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Research article

Effects of grazing and precipitation addition induced by functional groups on the relationship between aboveground biomass and species richness of a typical steppe

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ABSTRACT

Several studies have explored the influence of grazing or precipitation addition (PA), two important components of human activities and global climate change on the structure and function of communities. However, the response of communities to a combination of grazing and PA remains largely unexplored. We investigated the impact of grazing and PA on the relationship between aboveground biomass (AGB) and species richness (SR) of communities in three-year field experiments conducted in a typical steppe in the Loess Plateau, using a split-plot design with grazing as the main-plot factor and PA as the split-plot factor. AGB and SR have response threshold value to PA, which was decreased by grazing for AGB, but increased for SR. This indicates that implementing grazing management strategies is conducive to strengthening the protection of biodiversity in arid and semi-arid grasslands. Grazing promoted the AGB-SR coupling of the community by increasing the SR of medium drought tolerance (MD), low drought tolerance, and grazing tolerant functional groups. Grazing also accelerated the AGB-SR decoupling of the community by changing the AGB of high drought tolerance, MD, high grazing tolerance, and medium grazing tolerance functional groups. PA mediated changes in MD and SR of both drought and grazing tolerant functional groups and AGB of low grazing tolerance promoted the coupling of AGB-SR of the community. The Two-dimension functional groups classification method reflects the changes of AGB and SR in communities more reasonable than the division of single-factor functional groups.

1. Introduction

Among the global climate change-induced hydrological changes, one of the most definitive is the increase in precipitation (Donat et al., 2016), which has resulted in approximately 16% of the land experiencing an increase in seasonal precipitation, and the remaining part of the land facing significant interannual changes in precipitation (Zhang et al., 2021). Grassland is the most sensitive terrestrial ecosystem to precipitation changes (Sloat et al., 2018), and grazing is the predominant land-use mode of grasslands (Scasta et al., 2016), managing more than half of the global land area. The coefficient of variation of precipitation in 49% of the pasture has generally increased over the past century (Sloat et al., 2018). Although AGB and SR composition change with grazing and precipitation fluctuations (Fedrigo et al., 2022), the effects of the interaction between grazing and PA on the AGB-SR relationship is still unclear.

Intensity, frequency, and inter-annual variation in precipitation are predicted to increase with increasing future climatic variability

Abbreviations: PA, Precipitation addition; AGB, aboveground biomass; SR, species richness; HD, high drought tolerance; MD, medium drought tolerance; LD, low drought tolerance; HG, high grazing tolerance; MG, medium grazing tolerance; LG, low grazing tolerance; DT, drought tolerance functional group; GT, grazing tolerance functional group; DGT, drought and grazing tolerance function group; HDHG, high drought tolerance and high grazing; MDHG, medium drought tolerance and high grazing; MDMG, medium drought tolerance and medium; MDLG, medium drought tolerance and low grazing; LDHG, low drought tolerance and high grazing; LDMG, low drought tolerance and medium grazing; LDLG, low drought tolerance and low grazing.

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(Berdugo et al., 2020), which may strongly impact vegetation production across different regions (Otto et al., 2017). The AGB sensitivity to PA was saturated under extremely humid conditions and unaffected by precipitation duration (Maurer et al., 2020). However, SR sensitivity to PA decreases with increasing precipitation duration (Wilcox et al., 2017). A previous study reported a positive correlation between higher precipitation in grasslands and SR (Bai et al., 2007). PA inhibits grassland biomass, however, these negative effects may weaken the increase in precipitation years because of plant adjustment to physiological and/or morphological characteristics (Li et al., 2019). Additionally, plants may establish a "stress memory" in their physiology after experiencing extreme precipitation. Therefore, when faced with the pressure of PA again, they will regulate the tolerance of individuals to endure extreme conditions (Cheng et al., 2015) by altering morphological characteristics such as the root: shoot ratio (Insausti et al., 2005), or root and leaf structure (Shu et al., 2016), to maintain long-term ecosystem stability (Backhaus et al., 2014). The results indicate that the responses of AGB and SR to PA of vegetation show certain adaptability with an increase in precipitation years and will inherit and maintain this adaptability for a certain period.

Grazing alters the composition of plant species, increases grassland coverage, and reduces shrub coverage (Lyseng et al., 2018). In temperate grasslands, grazing increases the AGB of weeds and decreases that of gramineous grass (Batbaatar et al., 2021). Higher grazing intensity leads to the emergence of a large number of short and creeping grazing tolerant species (Rupprecht et al., 2000), which changes the plant community from perennial C_3 grass to C_4 grasses (Gonzalo et al., 2016). Long-term grazing increases alien species (Lyseng et al., 2018) and positively impacts various plants but has no impact on gramineous plants (Bork et al., 2012). Disturbances, such as resource availability, grazing, and precipitation change, are considered key driving factors of the structure and composition of plant communities (Liu et al., 2018). In areas with abundant precipitation, grazing promotes SR and AGB (Wang et al., 2021), whereas grazing reduces SR and AGB in environments with little precipitation (Zhou et al., 2019).

Species have unique tolerance and avoidance strategies for environmental disturbance. The tolerance to grazing indicates the sensitivity of species to grazing, and the drought tolerance reflects the sensitivity of species to precipitation (Serra-Maluquer et al., 2022; Conti et al., 2022). Previous studies on the impacts of two-factors on vegetation characteristics seldom included the sensitivity of species to factors to two factors, because there are few comprehensive divisions of functional groups according to the degree of sensitivity. Therefore, we divided the two-dimensional functional groups of both drought and grazing tolerance, which functional group based on the single factor of drought tolerance or grazing tolerance of populations (Fig. 1a). In term of the three base points theory of ecology, we extend the optimal point to three response phases of the functional groups along precipitation gradient, adaptation period (stable period at beginning), saturation period (stable period at end) and response period (between adaptation period and saturation period), and there are correspondingly three threshold values, adaptation point, saturation point, and optimal point (maximum or minimum). Grazing changed threshold values and response period because species sensitivity to PA, adapting grazing management potentially promoted AGB and SR of community under conditions of precipitation change (Fig. 1b).

The typical steppe of the Loess Plateau is an important part of the Eurasian steppe and located at the end of the East Asian monsoon climate, its inter-annual precipitation variation is greater than 20% (Ye et al., 2019). To test the hypothesis, a three-year of PA research was conducted based on a 19 years of grazing experiment in order to identify three objectives as following: (1) divided two-dimensional functional groups and studied the spatiotemporal pattern of their AGB and SR in response to grazing and PA. (2) Observed the changes and responses of functional groups with PA. (3) The response of AGB-SR coupling and decoupling of functional groups under grazing and PA was explored, which provided an alternative idea for the analysis of global change experiments. The relevant parameters could be used to establish or improve the global change model or evaluation reports of the IPCC.

