

Effects of Nutrient Addition and Disturbance on Desert Steppe Community Composition and Assembly (Postprint)

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Abstract

Using mixed linear models, principal component analysis, and null model methods, this study investigated the effects of short-term nutrient addition (NPK, 10 g · m⁻² each) and disturbance on plant community species diversity, functional traits, soil physicochemical properties, and community assembly processes in the herbaceous community of the Urat Desert Steppe. The results showed that: (1) Disturbance and interactive treatments significantly reduced species richness and β -diversity, while short-term nutrient addition significantly decreased soil pH and increased soil electrical conductivity. (2) Under disturbance and nutrient addition treatments, six traits of the dominant species *Stipa glareosa*, *Peganum harmala*, *Salsola collina*, and *Corispermum mongolicum*, as well as the community-weighted mean (CWM) of functional traits, changed significantly, revealing that disturbance and nutrient addition drove the shift of dominant species from conservative strategies to acquisitive strategies. (3) Results from two null models indicated that herbaceous community assembly under control conditions tended toward stochastic processes, community assembly under disturbance and interactive treatments tended toward deterministic processes, and community assembly under nutrient addition treatment tended toward weaker deterministic processes. Desert steppe herbaceous communities respond to and adapt to nutrient addition and disturbance through changes in dominant species and key functional traits.

Full Text

Preamble

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Effects of Nutrient Addition and Disturbance on Community Composition and Assembly in Desert Steppe

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Abstract: Using mixed linear models, principal component analysis, and null model approaches, this study examined the effects of short-term nutrient addition (NPK, $10 \text{ g} \cdot \text{m}^{-2}$) and disturbance on plant community species diversity, functional traits, soil physicochemical properties, and community assembly processes in the Urat desert steppe herbaceous community. The results demonstrated that both disturbance and interactive treatments significantly reduced species richness and β -diversity. Short-term nutrient addition significantly decreased soil pH and increased soil electrical conductivity. Disturbance and nutrient addition treatments induced significant changes in six functional traits of dominant species (*Stipa glareosa*, *Peganum harmala*, *Salsola collina*, and *Corispermum mongolicum*) and six community-weighted mean (CWM) functional traits, revealing that disturbance and nutrient addition promote a shift in community dominant species from conservative to acquisitive strategies. Two null model approaches indicated that community assembly under control conditions tended toward stochastic processes, while disturbance and interactive treatments tended toward deterministic processes, and nutrient addition treatments tended toward weaker deterministic processes. Desert steppe herbaceous plant communities respond to and adapt to nutrient addition and disturbance through changes in dominant species and key functional traits.

Keywords: desert steppe; nutrient addition; disturbance; species diversity; functional diversity; community assembly

Introduction

Desert steppe represents the most xerophytic type of grassland ecosystem, widely distributed globally and highly susceptible to environmental fluctuations. Since the Industrial Revolution, global nutrient deposition and human activities have severely impacted species composition, soil physicochemical properties, and ecosystem functions in desert steppe communities [1-3], altering the mechanisms underlying stable species coexistence and maintenance [4-5]

and posing significant challenges to the conservation of desert steppe ecosystem functions and services. Previous research has demonstrated that due to differences in resource use efficiency among plants [6-7], nutrient addition and disturbance affect local community species composition (α -diversity) and differences in species composition among communities (β -diversity). Because multiple nutrient additions reduce soil niche dimensionality and strengthen the directional selection of environmental filtering, they lead to species diversity loss [8-9]. Numerous studies have shown that disturbance impacts on biodiversity follow a hump-shaped pattern [10-11], where moderate disturbance levels maintain higher species diversity because low disturbance levels allow only a few highly competitive species to dominate, while excessively high disturbance levels permit only fast-growing, highly invasive species to survive [12-13]. However, even before species loss occurs, community trait structures may have already changed due to habitat degradation, making trait-based analyses more valuable for anticipating ecosystem responses to environmental change [14-15].

