	21.84
Precipitation reduction 40%	6.32	15.52	29.31	31.61	17.24
Precipitation reduction 60%	5.17	11.76	23.76	37.93	21.38
Precipitation reduction 90%	0.00	0.00	0.00	56.32	43.68

Fig. 4 Effects of different precipitation reduction treatments on community diversity in the temperate steppe on the Qinghai-Xizang Plateau

In-figure labels: natural precipitation; precipitation reduction 20%; precipitation reduction 30%; precipitation reduction 40%; precipitation reduction 60%;

precipitation reduction 90%; community diversity index; SH; SP; SR.

an increasing trend, but the increase was small and the difference was not significant; under 90% precipitation reduction it increased by 8.13% compared with natural precipitation. The aboveground biomass of legumes showed a fluctuating decreasing trend; under 90% precipitation reduction it decreased by 68.23% compared with natural precipitation, and the difference was significant. The aboveground biomass of forbs was relatively distinctive, overall showing a trend of first increasing and then decreasing; under 20% precipitation reduction it was significantly higher than under natural precipitation, 60% precipitation reduction, and 90% precipitation reduction by 81.82%, 161.40%, and 194.94%, respectively.

2.3.2 Importance values of functional groups

The analysis of the importance values of plant functional groups under different precipitation reduction treatments showed (Fig. 6) that the importance values of Cyperaceae plants decreased under all precipitation reduction treatments compared with natural precipitation. The greatest decrease occurred under 40% precipitation reduction, reaching 52.1%, while the decreases under the other treatments ranged from 30% to 40%. Except under 30% precipitation reduction, the importance values of Poaceae plants were the highest among the functional groups; they reached a maximum of 60.98% under 90% precipitation reduction, an increase of 27.39% compared with natural precipitation, indicating their dominant position under extreme-drought stress. The importance values of legumes decreased under all precipitation reduction treatments compared with natural precipitation; the decreases under 40% and 90% precipitation reduction reached 65%–80%, those under 20% and 30% precipitation reduction were 30%–50%, and the smallest decrease occurred under 60% precipitation reduction, at 9.94%. The importance values of forbs increased markedly under all precipitation reduction treatments compared with natural precipitation; except for the 60.94% increase under 90% precipitation reduction, the other treatments all showed increases of 1–2 times relative to natural precipitation.

2.4 Effects of precipitation reduction treatments on species niches in the temperate steppe of the Qinghai-Xizang Plateau

Simulated drought induced differentiated responses among plant functional groups. As the degree of precipitation reduction increased, Cyperaceae plants gradually declined, while the dominance of Poaceae plants increased significantly; legumes and forbs showed varying responses. These different response patterns indicate that drought stress may drive the reorganization of community structure by adjusting interspecific resource-use strategies and competitive relationships. To further clarify the mechanisms of coexistence or competition among species under drought conditions, species niche analysis can be used to quantitatively reveal species' capacities to use environmental resources and their functional positions within the community, thereby elucidating the ecological processes by which drought affects community assembly[31-32].

Fig. 5 Effects of different precipitation reduction treatments on the aboveground biomass of plant functional groups in the temperate steppe on the Qinghai-Xizang Plateau

In-figure labels: natural precipitation; precipitation reduction 20%; precipitation reduction 30%; precipitation reduction 40%; precipitation reduction 60%; precipitation reduction 90%; aboveground biomass ($g \cdot m^{-2}$); plant functional group; community; Cyperaceae; Poaceae; legumes; forbs.

Fig. 6. Effects of different precipitation reduction treatments on the importance values of plant functional groups in the temperate steppe on the Qinghai-Xizang Plateau