2. Materials and methods

2.1. Study site

The research area is located in the Huanxian Grassland Agricultural Trial Station of Lanzhou University, Gansu Province, China (37.12°N, 106.84°E, 1700 m a.s.l) (Fig. 2), which is the largest inter and intra-annual precipitation variability in the world (Erdős et al., 2022). Mean annual temperature (MAT) of 7.1 °C and mean annual precipitation (MAP) of 326.6 mm (Hu et al., 2019). Classified as a cool temperate-semiarid temperate typical steppe, where the SR is about 13–15/m^2 (Ren et al., 2018). The grassland is mainly utilized for grazing purposes (Zhang et al., 2023). The dominant species were *Stipa bungeana*, *Lespedeza bicolor*, and *Artemisia capillaries* (Huang et al., 2022).

2.2. Sampling and measurements

Since 2001, a rotational grazing experiment on Tan sheep has been conducted at four grazing intensities and three replicates at the station (Chen et al., 2010). The grazing started in early June and ended in mid-September with 10 days of grazing and 20 days of rest in each paddock, with an area of 100 × 50 m. According to the previous month's

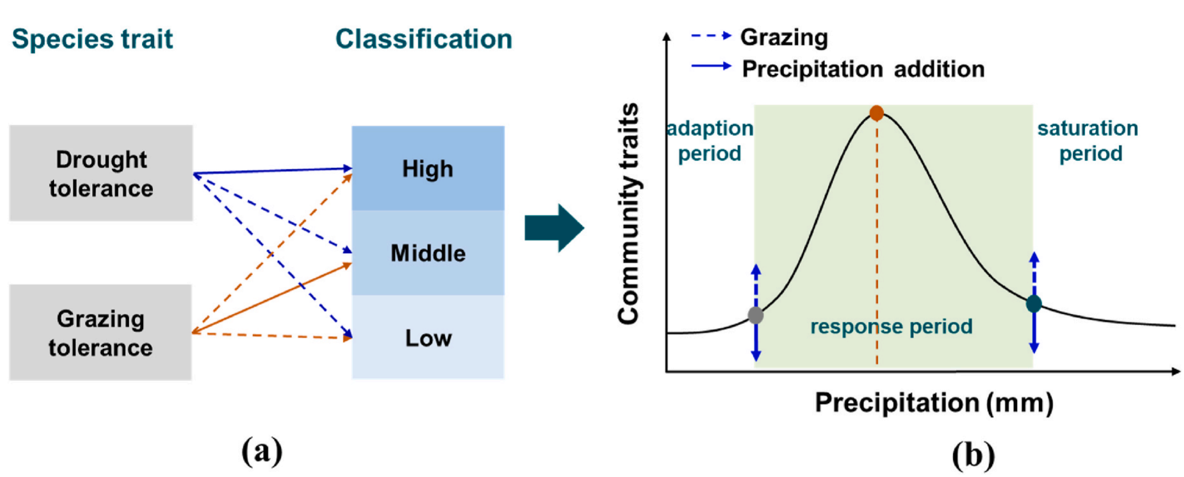

Fig. 1. A conceptual model of the effects of precipitation addition and grazing on communities and functional groups.

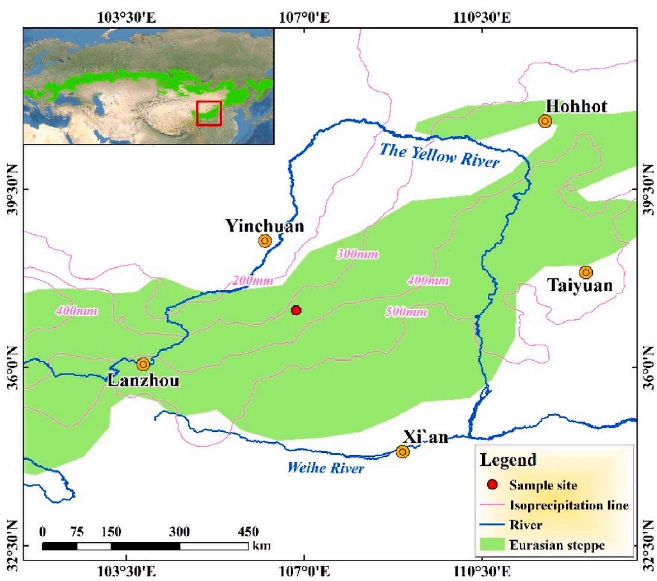

Fig. 2. Location of the study site.

precipitation, PA gradients of 0%, 30%, and 60% were randomly established (Fig. 3) with six replicates in the paddocks of two grazing intensities (0 and 2.67 sheep/ha), respectively, and each plot was 2 × 2 m with a 1 m space between two plots. PA was sprayed before or after sunrise.

2.3. Classification of functional groups

Species were classified into drought tolerance, grazing tolerance, and drought and grazing tolerance functional groups by integrating the plant morphological characteristics (Table S1). According to the degree, drought tolerance was classified into high drought tolerance (HD), medium drought tolerance (MD), and low drought tolerance (LD). Selective feeding of grazing livestock was observed, and grazing tolerance was divided into high grazing tolerance (HG), medium grazing tolerance (MG), and low grazing tolerance (LG) functional groups. Plants avoided by livestock grazing during the growing season were considered HG plants. Based on the combined grazing and drought tolerance of the species, they were divided into high drought tolerance and high grazing (HDHG), medium drought tolerance and high grazing (MDHG), medium

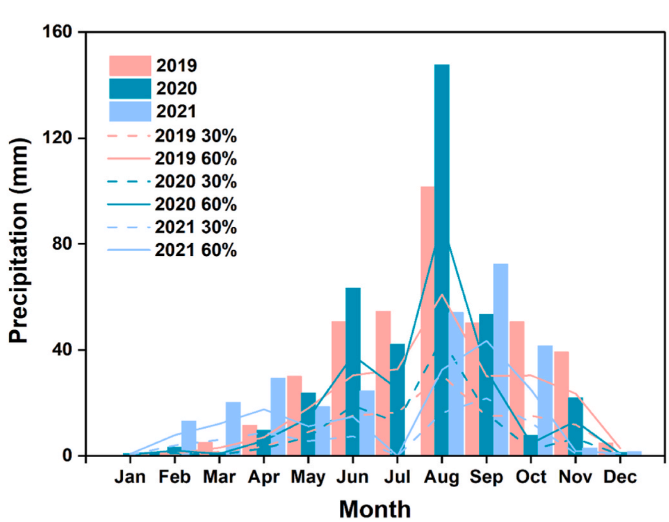

Fig. 3. The average monthly natural precipitation and precipitation addition over the three years.

drought tolerance and medium grazing (MDMG), medium drought tolerance and low grazing (MDLG), low drought tolerance and high grazing (LDHG), low drought tolerance and medium grazing (LDMG), and low drought tolerance and low grazing (LDLG) functional groups. More than 30 experts were invited to evaluate the drought and grazing tolerance of all species.