Functional traits characterize a series of attributes related to plant establishment, survival, growth, and death [16], reflecting plant responses and adaptations to external environmental changes and linking the environment with individual plants and ecosystems [17-18]. Through long-term natural selection and evolution, different functional plant types have formed trade-off relationships in resource acquisition and allocation among leaf functional traits according to their functional requirements, known as the leaf economics spectrum (LES) [19-20]. At one end of the LES are “fast investment-return” species with short lifespans, high leaf nitrogen content, high leaf phosphorus content, strong photosynthetic capacity, rapid respiration rates, and low leaf mass per area. At the other end are “slow investment-return” species with opposite functional trait characteristics [21-22]. Specific leaf area (SLA) is a core trait in the LES that characterizes plant resource acquisition, utilization, and adaptation across different habitats [23-24]. Leaf thickness and leaf dry matter content are closely related to plant water-holding capacity and stress resistance [25-26]. Studying how these traits respond to nutrient addition and disturbance is crucial for elucidating community functional structure changes and ecosystem succession mechanisms [27-28]. Furthermore, because ecosystem functions are largely determined by dominant species within communities [10, 17], comprehensively considering community species composition and functional trait characteristics, community-weighted mean (CWM) based on the mass ratio hypothesis (MRH) serves as a key indicator of functional diversity, effectively reflecting how communities respond to and adapt to environmental changes [3, 17]. Although some studies have focused on the effects of nutrient addition on functional traits in desert steppe plants, most have concentrated on single experimental treatments and functional traits, failing to comprehensively reveal the response and adaptation strategies of desert steppe plant communities to nutrient addition, disturbance, and their interactions. Therefore, investigating how several functional traits reflecting different ecological strategies change with nutrient addition and human disturbance, and examining the relationships between traits and local soil fac-

tors, can provide comprehensive understanding of resource utilization strategies of different plants in desert steppe and clarify how environmental fluctuations drive changes in local biodiversity through soil factor alterations, thereby providing theoretical foundations for the conservation of fragile ecosystems.

The mechanisms by which species stably coexist and maintain diversity within communities have long been central questions in ecological research [29-30]. Studies have shown that the relative importance of deterministic and stochastic processes is influenced by environmental conditions and ecosystem types [31-32]. Deterministic processes emphasize niche differentiation among coexisting species, including environmental filtering (primarily determined by climate and soil factors) and interactions among species (e.g., competition, facilitation), which determine species presence and relative abundance [33-34]. Stochastic processes are based on neutral theory, typically including random birth-death events, probabilistic dispersal, and ecological drift, emphasizing the randomness and contingency of species assemblages rather than environmentally determined adaptive outcomes [35-36]. Nutrient addition and disturbance may alter the relative importance of deterministic and stochastic processes in desert steppe, thereby changing community assembly trajectories. For example, soil nutrient enrichment and acidification caused by nutrient addition may favor stronger resource competitors or low-pH tolerant species, while disturbance-induced changes in soil environmental conditions may facilitate colonization and proliferation of early-successional species, strengthening deterministic processes [37-38].

Desert steppe is an important grassland type in northern China, facing severe degradation under global climate change and increasing human activities [1, 24-25]. The Urat Desert Steppe, as one of the concentrated natural grassland distributions in Inner Mongolia, constitutes an important component of the national ecological security strategic pattern of the “Northeast Forest Barrier Belt” and “Northern Sand Control Belt,” with strong ecological fragility due to harsh natural environmental conditions [24, 26]. In recent years, various human disturbances superimposed on global climate change have further exacerbated local desert steppe ecosystem degradation. Most current research has focused separately on the effects of nutrients and disturbance on plant community species diversity and functional traits in desert steppe, with few studies comprehensively examining the impacts of these two factors and their interactions on local herbaceous communities from the perspectives of species diversity, functional traits, soil physicochemical properties, and community assembly mechanisms. Therefore, this study used the Urat Desert Steppe herbaceous plant community as the research object, conducting field control experiments to investigate the effects of nutrient addition and disturbance treatments on local plant community composition and assembly mechanisms, aiming to reveal how desert steppe plant communities respond and adapt to global climate change and human disturbance, thereby providing theoretical foundations and practical guidance for maintaining and protecting the national ecological security and northern ecological barrier.

