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Effects of precipitation variation and trampling disturbance on seedling emergence of annual plants in a semi-arid grassland

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Precipitation change and grazing are the main factors influencing vegetation structure and dynamics in semi-arid grassland. However, the effects of precipitation variation and livestock trampling on the seedling emergence patterns of plants remain largely unknown. In this study, an experiment with four gradients of trampling (no-trampling, light, moderate, and heavy) and three precipitation treatments (ambient precipitation, +30% precipitation, and −30% precipitation) was conducted to assess the effects of trampling disturbance and precipitation variation on seedling emergence of annual plants. The results showed that an increase in precipitation significantly improved total seedling emergence by 3.5–3.6 times and seedling density of grasses by more than 4.1 times under trampling conditions, while significantly improving total seedling emergence and density of forbs under no-trampling conditions. Moreover, +30% precipitation significantly improved the seedling proportion of grasses under light, moderate, and heavy trampling, while decreasing the seedling proportion of forbs. Seedling emergence of forbs was more sensitive to trampling disturbance, and seedling emergence of grasses was more sensitive to precipitation changes, especially under trampling conditions. Light and moderate trampling with a +30% precipitation increase promoted seedling emergence of grasses, and no trampling with a +30% precipitation increase improved seedling emergence of forbs. Thus, targeted grazing management measures should be implemented for plant communities dominated by either grasses or forbs under changing precipitation conditions.

KEYWORDS

precipitation change, grazing, trampling disturbance, seedling emergence, sensitivity

1 Introduction

The seedling stage is the most sensitive period during plant life history, and seedling emergence and survival often determine the population regeneration (Rysavy et al., 2014; Fan et al., 2018). Many environmental factors influence seedling patterns, among which precipitation change and grazing disturbances are the major factors that severely affect seedling emergence in grasslands (Zhu et al., 2014; Kladivová and Münzbergová, 2016; Wang et al., 2018). Furthermore, precipitation change and grazing disturbance determines changes in vegetation dynamics mostly due to the impacts on seedlings (Bat-Oyun et al., 2016; Shan et al., 2018). Previous studies have indicated that most of the grasslands in the semi-arid areas are currently suffering from serious vegetation degradation because of overgrazing and variable precipitation regimes (Dube and Pickup, 2001; Zhao et al., 2005; Wan et al., 2015; Zhang et al., 2018; Filazzola et al., 2020). Thus, understanding the effects of precipitation variation and grazing disturbance on seedlings is crucial for recognizing the characteristics of vegetation changes and the mechanisms of grassland degradation in semi-arid regions (Messaoud and Houle, 2006; Chen et al., 2014; Wang et al., 2018).

During grazing activity, trampling disturbance has the characteristics of long duration, lasting effects, more profound and direct components compared with feeding and excretion effects, and plays a leading role in grassland degradation and development (Bouchard, et al., 2003; Munkhtsetseg, et al., 2017; Hong, et al., 2018; Chai et al., 2019). Trampling by livestock on the one hand results in seed burial in the surface layer, creating suitable conditions for germination and emergence (Eichberg and Donath, 2017). While on the other trampling compacts surface soil, reduces soil permeability, which changes the soil moisture environment of plant emergence and growth, and causes more water runoff, which reduces the water availability for seedlings, and subsequently affects the survival of seedlings (Tjelele et al., 2015). In addition, livestock trampling influences the changes in soil compactness and other properties (e.g., soil aeration and water permeability), resulting in variations in precipitation infiltration and water availability for seedlings (Tobe et al., 2005; Okach et al., 2019). Researchers have reported that even a single event of heavy trampling by cattle could change soil water availability and influence plant seedling emergence in the Chihuahuan semi-desert grasslands (Roundy et al., 1992).

As the main source of water, precipitation influences seedling emergence, survival, and establishment noticeably through water availability and water-related abiotic factors, particularly in arid and semi-arid regions (Dube and Pickup, 2001; Knapp and Smith, 2001; Wang et al., 2019). Accordingly, seedlings are more sensitive to precipitation than other life stages owing to their fragility; they may emerge, survive, or die due to the variations in precipitation and water availability (Rysavy et al., 2014). Studies have extensively demonstrated the effects of precipitation changes on seedlings emergence and growth (Didiano et al., 2016; Gibson-Forty et al., 2016). Generally, increasing precipitation promotes the seedling emergence and improves seedling survival significantly (Robinson and Gross, 2010; Shan et al., 2018), and there is a positive relationship between precipitation and seedling emergence and growth (Zhu et al., 2014). In the grassland ecosystems, the effects of precipitation variation on plants often combines with grazing effects, even buffers by grazing disturbances (Wang D. B. et al., 2019; Batbaatar et al., 2021). However, how were the effects of precipitation variation on seedlings combined with grazing disturbances, and whether the effects of precipitation change on seedling emergence differed under different livestock trampling situations, have rarely been addressed.