2.4.1 Species importance value Vegetation surveys recorded a total of 17 plant species; their importance values under different precipitation reduction treatments are shown in Table 2. Cyperaceae included only one representative species, *Kobresia humilis*, whose importance value generally decreased by 5%-9% under the different precipitation reduction treatments compared with natural precipitation. Poaceae species were abundant, and their responses to water stress showed marked interspecific differences. Among them, *Agropyron cristatum* and *Stipa krylovii* exhibited strong drought resistance and showed a certain complementary distribution under different drought conditions. The sum of their importance values was 26.37% under natural precipitation and increased to 56.44% under the 90% precipitation reduction treatment, making them the absolute dominant species. In contrast, the importance values of other Poaceae plants such as *Koeleria cristata* decreased or even disappeared as drought intensified. Fabaceae plants showed clear interspecific differences in their responses to drought: *Astragalus adsurgens* declined rapidly under drought stress, *Gueldenstaedtia verna* appeared only briefly under the 30% precipitation reduction treatment, whereas *Medicago ruthenica* occurred in all treatments and reached its peak importance value under the 60% precipitation reduction treatment (19.48%). Forbs were diverse and displayed markedly different response patterns. Among them, *Potentilla bifurca* reached its peak importance value under the 30% precipitation reduction treatment; the importance value of *Heteropappus hispidus* rose to 19.51% under the 20% precipitation reduction treatment and then declined rapidly; and species such as *Taraxacum mongolicum* and *Artemisia frigida* appeared only under mild to moderate drought stress.

2.4.2 Niche breadth As shown in Table 3, five plant species had niche breadths greater than 0.9, forming the basis of community stability. Among them, *Kobresia humilis* and *Stipa krylovii* occupied the top two positions in niche breadth, both exceeding 0.98, followed by *Medicago ruthenica*, *Agropyron cristatum*, and *Potentilla bifurca*. Seven plant species had niche breadths below 0.5; among these, the niche breadths of *Gueldenstaedtia verna*, *Bupleurum* *chinense*, and *Artemisia scoparia* were all 0, and they appeared only under a single or a few precipitation reduction treatments, indicating high sensitivity and vulnerability to environmental conditions.

2.4.3 Niche overlap As shown in Fig. 7, the niche overlap values of the 17 plant species ranged from 0 to 1. According to the clustering results, the niche overlap values of the 17 plant species could be divided into four categories, among which Category 1 contained 5

Table 2. Important values of dominant species in the temperate steppe on the Qinghai-Xizang Plateau under different precipitation reduction treatments

Plant functional group	Species	Plant importance value/%: Natural precipitation	Plant importance value/%: 20% precipitation reduction	Plant importance value/%: 30% precipitation reduction	Plant importance value/%: 40% precipitation reduction	Plant importance value/%: 60% precipitation reduction	Plant importance value/%: 90% precipitation reduction
Cyperaceae	Dwarf kobresia *Kobresia humilis*	16.17	10.22	9.69	7.75	10.82	10.28
Poaceae	Krylov needlegrass *Stipa krylovii*	10.35	13.92	22.62	20.95	19.13	18.68
Poaceae	Crested wheatgrass *Agropyron cristatum*	16.02	15.1	6.98	24.04	21.67	37.76

Plant functional group	Species	Plant importance value/%: Natural precipitation	Plant importance value/%: 20% precipitation reduction	Plant importance value/%: 30% precipitation reduction	Plant importance value/%: 40% precipitation reduction	Plant importance value/%: 60% precipitation reduction	Plant importance value/%: 90% precipitation reduction
Poaceae	Annual bluegrass *Poa annua*	7.41	7.61	–	7.78	–	4.54
Poaceae	Crested koeleria *Koeleria cristata*	7.47	1.72	6.19	1.69	–	–
Poaceae	Drooping wildrye *Elymus nutans*	6.62	6.36	–	–	–	–
Fabaceae	Russian medic *Medicago ruthenica*	8.22	11.93	12.98	5.33	19.48	7.77
Fabaceae	Milkvetch *Astragalus adsurgens*	14.71	–	1.97	–	1.17	–
Fabaceae	Spring gueldenstaedtia *Gueldenstaedtia verna*	–	–	0.8	–	–	–