2.4. Calculation of indicators

Decoupling index is adopted to describe the interactions between AGB and SR. The decoupling index refers to the ratio of the changing rate per unit increasing the fitted functions for SR and AGB ($\triangle$SR/$\triangle$AGB). When the rate of change of SR exceeds that of AGB with a rise in precipitation, the Decoupling index is greater than 1. When the situation is reversed, the decoupling index varies from 0 to 1 but is less than 0 when SR decreases and AGB remains unchanged (Lu et al., 2019).

2.5. Data analysis

The nonlinear mixed model was adopted to analyze the changing trends of AGB and SR of communities and functional groups in grazing and no grazing with total precipitation (natural precipitation + PA) (Figs. 4 and 5). The location of plots is used as a random factor, whereas the PA and grazing were taken as fixed factors. The peak value of the curve represents the threshold, and the data were standardized using a threshold value. The relative values of AGB and SR of the functional groups and communities under grazing and no grazing were calculated, and linear regression was conducted for the relative values. The distribution curves for the communities, functional groups AGB, and SR under PA and grazing were obtained (Fig. 8). Structural equation model (SEM) was used to evaluate the effects of PA and grazing on AGB-SR of community.

3. Results

3.1. Effects of precipitation addition and grazing on aboveground biomass

PA, grazing (G), and their interaction (PA*G) explained 21% ($P <$ 0.001), 76% ($P < 0.001$), and 3% ($P < 0.05$) of the variation in community AGB, respectively. The optimal point AGB was evident when total precipitation was 563 and 425 mm under no grazing and grazing, respectively (Fig. 4 n), indicating that grazing reduced the optimum point of AGB for precipitation in the community.

PA contributed 36% and 22% variations in HD and MD ($P < 0.05$), grazing contributed 86%, 91%, and 84% ($P < 0.001$), and PA*G contributed 19%, 10%, and 20% ($P < 0.05$) variations in the ABG of HD, MD, and LD, respectively. For no grazing, the AGB reached the optimum point of HD, MD, and LD when the total precipitation was 630, 492, and 575 mm, while for grazing, it was 551, 798, and 396 mm, respectively. (Fig. 4 a-c). PA, grazing, and their interaction explained 12%, 12%, and 14% ($P < 0.05$), 87%, 87%, and 80% ($P < 0.001$), and 30%, 30%, and 29% ($P < 0.001$) of the variations in AGB of the HG, MG, and LG, respectively. Grazing increased the optimum point of PA for HG and MG, whereas it decreased for LG (Fig. 4 d-f).

PA explained 47%, 25%, 24%, 16%, 45%, 62%, and 43% of the variation in AGB in the HDHG, MDHG, MDMG, MDLG, LDHG, LDMG, and LDLG functional groups ($P < 0.001$), respectively. Grazing explained 75%, 77%, 62%, 86%, 87%, 72%, and 70% ($P < 0.001$), while PA*G explained 31%, 29%, 43%, 48%, and 32% of the variations in AGB in the HDHG, MDLG, LDHG, LDMG, and LDLG function groups ($P <$ 0.001), respectively. Grazing increased the optimum point for the AGB of the HDHG, MDMG, LDMG, and LDLG by 204, 34, 603, and 502 mm, respectively (Fig. 4 g, h, j, m), whereas it decreased the optimum point for AGB in MDHG and LDMG by 124 and 603 mm (Fig. 4 i, l).