Annual plants must germinate and establish sufficient seedlings in suitable environments every year to maintain the succession of their populations (Xie et al., 2018), and they are often regarded as good candidates for exploring the above ecological issues because they are always the main component of vegetation in arid and semi-arid regions and play an important role in the stability of grassland ecosystems (Li et al., 2008; Yue et al., 2016). While evidence suggested that the plant growth of different functional groups (e.g., grass and forb) might respond differently to precipitation variation or grazing disturbance (Yan, et al., 2013; Van Coller et al., 2018; Batbaatar et al., 2021). For example, annual forbs are more resilient to livestock grazing (Van Coller et al., 2018), whereas annual grasses showed stronger drought-resistance ability than annual forbs (Yan, et al., 2013). However, how seedling emergence of these different functional groups in semi-arid regions respond to precipitation changes and trampling disturbance remains unclear. Thus, special experimental research on the effects of precipitation changes and livestock trampling on seedling emergence of these different functional groups is necessary to promote a comprehensive understanding of the influence of precipitation change and grazing activity in the grassland ecosystems. Therefore, in this study, we investigated the seedling emergence of annual plants from different functional groups under different precipitation and livestock trampling manipulation treatments in semi-arid grasslands. The objectives of this study were to investigate: 1) how the seedling emergence of annual plants respond to precipitation variation and

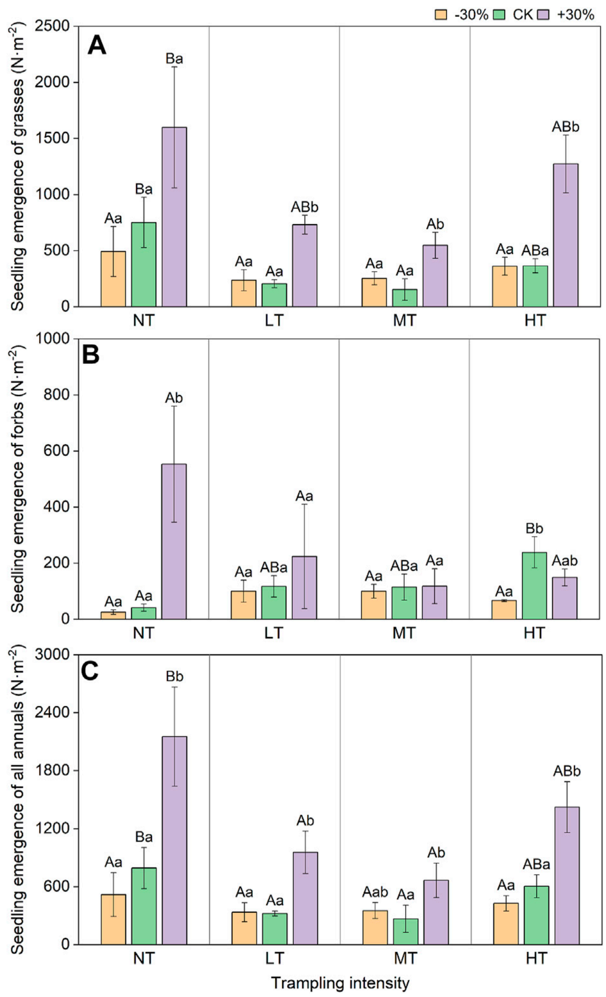

FIGURE 1
Effects of precipitation variation on total seedling emergence under different trampling intensities. Seedling emergence of grasses **(A)**; Seedling emergence of forbs **(B)**; Seedling emergence of all annuals **(C)**. NT, no trampling; LT, light trampling; MT, moderate trampling; HT, heavy trampling. −30%, decreased precipitation by 30%; CK, ambient precipitation; +30%, increased precipitation by 30%. Different lower-case letters indicate significant difference among precipitation treatments under same trampling intensity at 0.05 level, different capital letters indicate significant difference among trampling treatments in same precipitation condition at 0.05 level.

TABLE 1 Effects of precipitation changes and trampling intensities on functional composition.