Plant functional group	Species	Plant importance value/%: Natural precipitation	Plant importance value/%: 20% precipitation reduction	Plant importance value/%: 30% precipitation reduction	Plant importance value/%: 40% precipitation reduction	Plant importance value/%: 60% precipitation reduction	Plant importance value/%: 90% precipitation reduction
Forbs	Bifurcate cinquefoil *Potentilla bifurca*	4.81	2.9	13.09	9.71	9.57	5.31
Forbs	Bristly heteropappus *Heteropappus hispidus*	8.22	19.51	6.83	11.51	1.11	2.93
Forbs	Multifid cinquefoil *Potentilla multifida*	–	7.09	7.43	1.1	1.56	7.48
Forbs	Heterophyllous dragonhead *Dracocephalum heterophyllum*	–	–	4.39	4.90	6.54	3.05

Plant functional group	Species	Plant importance value/%: Natural precipitation	Plant importance value/%: 20% precipitation reduction	Plant importance value/%: 30% precipitation reduction	Plant importance value/%: 40% precipitation reduction	Plant importance value/%: 60% precipitation reduction	Plant importance value/%: 90% precipitation reduction
Forbs	Mongolian dandelion *Taraxacum mongolicum*	–	0.98	2.14	5.24	–	–
Forbs	Fringed sagebrush *Artemisia frigida*	–	2.66	4.89	–	–	–
Forbs	Chinese thorowax *Bupleurum chinense*	–	–	–	–	8.95	–
Forbs	Scoparia wormwood *Artemisia scoparia*	–	–	–	–	–	2.2

Tab. 3 Niche width of dominant species in temperate steppe on the Qinghai-Xizang Plateau

Plant functional group	Species	Niche width
Cyperaceae	dwarf kobresia *Kobresia humilis*	0.985
Poaceae	Krylov needlegrass *Stipa krylovii*	0.983
Poaceae	crested wheatgrass *Agropyron cristatum*	0.938

Plant functional group	Species	Niche width
Poaceae	annual bluegrass *Poa annua*	0.762
Poaceae	crested koeleria *Koeleria cristata*	0.664
Poaceae	drooping wildrye *Elymus nutans*	0.387
Fabaceae	Ruthenian medic *Medicago ruthenica*	0.953
Fabaceae	*Astragalus adsurgens*	0.325
Fabaceae	*Gueldenstaedtia verna*	0
Forbs	bifurcate cinquefoil *Potentilla bifurca*	0.938
Forbs	*Heteropappus hispidus*	0.851
Forbs	multifid cinquefoil *Potentilla multifida*	0.779
Forbs	*Dracocephalum heterophyllum*	0.754
Forbs	Mongolian dandelion *Taraxacum mongolicum*	0.498
Forbs	fringed sage *Artemisia frigida*	0.362
Forbs	Chinese thorowax *Bupleurum chinense*	0
Forbs	redstem wormwood *Artemisia scoparia*	0

1 dwarf kobresia *Kobresia humilis*; 2 crested wheatgrass *Agropyron cristatum*; 3 *Astragalus adsurgens*; 4 Krylov needlegrass *Stipa krylovii*; 5 Ruthenian medic *Medicago ruthenica*; 6 *Heteropappus hispidus*; 7 crested koeleria *Koeleria cristata*; 8 annual bluegrass *Poa annua*; 9 drooping wildrye *Elymus nutans*; 10 bifurcate cinquefoil *Potentilla bifurca*; 11 multifid cinquefoil *Potentilla multifida*; 12 Mongolian dandelion *Taraxacum mongolicum*; 13 fringed sage *Artemisia frigida*; 14 *Dracocephalum heterophyllum*; 15 *Gueldenstaedtia verna*; 16 Chinese thorowax *Bupleurum chinense*; 17 redstem wormwood *Artemisia scoparia*.

Fig. 7 Niche overlap values of dominant species in temperate steppe on the Qinghai-Xizang Plateau

species; the plants were crested wheatgrass, Krylov needlegrass, Ruthenian medic, bifurcate cinquefoil, and dwarf kobresia, and their niche overlap values were all above 0.8, indicating a high degree of niche overlap. The second class contained eight plant species, namely *Heteropappus hispidus*, crested koeleria, annual bluegrass, drooping wildrye, multifid cinquefoil, Mongolian dandelion, fringed sage, and *Dracocephalum heterophyllum*; their mean niche overlap value was 0.50, indicating moderate niche overlap and resource sharing with the first core group, but at a relatively low level. The third class comprised *Astragalus adsurgens* and Chinese thorowax, and the fourth class comprised *Gueldenstaedtia verna* and redstem wormwood; their niche overlap values were all below 0.2, indicating that they competed only weakly with other plants, had an extremely low degree of similarity in resource use, and exhibited strong niche segregation.