1. Materials and Methods

1.1 Study Area Overview

The study area is located at the Urat Desert Grassland Research Station's Disturbance and Restoration Experimental Field in Bayannur City, Inner Mongolia (107°E, 41.4°N). The region has a mid-temperate plateau continental climate characterized by cold, dry winters and dry, rainless summers with strong solar radiation and high evaporation. The average annual temperature is approximately 3.8°C, with average precipitation of about 100 mm, of which 70% occurs from June to August. Due to long-term wind erosion, soil nutrient content is low [39]. The annual frost-free period is 130 days, and annual frozen soil depth reaches 2.3 m. According to the Chinese Soil Classification System (National Soil Survey Bureau, 1993), soil types are classified as brown soil and gray-brown desert soil, with soil pH ranging from 7.5 to 9.5. The constructive species in the study area is *Stipa glareosa*, with dominant species primarily including *Peganum harmala* and *Salsola collina*. Additionally, *Corispermum mongolicum*, *Allium polyrhizum*, *Allium mongolicum*, *Asparagus cochinchinensis*, *Scorzonera austriaca*, *Lagochilus ilicifolium*, *Artemisia frigida*, *Cleistogenes squarrosa*, *Convolvulus ammannii*, *Echinops gmelini*, and *Agropyron cristatum* are also common species in the study area (Table 1).

1.2 Experimental Design

This study site is part of the global Disturbance and Resources Across Global Grasslands Network (DRAGNet; <https://dragnetglobal.weebly.com>). To minimize the impact of environmental heterogeneity on experimental results, we selected representative plots with relatively uniform environmental conditions and flat terrain within a large fenced area established in 2018. The experiment included four treatments: control (Control), nutrient addition (NPK), physical disturbance (Dis), and nutrient addition plus disturbance interaction (NPK +Dis), with six replicate plots per treatment, each measuring 5 m × 5 m. To minimize interference between adjacent plots, a 1 m buffer zone was established between them.

Nutrient addition involved both macro- and micronutrients applied annually in mid-to-late May starting in 2019. Macronutrients followed the same addition protocol as the global Nutrient Network (NutNet), with N, P, and K added at 10 g · m⁻² each. Micronutrients were applied using a micronutrient compound fertilizer with composition and ratios of Ca:Mg:S:B:Cu:Fe:Mn:Mo:Zn = 6:3:12:0.10:1:17:2.50:0.05:1, applied at 100 g · m⁻² only in the first year of treatment.

The physical disturbance method simulated human impacts on typical desert steppe plant communities. Conducted annually in mid-to-late May, the procedure involved: (1) removing all aboveground plant parts and tilling to 15

cm depth, then removing roots within 15 cm depth; (2) investigating plant community species composition and succession processes after disturbance. Additionally, to examine how communities respond and adapt to the interaction of nutrient addition and disturbance, we established an interactive treatment (NPK +Dis) where aboveground vegetation was removed and soil tilled in mid-to-late May each year, followed by nutrient addition using the same method and amount as the nutrient addition treatment alone.

1.3 Survey Methods

Sampling was conducted during the peak biomass period in early August of the third experimental year (2021). Vegetation surveys were performed using quadrat methods, with one 1 m × 1 m quadrat randomly selected in each plot, positioned at least 0.5 m from plot edges to avoid edge effects. After surveying, all plants within quadrats were harvested at ground level and transported to the laboratory, where they were dried at 65°C to constant weight to measure aboveground biomass for each species.

Following standardized functional trait sampling and measurement protocols [40], we sampled and measured leaves of dominant species (primarily *Stipa glareosa*, *Peganum harmala*, *Salsola collina*, and *Corispermum mongolicum*) in each quadrat. Measured traits included: plant height (Height, cm), leaf thickness (Thickness, mm), specific leaf area (SLA, m² · kg⁻¹), leaf dry matter content (LDMC, g · kg⁻¹), leaf nitrogen content (LNC, g · kg⁻¹), and leaf carbon content (LCC, g · kg⁻¹). For each species, 10-60 fully expanded, healthy sun-exposed leaves were collected, placed between moist filter paper, and stored in sealed bags in a portable refrigerator (<5°C). In the laboratory, leaf petioles were removed, and leaves were soaked in water for 12 hours to fully rehydrate and expand. After soaking, leaves were removed, surface water was blotted dry, and fresh weight was measured using a 0.001 g precision electronic balance. Leaves were then scanned using a scanner, and images were processed using ImageJ software (Version 1.52a) to obtain total leaf area. Finally, leaves were oven-dried at 65°C for 48 hours and weighed to obtain dry weight.