Items	Treatments	-30%	CK	30%
The percentage of grass species (%)	NT	48.33 ± 25.87 Aa	21.43 ± 3.57 Aa	23.33 ± 5.07 Aa
	LT	43.90 ± 12.19 Ab	13.33 ± 6.67 Aa	25.00 ± .00 Aab
	MT	33.33 ± 8.33 Aa	26.67 ± 6.67 Aa	45.00 ± 5.00 Ba
	HT	30.53 ± 2.77 Aa	30.00 ± 5.00 Aa	35.00 ± 5.00 ABa
The percentage of forb species (%)	NT	51.67 ± 25.87 Aa	78.57 ± 3.57 Aa	76.67 ± 5.07 Ba
	LT	56.10 ± 12.19 Aa	86.67 ± 6.67 Ab	75.00 ± .00 Bab
	MT	66.67 ± 8.33 Aa	73.33 ± 6.67 Aa	55.00 ± 5.00 Aa
	HT	69.47 ± 2.77 Aa	70.00 ± 5.00 Aa	65.00 ± 5.00 ABa
The percentage of grass seedlings (%)	NT	72.60 ± 17.51 Aa	73.73 ± 9.19 Ba	63.07 ± 6.00 Aa
	LT	68.20 ± 11.82 Aab	23.37 ± 21.69 Aa	84.80 ± 2.40 Bb
	MT	58.97 ± 9.73 Aa	63.07 ± 3.62 ABa	97.90 ± .70 Bb
	HT	49.10 ± 2.80 Aa	59.57 ± 13.60 ABab	88.47 ± 3.84 Bb
The percentage of forb seedlings (%)	NT	27.40 ± 17.51 Aa	26.27 ± 9.19 Aa	36.93 ± 6.00 Ba
	LT	31.80 ± 11.82 Aab	76.63 ± 21.69 Bb	15.20 ± 2.40 Aa
	MT	41.03 ± 9.73 Ab	36.93 ± 3.62 ABb	2.10 ± .70 Aa
	HT	50.90 ± 2.80 Ab	40.43 ± 13.60 ABab	11.53 ± 3.84 Aa

Note: Mean ± SE., Different lower-case letters indicate significant difference among precipitation treatments in same trampling intensity at $p < 0.05$, the same capital letters indicate no significant difference among trampling treatments in same precipitation condition at $p < 0.05$.

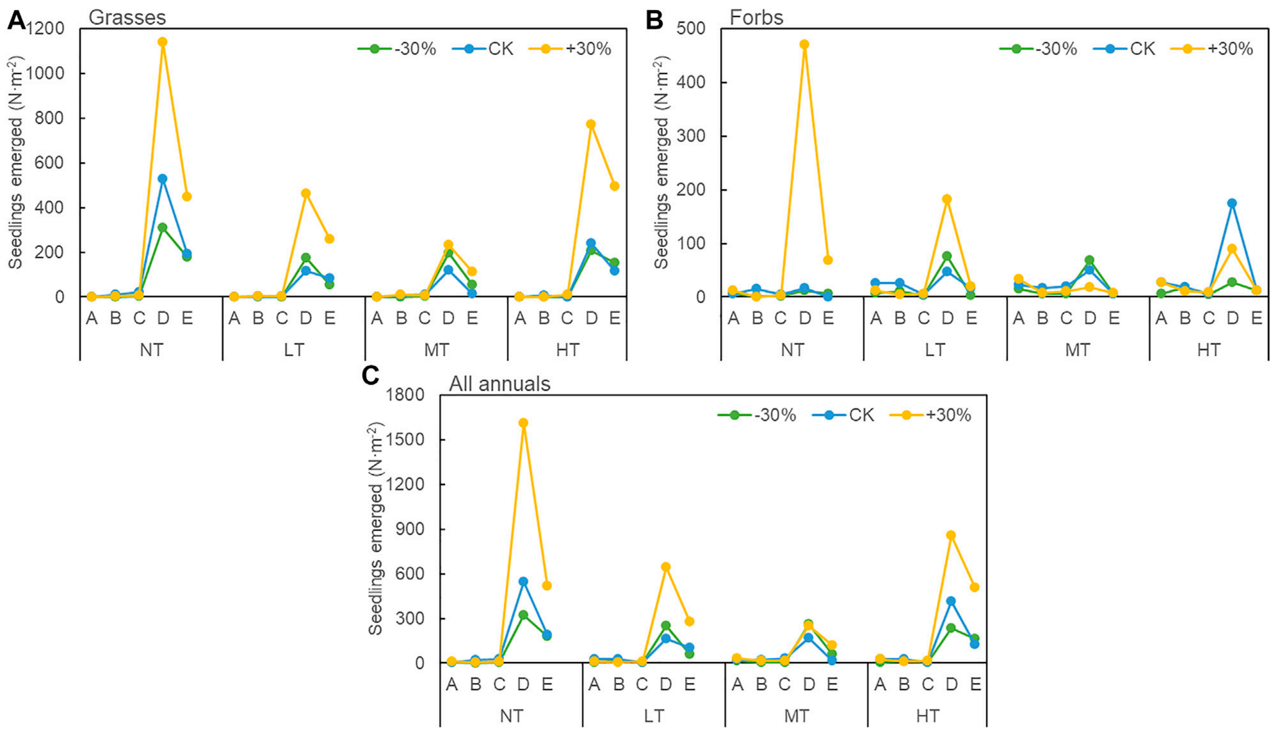

FIGURE 2
Temporal dynamics of seedling emergence with precipitation variation under different trampling intensities. Seedling emergence of grasses **(A)**; Seedling emergence of forbs **(B)**; Seedling emergence of all annuals **(C)**. NT, no trampling; LT, light trampling; MT, moderate trampling; HT, heavy trampling. A, mid-April; B, the begin of May; C, mid-May; D, the begin of June; E, mid-June. −30%, decreased precipitation by 30%; CK, ambient precipitation; +30%, increased precipitation by 30%.