3 Discussion

Precipitation is an important limiting factor for the stability of grassland ecosystem structure and function. In the early part of the growing season in the study area (April–June), reduced precipitation and frequent droughts[25] make it difficult for soil-water recharge to meet evapotranspiration demand, resulting in substantial consumption of soil water. Shallow soil receives atmospheric precipitation directly and is most strongly affected by evapotranspiration; therefore, it becomes the primary response layer under drought stress[33]. The sensitivity of this positive response is significantly related to vegetation coverage[34]. In plateau grasslands with relatively good vegetation coverage, the infiltration rate into deep soil is slightly higher than that into shallow soil; owing to differences in water-holding capacity and evaporation, deep soil has a higher water content[35]. In desert steppes with poor vegetation coverage, however, surface soil water declines rapidly after rainfall, whereas changes in deep soil water lag relatively behind[36]. This pattern is also broadly consistent with the changes in soil water observed under the 90% rainfall-reduction treatment in the present study. In the temperate steppe of the Qinghai-Xizang Plateau, Poaceae plants generally have deeper root systems and can use water from deeper soil layers, whereas Cyperaceae plants and forbs have shallower root systems and depend more strongly on surface soil water[37]. Therefore, surface-soil drought caused by reduced precipitation has a more severe effect on shallow-rooted plants.

Plant community diversity is an important basis for maintaining ecosystem stability and function. In this study, simulated drought treatments had a significant effect on plant community diversity in the temperate steppe of the Qinghai-Xizang Plateau. Specifically, as the degree of rainfall reduction increased, species richness and the Shannon-Wiener diversity index decreased significantly. This result is consistent with the conclusions of many studies. For example, Zhang Rui et al.[38] and Sun Yan et al.[39], by analyzing the effects of precipitation on grassland vegetation in arid and semi-arid regions, found that unstable precipitation significantly affects the soil-water supply for grassland vegetation, further leading to decreases in community diversity and cumulative biomass. Zhang Xiaoyan et al.[40] showed that precipitation is positively correlated with species richness, and that reduced precipitation affects plant growth by weakening soil-water and other nutrient conditions.

It is worth noting that the response of plant diversity to changes in precipitation may involve a threshold effect. When the magnitude of rainfall reduction is small, plant communities may adapt to changes in water conditions by adjusting species composition, so diversity changes are not significant; however, when rainfall reduction exceeds a certain threshold, diversity declines sharply. In this study, under 40% rainfall reduction and rainfall reduction

60% and 90% precipitation-reduction treatments both led to declines in diversity to varying degrees, indicating that the temperate grassland of the Qinghai-Xizang Plateau is relatively sensitive to reduced precipitation. The ecosystem may have a relatively low threshold of water tolerance, causing synchronous declines in grassland productivity and plant-community diversity, thereby inducing grassland degradation and constraining sustainable development[41–42].

Reduced precipitation lowers the availability of soil water and, at the same time, induces coordinated changes in the shift of dominance among plant functional groups and in species niche traits. A marked decrease in precipitation weakens the originally dominant species and maintains ecosystem stability by altering the plant community[43]. In the grassland ecosystem of the Qinghai-Xizang Plateau, dominant species are core elements driving community dynamics and ecosystem function[44]. In this study, the significant reduction in precipitation made soil water a key limiting factor. As a result, drought-tolerant species such as *Agropyron cristatum* could increase their dominance under the relatively severe 60% and 90% precipitation-reduction treatments by prolonging the vegetative growth period and shortening the reproductive growth period, thereby becoming dominant in the community[45]. By contrast, shallow-rooted Cyperaceae plants and forbs declined because of intensified competition for water. This process was accompanied by a general contraction of species niche breadth and a decrease in niche overlap, reflecting the differentiation of resource-use strategies and simplification of the competitive pattern of grassland plants under drought stress. In the long term, although such functional-group reorganization and niche adjustment may reduce interspecific competition and maintain basic ecosystem functions, it may also lead to simplification of community structure and the loss of some shallow-rooted species. In this study, species with relatively weak resistance, such as *Elymus nutans* and *Astragalus adsurgens*, gradually disappeared as drought stress intensified, resulting in weakened fluctuations in community diversity[46]. The positive interaction between temporal community stability and species richness was disrupted, causing reductions in community species number and community productivity, accelerating the possible replacement of temperate grassland by desert grassland, and thereby indirectly affecting ecosystem stability[47].