Concurrently, leaves of dominant plants were collected, dried at 65°C for 48 hours, then ground and analyzed using an elemental analyzer (Costech Ecs4010, Italy) to determine leaf carbon and nitrogen content. In each plot, three soil samples were collected from 0-10 cm depth using a 5 cm diameter soil auger, mixed, air-dried in a ventilated area, sieved through a 2 mm mesh, and analyzed for: total carbon content (TCC, g · kg⁻¹), total nitrogen content (TNC, g · kg⁻¹), soil water content (SWC), and electrical conductivity (EC, S · cm⁻¹). Soil water content was measured using the oven-drying method [41].

The calculation formulas are:

$$\text{LDMC} = \frac{\text{leaf dry weight}}{\text{leaf fresh weight}} \times 1000$$

$$SLA = \frac{\text{leaf area}}{\text{leaf dry weight}}$$

Community-level functional diversity was represented by community-weighted mean (CWM), calculated as:

$$CWM = \sum_{i=1}^n P_i \times \text{trait}_i$$

where P_i represents the relative biomass of species i in the community, trait_i represents the trait value of species i , and n represents the number of species in the community.

1.4 Statistical Analysis

All statistical analyses and plotting were completed in RStudio (2022.02.1+461). Treatment effects on species diversity, soil physicochemical properties, functional traits, and community assembly indices were compared using linear mixed models with treatment as a fixed effect and block as a random effect. The “sjstats” package was used for model comparisons. Species non-metric multidimensional scaling (NMDS) and β -diversity calculations were performed using the “vegan” and “adespatial” packages. Principal component analysis of soil and trait data was conducted using the “FactoMineR” and “factoextra” packages. To explore relationships between soil physicochemical property changes and CWM traits under different treatments, mixed linear models were used for regression analysis. The null model approach used the “Crick” method based on species presence-absence data and the “RC” method based on species abundance data to explore deterministic or stochastic processes in community assembly under different treatments. Duncan’s method was used for multiple comparisons.

2. Results

2.1 Effects of Nutrient Addition and Disturbance on Community Species Composition and Soil Physicochemical Properties

NMDS analysis revealed significant differences in community species composition among treatments (Stress<0.05). Under disturbance and interactive treatments, species composition was relatively simple, with *Corispermum mongolicum* and *Salsola collina* as the two dominant species. Under control and nutrient addition treatments, species composition was relatively rich, primarily including *Stipa glareosa*, *Peganum harmala*, *Cleistogenes squarrosa*, *Agropyron cristatum*, *Allium polyrhizum*, and *Lagochilus ilicifolium* (Fig. 1).

[Figure 1: see original paper]

Species richness and β -diversity showed highly significant differences among treatments. Compared with the control, disturbance and interactive treatments significantly reduced species richness and β -diversity, while nutrient addition treatments showed no significant changes in species richness or β -diversity ($P < 0.01$) (Fig. 2).

[Figure 2: see original paper]

Disturbance treatment had no significant effect on soil properties, while nutrient addition and interactive treatments significantly reduced soil pH but had no significant effect on soil water content (Table 2). Nutrient addition and interactive treatments also significantly increased soil electrical conductivity ($P < 0.001$).