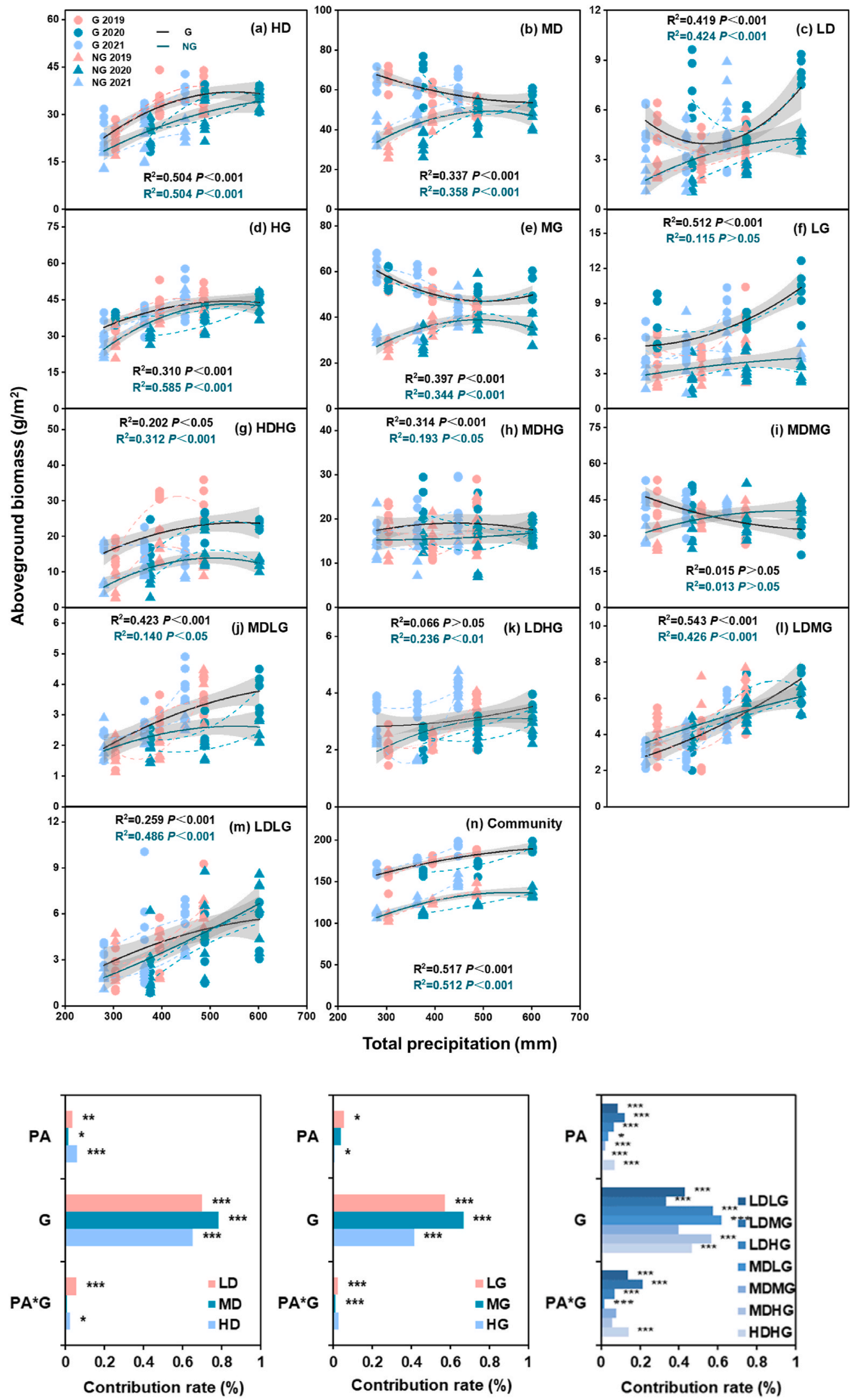

Fig. 4. Effects of precipitation addition and grazing on aboveground biomass of high drought tolerant (a), medium drought tolerance (b), low drought tolerance (c), high grazing tolerance (d), medium grazing tolerance (e), low grazing tolerance (f), high drought tolerance and high grazing (g), medium drought tolerance and high grazing (h), medium drought tolerance and medium grazing (i), medium drought tolerance and low grazing (j), low drought tolerance and high grazing (k), low drought tolerance and medium grazing (l), low drought tolerance and low grazing (m), and community (n).

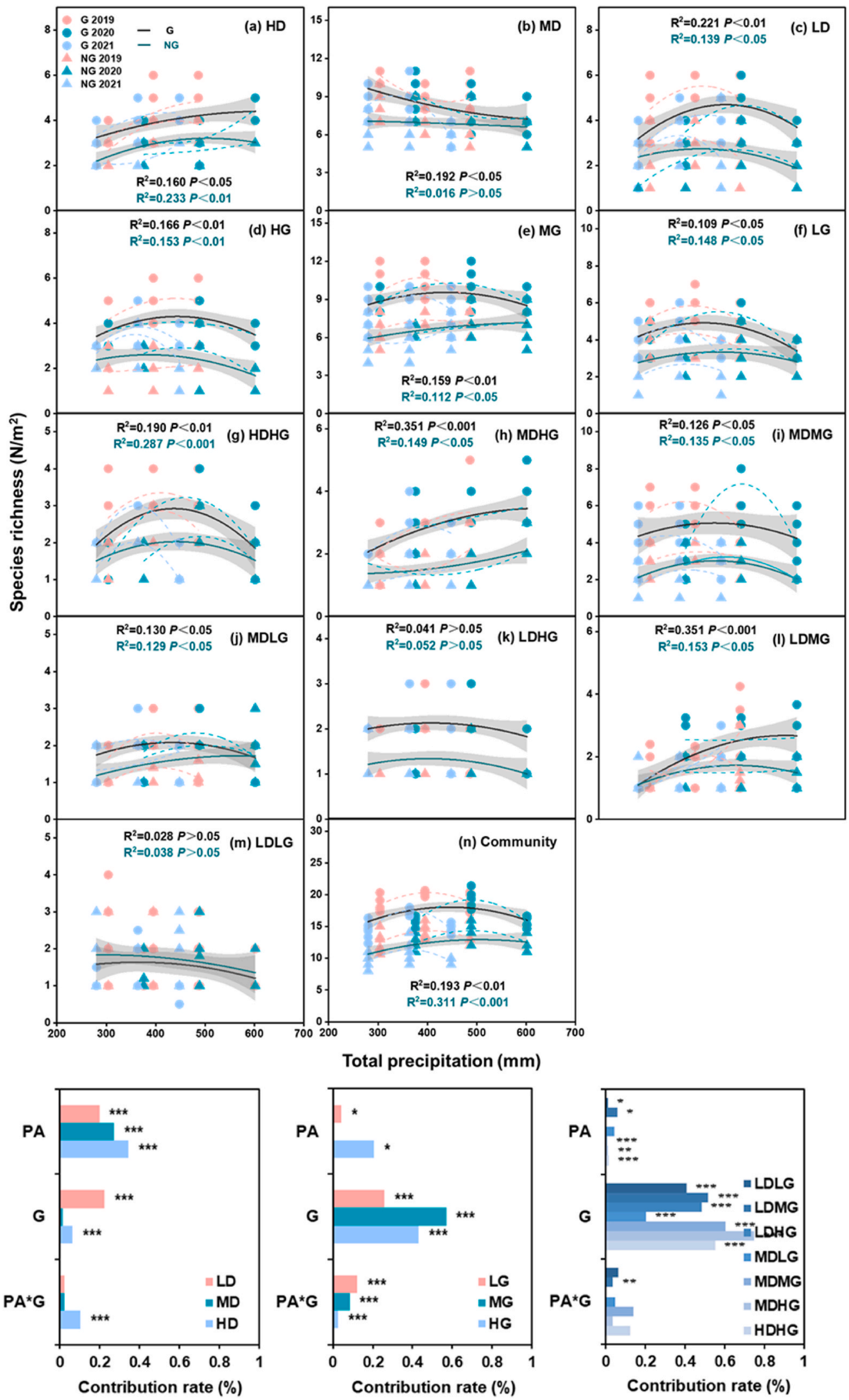

Fig. 5. Effects of precipitation addition and grazing on species richness of high drought tolerant (a), medium drought tolerance (b), low drought tolerance (c), high grazing tolerance (d), medium grazing tolerance (e), low grazing tolerance (f), high drought tolerance and high grazing (g), medium drought tolerance and high grazing (h), medium drought tolerance and medium grazing (i), medium drought tolerance and low grazing (j), drought tolerance and high grazing (k), low drought tolerance and medium grazing (l), low drought tolerance and low grazing (m) and community (n).

3.2. Effects of precipitation addition and grazing on species richness

PA, grazing, and PA*G explained 21%, 76%, and 3% variation of community SR ($P < 0.001$), respectively. SR was maximum when total precipitation was 545 and 537 mm under no grazing and grazing (Fig. 5 n), which indicated that grazing promoted the optimum point for SR in the community.