This study still has several limitations. First, the study was restricted to fenced grassland, and therefore may not fully capture the response of temperate grassland ecosystems to reduced precipitation under grazing management. Second, the spatial representativeness of the study is limited. The Qinghai-Xizang Plateau is vast, and climate conditions, soil types, and vegetation characteristics differ markedly among regions. In the future, multi-site comparative studies should be conducted across different ecological zones of the Qinghai-Xizang Plateau to reveal regional differences in the effects of reduced precipitation on grassland ecosystems and their regulatory mechanisms.

4 Conclusions

Through a multi-gradient precipitation-control experiment in temperate grassland on the Qinghai-Xizang Plateau, this study revealed the mechanisms by which drought affects soil water and plant communities, and obtained the following main conclusions:

(1) Soil water is the key factor regulating community responses to drought. Shallow soil water is most sensitive to reduced precipitation, while deep soil shows a certain buffering capacity; however, under extreme drought conditions, the

overall soil-water supply remains severely constrained.

(2) The response of plant communities to drought is nonlinear. Mild to moderate drought can promote species diversity, whereas extreme drought leads to simplification of community structure; grasses become dominant under drought stress and drive the community toward drought-tolerant succession.

(3) Niche differentiation is an important mechanism by which communities adapt to drought. Species with broad niche breadth and high niche overlap form the core competitive group and become the basis for maintaining community stability. Under future trends of climatic extremity, priority should be given to the protection of drought-resistant dominant species in order to maintain the stability of grassland ecosystems.

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Impact of simulated drought on soil moisture and community structure in temperate steppes on the northeastern edge of the Qinghai-Xizang Plateau

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Abstract: Soil moisture is a key factor regulating the structure and function of grassland ecosystems. This study investigated how the vulnerable ecosystem in the transitional zone between the Qinghai-Xizang Plateau and the Loess Plateau responds to drought, selecting a typical temperate steppe area on the northeastern edge of the Qinghai-Xizang Plateau. A simulated precipitation reduction experiment with varying gradients was conducted continuously for 6 years (2019–2024) to examine the effects of six treatments—natural precipitation and 20%, 30%, 40%, 60%, and 90% precipitation reduction—on soil moisture, community structure, species diversity, and ecological niches in the region. The results were as follows: (1) Shallow soil moisture was the most sensitive to drought, showing a clear decline and increasing drought severity as precipitation reduction intensified. (2) Plant community responses exhibited nonlinear transitions: species diversity increased under light to moderate drought but decreased under extreme drought, leading to community simplification. (3) The drought resistance of Gramineae species, such as *Agropyron cristatum*, increased progressively with drought stress intensity. Under the 90% precipitation reduction treatment, the importance value of *Agropyron cristatum* reached 37.8%, indicating clear dominance, whereas Cyperaceae species and legume species gradually declined. (4) Five key plant species—*Kobresia humilis*, *Stipa krylovii*, *Agropyron cristatum*, *Medicago ruthenica*, and *Potentilla bifurca*—exhibited niche breadths greater than 0.9 and niche overlap values exceeding 0.8. Under drought stress, these species formed a competitively dominant group and served as an important foundation for maintaining community stability. This study indicates that intensified drought driven by reduced precipitation is a key factor limiting the stability of temperate steppe ecosystems on the Qinghai-Xizang Plateau and that extreme drought events are likely to accelerate grassland desertification.

Keywords: the northeastern edge of the Qinghai-Xizang Plateau; temperate steppes; drought; soil moisture; community structure

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