Nutrient addition, disturbance, and their interaction significantly affected functional traits of the dominant species *Stipa glareosa*, *Peganum harmala*, *Salsola collina*, and *Corispermum mongolicum*. Compared with the control, nutrient addition significantly reduced *Stipa glareosa*'s LDMC ($P < 0.05$) and significantly increased its LNC ($P < 0.01$). Disturbance significantly increased *Peganum harmala*'s Thickness ($P < 0.05$), while nutrient addition significantly increased its LNC ($P < 0.01$). Disturbance, nutrient addition, and interactive treatments all significantly increased *Salsola collina*'s Height ($P < 0.001$). Nutrient addition and interactive treatments significantly increased *Salsola collina*'s SLA ($P < 0.01$), with interactive treatment showing significantly higher SLA than nutrient addition treatment ($P < 0.05$). Disturbance and interactive treatments significantly increased *Salsola collina*'s LNC ($P < 0.001$), with nutrient addition and interactive treatments showing significantly higher LNC than disturbance treatment ($P < 0.05$). Disturbance significantly increased *Corispermum mongolicum*'s Height ($P < 0.05$), with interactive treatment showing significantly higher Height than nutrient addition treatment ($P < 0.05$). Nutrient addition significantly increased *Corispermum mongolicum*'s SLA ($P < 0.05$), with interactive treatment showing significantly higher SLA than disturbance treatment ($P < 0.05$). Disturbance and interactive treatments significantly increased *Corispermum mongolicum*'s LNC ($P < 0.001$), with nutrient addition and interactive treatments showing significantly higher LNC than disturbance treatment ($P < 0.05$) (Figs. 3-6).

[Figure 3: see original paper] [Figure 4: see original paper] [Figure 5: see original paper] [Figure 6: see original paper]

2.2 Effects of Nutrient Addition and Disturbance on Community Functional Traits

Treatments significantly affected community height, leaf dry matter content, and specific leaf area ($P < 0.05$), and highly significantly affected community thickness, leaf nitrogen content, and leaf carbon content ($P < 0.01$). Compared with the control, interactive treatment significantly increased CWMHeight ($P < 0.05$). Disturbance and interactive treatments significantly increased CWMThickness ($P < 0.01$) but decreased CWMLDMC ($P < 0.05$). Nutrient

addition and interactive treatments significantly increased CWMSLA ($P < 0.05$). Nutrient addition, disturbance, and interactive treatments all significantly increased CWMLNC ($P < 0.001$). Interactive treatment significantly reduced CWMLCC ($P < 0.001$) (Fig. 7).

[Figure 7: see original paper]

2.3 Principal Component Analysis of Soil Properties and Community Functional Traits and Their Relationships

Principal component analysis of soil properties showed that soil pH and EC had high loadings on the first principal component, TNC and TCC had high loadings on the second principal component, and SWC had high loadings on both components. The first principal component explained 27.1% of variance, the second explained 45.0%, with a cumulative explanation of 72.1%. Principal component analysis of community functional traits showed that CWMLCC and CWMThickness had high loadings on the first principal component, CWMHeight and CWMLDMC had high loadings on the second principal component, and CWMLNC and CWMSLA had high loadings on both components. The first principal component explained 50.1% of variance, the second explained 20.7%, with a cumulative explanation of 70.8% (Fig. 8).

[Figure 8: see original paper]

Regression analysis revealed a highly significant positive correlation between soil pH and CWMLDMC ($P < 0.01$) and a highly significant negative correlation between soil pH and CWMSLA ($P < 0.01$). Soil EC showed a highly significant positive correlation with CWMLNC ($P < 0.01$) (Fig. 9).

[Figure 9: see original paper]

2.4 Effects of Nutrient Addition and Disturbance on Community Assembly Mechanisms

The RC index showed highly significant differences among treatments ($P < 0.001$). RC indices under disturbance and interactive treatments were significantly smaller than zero, while those under control and nutrient addition treatments were greater than zero. Compared with the control, RC indices under nutrient addition treatment decreased but remained significantly greater than those under disturbance and interactive treatments. These results indicate that stochastic processes dominated community assembly under control and nutrient addition treatments, while deterministic processes dominated under disturbance and interactive treatments. Different treatments showed highly significant differences in the Crick index ($P < 0.001$). All treatment Crick indices were smaller than zero. Compared with the control, Crick indices under disturbance, nutrient addition, and interactive treatments significantly decreased. Crick indices under nutrient addition treatment were significantly smaller than the control but significantly larger than those under disturbance and

interactive treatments. These results indicate that deterministic processes had greater influence on community assembly under nutrient addition, disturbance, and interactive treatments (Fig. 10).