PA contributed 56%, 40%, and 31% variations of the HD, MD, and LD functional groups ($P < 0.001$), while grazing contributed 19%, 3%, and 34% ($P < 0.05$). Whereas, PA*G contributed 28% variations of the HD functional groups SR ($P < 0.001$). For no grazing, the SR for HD, MD, and LD reached the peak values at 504, 90, and 430 mm total precipitation, while for grazing it reached maximum values at 594, 1025, and 437 mm (Fig. 5 a-c). These results indicated that grazing increased the optimum point for SR in HD, MD, and LD functional groups.

The contribution of PA and grazing were 12% and 70% to variations of SR in HG, 27% and 72% SR in MG, while 27% and 44% SR in LG, respectively. In addition, PA*G explained 53% and 11% variations of the SR in HG and MG ($P < 0.001$). For no grazing, the peak SR values for HG, MG, and LG were achieved at total precipitation of 350, 628, and 496 mm, while for grazing peak values were achieved at 485, 250, and 435 mm, respectively (Fig. 5 d-f). PA contributed 44%, 20%, 48%, 14%, and 14% variations of the LDHG, MDHG, MDMG, LDMG, and LDLG function groups' SR ($P < 0.05$), respectively. Grazing contributed 78%, 84%, 80%, 29%, 61%, 71%, and 50% variations of the HDHG, MDHG, MDMG, MDLG, LDHG, LDMG, and LDLG ($P < 0.001$), respectively. PA*G contributed 21% SR variations of LDMG functional group ($P < 0.05$).

3.3. Coupling and decoupling between aboveground biomass and species richness

Grazing promoted the decoupling of the AGB-SR relationship of the drought tolerance functional group at PA gradients, indicating that PA and grazing led to the instability of the drought tolerance functional group (DTF) (Fig. 6). The growth rates of SR for MD and LD were lower than that for AGB. Furthermore, the growth rate of SR for the HD was lower than that for AGB when the precipitation was lower than 550 mm, whereas the opposite was observed when it was greater than 550 mm. Grazing inhibited the decoupling of the AGB-SR relationship of the grazing tolerance functional group across the PA gradients, and the SR for the HG, MG, and LG decreased with PA, whereas it remained unchanged for AGB. These results indicated that grazing promoted the coupling of AGB-SR in the grazing tolerance functional group (GTF), thus maintaining the stability of the GTF. In addition, grazing promoted

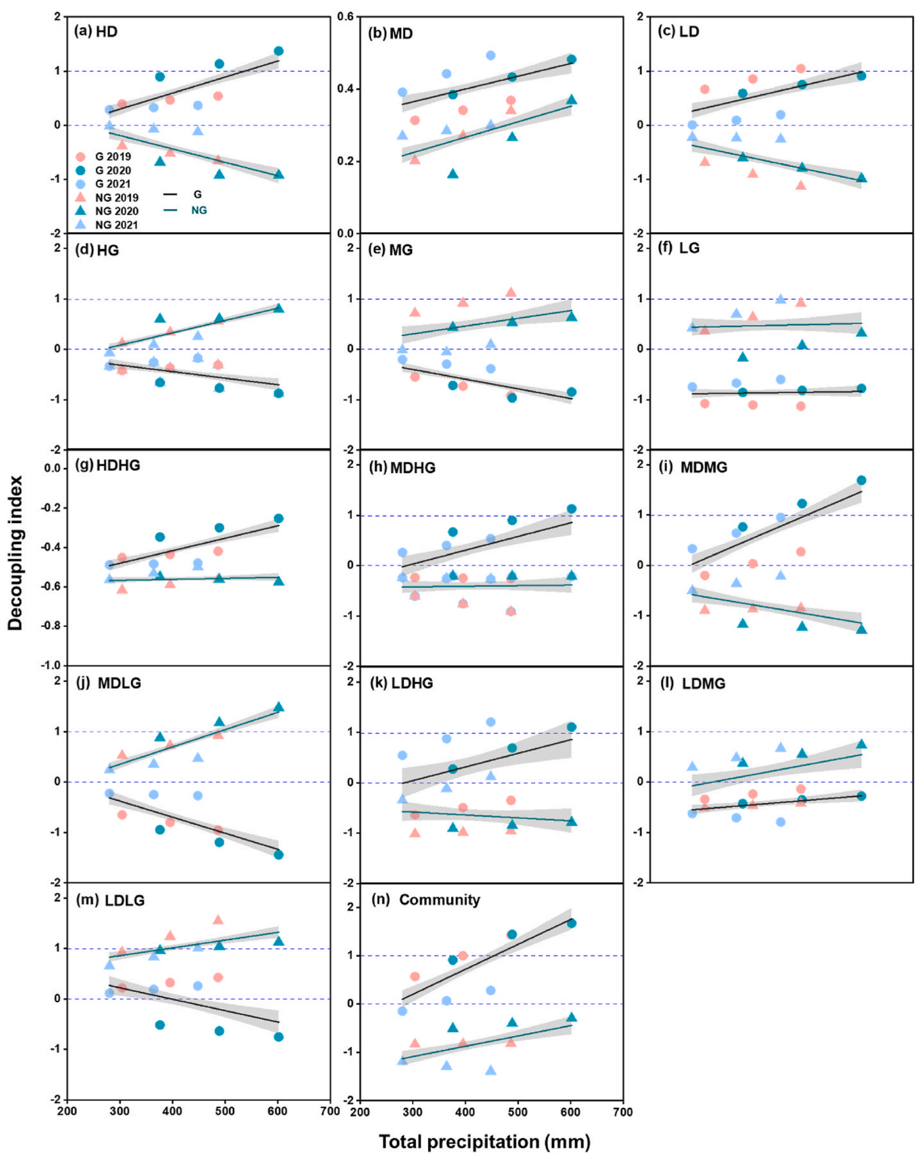

Fig. 6. Effects of precipitation addition and grazing on the decoupling index of high drought tolerant (a), medium drought tolerance (b), low drought tolerance (c), high grazing tolerance (d), medium grazing tolerance (e), low grazing tolerance (f), high drought tolerance and high grazing (g), medium drought tolerance and high grazing (h), medium drought tolerance and medium grazing (i), medium drought tolerance and low grazing(j), drought tolerance and high grazing (k), low drought tolerance and medium grazing (l), low drought tolerance and low grazing (m), and community (n).

the AGB-SR decoupling of the HDHG, MDMG, MDHG, and LDHG and inhibited the AGB-SR decoupling of MDLG, LDMG, and LDLG. The growth rate of SR for the MDHG and LDHG was lower than that for AGB. The SR for the HDHG, MDLG, and LDMG decreased with the PA gradient, whereas the AGB remained unchanged.

3.4. Analysis of driving forces affecting the relationship between aboveground biomass and species richness of communities

Grazing promoted the increase of community SR by increasing the MD and LD functional group SR, promoting the coupling of the community AGB-SR relationship. Simultaneously, grazing also inhibited the coupling of the AGB-SR relationship of the community by promoting changes in the AGB of HD and MD. Although grazing increased the AGB of HD, MD, and LD, thus promoting changes in community AGB, community AGB did not affect the coupling of community AGB-SR relationships (Fig. 7 a). PA mainly changed the SR of the community by reducing the SR of MD and increasing the AGB of HD, consequently promoting the coupling of AGB-SR relationships in the community (Fig. 7 a).

Grazing promoted changes in community AGB by increasing the AGB of HG and MG, which inhibited the coupling of the community AGB-SR relationship. Grazing also increased community SR by increasing the SR of the HG, MG, and LG, which further promoted the coupling of the community AGB-SR relationship. In contrast, PA affected community AGB by promoting the AGB of the HG, inhibiting the coupling of the community AGB-SR relationship. In addition, PA also promoted the coupling of the community AGB-SR relationship by mediating the change in the LG (Fig. 7b).

Grazing promoted changes in community SR by increasing the SR of DGT, which promoted the coupling of the community AGB-SR relationship. PA also promoted the coupling of community AGB-SR relationships through the mediation of the DGT and community SR. However, although grazing and PA increased the AGB of the DGT, this change did not affect the coupling of AGB-SR relationships in the community through the mediation of the DGT but directly affected the AGB-

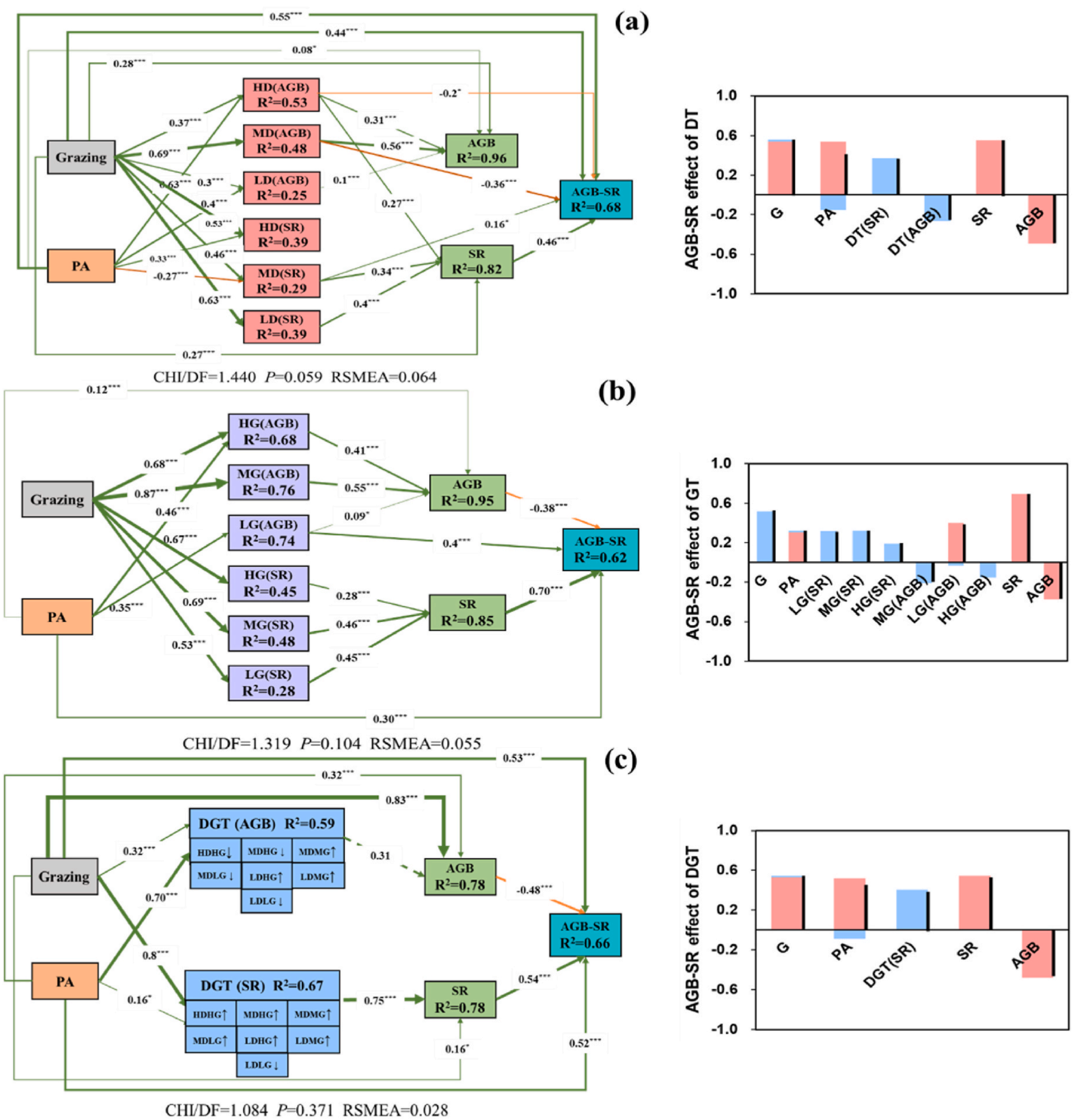

Fig. 7. Analysis of the SEM for drought tolerant functional group (a), grazing tolerant functional group (b), both drought and grazing tolerant functional group (c), and the effects of various factors on AGB, SR, and AGB-SR (d).