[Figure 10: see original paper]

3. Discussion

Previous studies have shown that nutrient addition negatively affects species richness, associated with soil acidification, light limitation, and stochastic loss of low-abundance species [4, 7, 25]. In this study, nutrient addition had no significant effect on species richness, likely due to the short experimental duration. Desert steppe soils have loose texture and poor water and nutrient retention capacity. Impoverished soils and low precipitation create dual limitations of nutrients and water for plants in this region [39]. Local plants have adapted to these ecological conditions through long-term natural selection and evolution. The ecological amplitude and tolerance range of plants will not change in the short term due to nutrient addition, resulting in minimal establishment of new species and loss of existing species, and thus insignificant changes in species richness. Species richness generally responds to disturbance following a hump-shaped pattern (intermediate disturbance hypothesis) [10-11], where species richness is highest at intermediate disturbance levels and decreases at both low and high disturbance levels. This study found that disturbance and interactive treatments significantly reduced species richness, consistent with previous results [6, 33] showing that severe disturbance strongly negatively impacts species richness.

β -diversity reveals differences in species composition among communities [4, 33] and is strongly driven by local environmental conditions, particularly soil factors. Previous studies have shown that nutrient addition significantly reduces plant community β -diversity [4, 34]. In this study, β -diversity under nutrient addition treatment decreased but not significantly, indicating that short-term nutrient addition makes community species composition more similar but with relatively mild effects. β -diversity significantly decreased under disturbance and interactive treatments, consistent with previous findings [6, 33] that community species composition becomes more similar under severe disturbance. Vegetation-soil feedback indicates mutual interactions between plant growth and soil property evolution: soil provides water and mineral nutrients for plant growth, determining plant community types and species composition, while vegetation is the primary source of soil organic matter [42]. In this study, nutrient addition and disturbance treatments altered community species composition and diversity by affecting soil properties. Consistent with numerous previous studies [4, 7, 25], nutrient addition significantly reduced soil pH and increased soil EC, while SWC showed no significant changes, possibly due to the relatively low nutrient addition amount and short experimental duration.

Disturbance treatment fundamentally altered surface soil characteristics, making soil texture looser and increasing soil porosity. These soil conditions favored the growth and reproduction of early-successional pioneer annual species *Salsola collina* and *Corispermum mongolicum*, which have characteristics of rapid growth, high seed production, and strong dispersal ability. Under interactive treatment, increased soil nutrient content promoted faster growth of pioneer plants after disturbance. Disturbance acts as a strong directional environmental filter on local communities, allowing only species adapted to post-disturbance soil conditions to colonize and reproduce early.

Plant functional traits reflect plant response and adaptation strategies to environmental changes, embodying intrinsic trade-offs between resource acquisition efficiency and investment [14, 16]. For example, annual plants invest more resources in leaf area and less in structural construction, while perennial plants show the opposite pattern, resulting in negative correlations between SLA and LDMC [19, 21]. In this study, under disturbance and interactive treatments, the annual species *Salsola collina* and *Corispermum mongolicum* with “fast investment-return” (acquisitive) strategies were dominant, characterized by low LDMC and high SLA. This functional trait combination allows them to rapidly utilize limited environmental resources, achieve stronger carbon assimilation, and rapidly increase biomass in short time periods. In contrast, under control and nutrient addition treatments, the perennial dominant species *Stipa glareosa* and *Peganum harmala* tended toward “slow investment-return” (conservative) strategies with opposite leaf functional trait characteristics, providing stronger resistance to adverse environmental conditions, particularly nutrient and water deficits [11, 15].