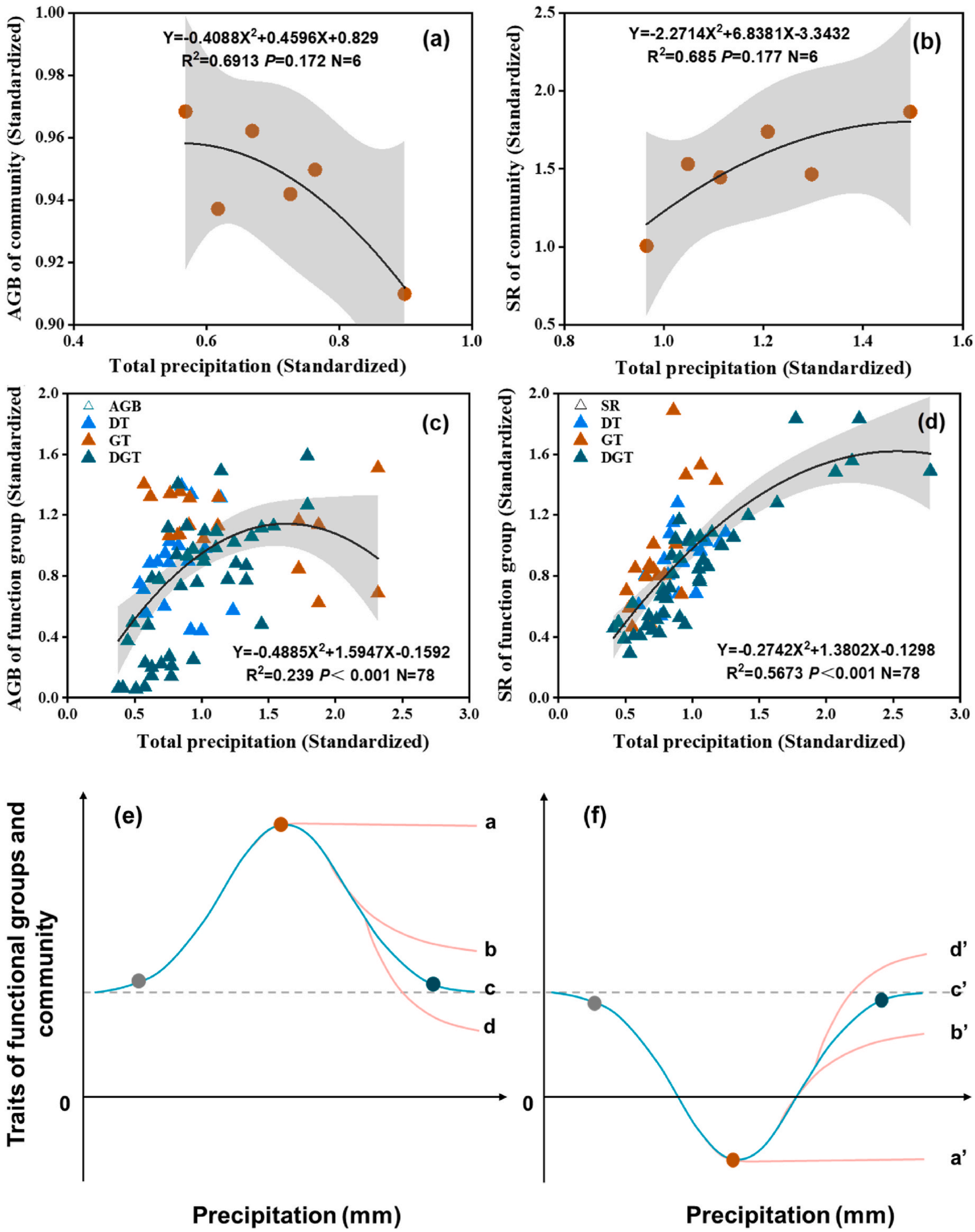

Fig. 8. Changes in functional groups (c and d) and community (a and b) traits under precipitation addition and grazing conditions.

SR of the community (Fig. 7c). Grazing and PA promoted the coupling of AGB, SR, and AGB-SR, however, the total effect of grazing was always greater than that of PA.

Grazing promoted changes in community SR by increasing the SR of the DGT, which promoted the coupling of the community AGB-SR relationship. PA also promoted the coupling of community AGB-SR relationships through the mediation of the DGT and community SR. However, although grazing and PA increased the AGB of the DGT, this change did not affect the coupling of AGB-SR relationships in the community through the mediation of the DGT but directly affected the AGB-SR of the community (Fig. 7 c). Grazing and PA promoted the coupling of AGB, SR, and AGB-SR. However, the total effect of grazing was always greater than that of PA.

The AGB of MDHG, LD, and LG in grazing shows deficit saturation (lower than the beginning), while the AGB of HD, HG, HDHG, MDLG, LDLG, LDHG, LDMG, and community in grazing and no grazing belongs to super saturation (the maximum value), the same as AGB of MD, LD, MG, LG, MDMG in no grazing and AGB of MD, MG, MDMG in grazing

(Fig. 4). SR of HG, MG, LG, LD, HDHG, MDLG, LDHG, MDMG, and community in grazing and no grazing and MDLG in no grazing belongs to deficit saturation, while the SR of HD, MDHG, LDLG, LDMG in grazing and no grazing and SR of MD in grazing shows super saturation (Fig. 5). Our hypothesis only considers the deficit saturation and missed the super saturation. However, sufficient saturation (higher than the beginning) and equal saturation (same as the value at beginning) of AGB and SR of functional groups also appeared with the PA (Fig. 8 e and f), which identified that our results validated and extended the hypothesis.

4. Discussion

4.1. Response of functional groups to precipitation addition and grazing

Three functional group classification techniques were used to summarize and highlight the consistent responses of grassland ecosystems to complex environments (Anja et al., 2014). The fundamental principle of this classification method is to classify various species that have comparable responses to PA or grazing into new functional groups (Pontes et al., 2012). Our study only verified deficit saturation and super saturation. We still need longer tests and more data analysis to determine the threshold of sufficient saturation and equal saturation. The interpretation degrees of drought tolerance, grazing tolerance, and both drought and grazing tolerance AGB were 16%, 30%, and 37%, respectively (Fig. 4), and the interpretation degrees of SR were 28%, 11%, and 21% (Fig. 5), which were 4–12 times higher than that of the community. These findings show that functional groups better reflect the function and composition of an ecosystem and more reasonable than communities for studying in complex environments. The classification method of two-dimension functional groups reflected the responses of AGB and SR to precipitation more reasonable than those of the single-factor functional groups (Figs. 7 and 8). Therefore, replenishing the seeds of both drought and grazing tolerant functional groups or strengthening grazing management during the breeding period of the forage will promote the germination of its soil seed bank, which is conducive to further improving grassland productivity.

4.2. Effects of precipitation addition and grazing on aboveground biomass and species richness of community

Significant differences in the responses of functional groups to PA and grazing led to an increased or decreased in the threshold values of AGB and SR for each functional group under PA and grazing (Figs. 3 and 4). Simultaneously, PA and grazing promoted the threshold of AGB and SR of communities in response to precipitation. A possible reason for the perceived results might be the stronger synergistic effects among plants than the competitive effects under environmental stress in low-precipitation resource habitats (Wang et al., 2022). Therefore, the relationship between the AGB-SR of communities and PA was also positive. In addition, the vegetation in the low-precipitation resource habitat has a certain adaptability (Bai et al., 2022) and resistance to environmental stress, the functional group may have an adaptation period in the area with low precipitation (Rauschkolb et al., 2022). In medium and high precipitation resource habitats, both interspecific competition and negative soil feedback effects were strong (Luo et al., 2017), and the interaction between plants also changes from complementary to competitive which could lead to a negative relationship between plant AGB-SR and PA (Du et al., 2022). The AGB and SR of the functional groups did not change significantly with an increase in precipitation when the PA increased to a certain extent. This is because of the vegetation saturation effect on precipitation, resulting in the community entering a saturative period (Xu et al., 2022). Essentially, these results were consistent with the principle of the standard "single peak" relationship between AGB and SR along the resource gradient, revealed in the pressure gradient hypothesis (Du et al., 2022).

Grazing increased the thresholds of AGB and SR to precipitation by 96 and 50 mm, respectively (Fig. 8). As a result, the grazing rate increased by 1 sheep/ha, the water consumption increased by 36 mm, and the AGB and SR of the community increased by an average of 48 g/m^2 and 4 species/m^2 under PA conditions. These findings indicate that grazing improves AGB and SR as well as results in greater livestock products in rain-fed agricultural ecosystems. Adjust grassland management strategies and appropriately increase grazing intensity in years with high precipitation. One possible result of this phenomenon is that grazing removed the aboveground part of vegetation and reduced light restriction (Elizabeth et al., 2014), enhanced solar radiation and increased soil temperature (Li et al., 2021a, b), and promoted the formation of a microclimate (Schnitzer et al., 2015), thus improving the water use efficiency of vegetation. In addition, grazing activates the germination of dormant buds of some functional groups and stimulates the regeneration ability of vegetation, increasing water utilization. Another possible reason could be the potential of grazing to stimulate plant growth (Michaletz et al., 2018), particularly in sufficient water resources. Furthermore, an increase in precipitation improves the absorption of mineral resources by plant roots, enhances soil microbial activity, and stimulates the absorption of soil nutrients and water (Zhou et al., 2019) consequently promoting the plant growth. In addition, grazing results in soil compaction (Mu et al., 2016), decreased soil aeration and water permeability, reduced infiltration (Jones et al., 2019) and increased surface runoff (Slessarev et al., 2016). Therefore, only high amounts of precipitation can ensure sufficient plant infiltration and utilization.

4.3. Effects of precipitation addition and grazing on the relationship between aboveground biomass and species richness

The effects of PA and grazing on AGB and SR of the community were not synchronous. They first affected community function and then composition (Fig. 8 a and b). This conclusion provides new scientific evidence that the AGB-SR relationship is complex and changeable at the mechanism level (Pan et al., 2021). A potential explanation is that PA promotes an increase in AGB in the community (Zheng et al., 2019), which provides more litter for the community. Consequently, litter helps to improve the availability of grassland temperature, precipitation, and other resources and accelerates the decomposition of substances and nutrient return (Zhang et al., 2022a), thus directly promoting the increase in AGB of the community. Second, the legacy effect is another potential mechanism to explain why the PA and grazing effects on AGB are greater than those of SR. Grazing and PA had noticeable residual effects, and the effect of AGB on AGB in the following year ($y = 0.9595x+5.9599$ $R^2 = 0.9098$ $P < 0.001$) was stronger than that on SR ($y = 0.0599x+7.0676$ $R^2 = 0.4431$ $P < 0.001$), resulting in a higher growth rate of AGB in the community-than that of SR, which was also supported by Wang et al. (2021). Finally, resource types and abundance affected the AGB and SR communities to varying degrees. SR may be limited by the local species pool (Huston, 2014), whereas AGB may be limited by light or heat (Huang et al., 2019) resources. With the increase in precipitation, the competition between species shifts from water resources to light resources, resulting in the substitution of drought-tolerant species (Demalach et al., 2016) by non-drought-tolerant species through asymmetric light competition. This asymmetry of resource allocation accelerates the speed of competitive exclusion, as well as inhibits the increase in community SR (James et al. 2016). Therefore, uncertain resource effects, such as heat, changes in the local species pool, and different responses of species to light competition may also lead to asynchronous changes in AGB and SR.

Dominant functional groups control the energy flow and biogeochemical cycles of ecosystems (Liu et al., 2022). Owing to their high AGB and wide community distribution, they are not easily affected by PA and grazing (Avolio et al., 2019). The proportions of AGB and SR in the community MD, MG, and MDMG functional groups were approximately half. Under PA and grazing conditions, these dominant functional groups had no significant effect on the AGB-SR relationship of the community. In contrast, other sensitive functional groups that accounted for less than half of the community promoted changes in the AGB-SR relationship of the community (). These findings demonstrated that the primary mechanism altering the function and composition of grassland ecosystems was changes in the community AGB-SR relationship, which were mediated by functional groups that were extremely sensitive (the highest or the lowest) to PA or grazing. Functional groups with moderate drought or grazing tolerance play a major role in maintaining community stability. This might be because sensitive or rare functional groups have low resistance (Zhang et al., 2022b) to PA and grazing disturbance, resulting in the instability of community function and composition. Additionally, the findings supported our hypothesis that the ecosystem has moderate disturbance (Chen et al., 2022).

4.4. Implementation of this study and limitation

The study divided two-dimensional functional groups and clarified the changing trend and response threshold of AGB and SR in each functional group under PA and grazing. This is an extension of the three base points theory and the moderate grazing hypothesis, providing a scientific basis for adaptive management of grazing under global change conditions. The limitation of the study is that we need longer test and more data analysis to determine the threshold of sufficient saturation and equal saturation. The two-dimensional function group classification method of the feasibility will be sufficient improved if the traditional and new methods combined in future research.

5. Conclusions

The effect of grazing on the AGB and SR of the community is not synchronous with PA, and its effect on AGB is faster than that of SR. PA potentially improves water use efficiency and enhances the protection of biodiversity in the grazing lands of semi-arid regions, which could play an important role in decision making of regional ecological protection.

Authors contribution statement

Fujiang Hou and Xiaojuan Huang conceived the ideas and designed methodology; Xiaojuan Huang, Meiyue He, Zhaoxia Guo collected the data; Lan Li modify manuscript language; Xiaojuan Huang conducted all other analyses and wrote the manuscript with input from all authors. All authors contributed critically to the drafts and gave final approval for publication.

Declaration of competing 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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.117924.

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