Nutrient-enriched conditions prompted annual species to invest more resources in leaf area and reduce LDMC, while increased Thickness of *Peganum harmala* and *Corispermum mongolicum* under disturbance may enhance resistance to adverse environments. Plant height typically reflects light resource competition capacity, while leaf thickness is closely related to water-holding capacity [26, 28]. Traits characterized by high Height, Thickness, and SLA facilitate rapid vegetative growth [43]. In this study, the significant increase in height of acquisitive species *Salsola collina* and *Corispermum mongolicum* under disturbance and interactive treatments may result from simplified species composition and reduced interspecific competition. Increased height enhances light acquisition capacity, while thicker leaves help acquisitive species store water under dry conditions. Unlike previous studies [44], CWMLDMC under nutrient addition treatment decreased but not significantly. Due to dual limitations of nutrients and water in desert steppe, plant community LDMC does not linearly decrease with N input, so plant community assembly under N enrichment is dominated by deterministic processes [37], consistent with our results. Compared with nutrient addition treatment, disturbance treatment resulted in more homogeneous community species composition, stronger environmental filtering, lower β -diversity, and thus community assembly tended more toward deterministic processes. Additionally, community assembly under control treatment tended

toward stochastic processes, indicating that desert steppe herbaceous communities are naturally susceptible to stochastic processes such as birth, death, migration, and dispersal events. In summary, both disturbance and short-term nutrient addition affect local plant community assembly mechanisms, with disturbance having more pronounced effects. These results demonstrate that stable species coexistence and maintenance in desert steppe communities are strongly influenced by global climate change and human activities, consequently altering ecosystem structure and function.

This study examined desert steppe community responses in species composition, soil physicochemical properties, functional traits, and community assembly mechanisms to nutrient addition and disturbance. However, the study duration was relatively short. Future research will continue to monitor long-term dynamics of aboveground and belowground communities under different treatments and observe recovery trends in disturbed experimental plots to more systematically and clearly elucidate the response and adaptation mechanisms of desert steppe communities to nutrient enrichment and disturbance, thereby providing theoretical foundations for desert steppe ecosystem conservation and restoration.

4. Conclusion

Desert steppe herbaceous communities showed differential responses in species diversity, functional traits, soil physicochemical properties, and community assembly processes to nutrient addition, disturbance, and their interactive treatments:

- 1) *Stipa glareosa* and *Peganum harmala* were dominant species under control and nutrient addition treatments, while *Salsola collina* and *Corispermum mongolicum* were dominant under disturbance and interactive treatments. Disturbance and interactive treatments significantly reduced community species richness and β -diversity, while nutrient addition had similar but milder effects. Nutrient addition and interactive treatments significantly reduced soil pH, while nutrient addition, disturbance, and interactive treatments significantly increased soil EC.
- 2) Compared with the control, nutrient addition reduced *Stipa glareosa*'s LDMC and increased LNC of all four dominant species, as well as SLA of *Stipa glareosa* and *Peganum harmala*. Disturbance increased Height of *Salsola collina* and *Corispermum mongolicum*, Thickness of *Peganum harmala* and *Corispermum mongolicum*, and LNC of *Salsola collina* and *Corispermum mongolicum*. Nutrient addition significantly increased CWMSLA and CWMLNC, disturbance significantly increased CWMLDMC, and interactive treatment significantly increased CWMHeight, CWMThickness, CWMSLA, and CWMLNC but decreased CWMLCC.

- 3) Principal component and regression analyses revealed significant positive correlations between soil pH and CWMLDMC, and significant negative correlations between soil pH and CWMSLA. Soil EC showed significant positive correlation with CWMLNC.
- 4) Null model analysis revealed that community assembly under control conditions tended toward stochastic processes, while disturbance and interactive treatments tended toward deterministic processes, and nutrient addition treatment tended toward weaker deterministic processes.
- 5) Disturbance and nutrient addition promoted a shift in desert steppe community dominant species from conservative to acquisitive strategies, with disturbance having stronger effects. Perennial plants such as *Stipa glareosa* with conservative strategies have stronger stress resistance under natural conditions of dual nutrient and water limitation, thus dominating; annual plants such as *Salsola collina* with acquisitive strategies act as pioneer species that can rapidly occupy niches in disturbed communities, colonize early environments with loose soil, and grow and reproduce abundantly. Different treatments affected local environmental conditions, particularly soil properties, further altering community species composition and functional traits. Environmental filtering, especially soil conditions after disturbance and nutrient addition, determined species presence and relative abundance within communities, thereby influencing ecosystem functions and community assembly mechanisms. Trade-offs between dominant species traits and community traits reflected resource acquisition and allocation trade-offs at both species and community levels, closely related to species lifespan and ecological strategies.

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