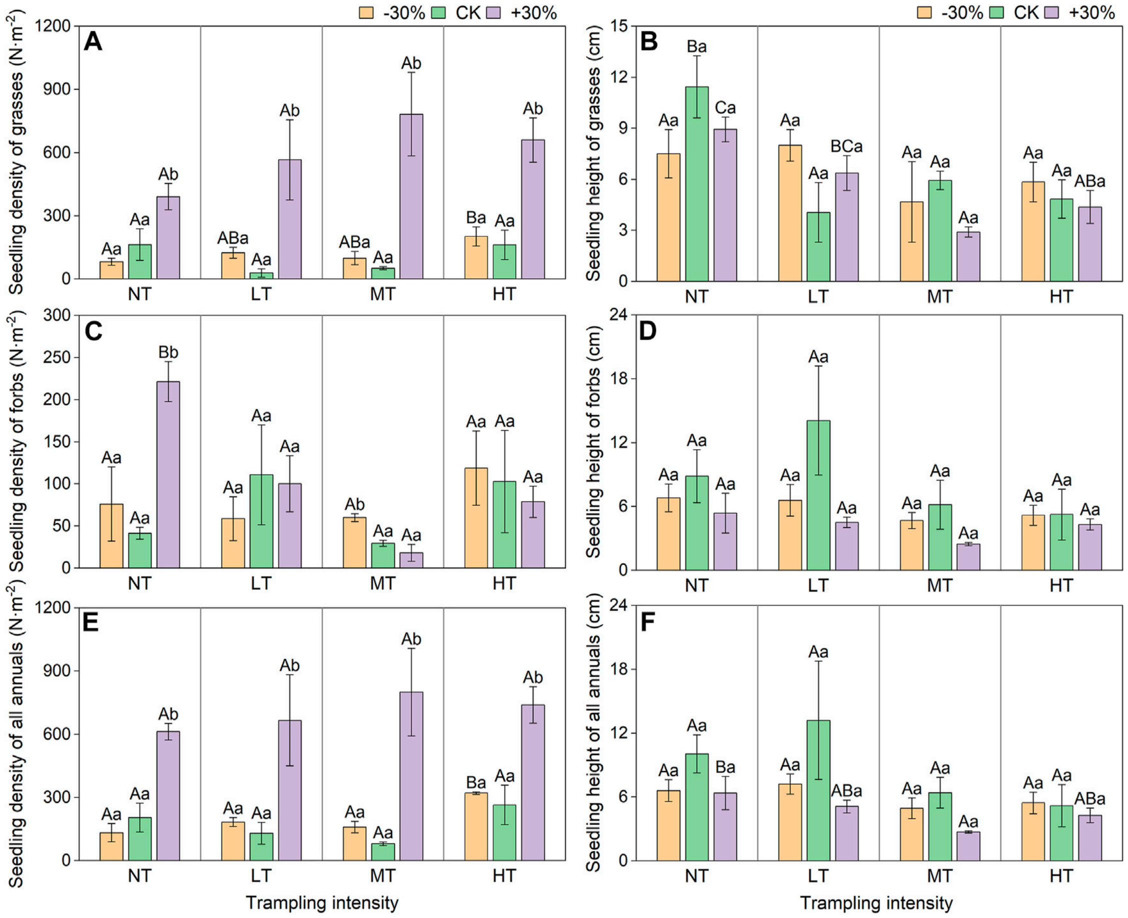

FIGURE 3
Effects of precipitation changes on seedling density and height under different trampling intensities. **(A, B)**: seedling density and height of grasses; **(C, D)**: seedling density and height of forbs; **(E, F)**: seedling density and height of all annuals. NT, no trampling; LT, light trampling; MT, moderate trampling; HT, heavy trampling. −30%, decreased precipitation by 30%; CK, ambient precipitation; +30%, increased precipitation by 30%. Different lower-case letters indicate significant difference among precipitation treatments under same trampling intensity at 0.05 level, the same capital letters indicate no significant difference among trampling treatments in same precipitation condition at 0.05 level.

trampling disturbances; 2) Whether the pattern of seedling emergence responding to precipitation variation changes with trampling disturbances; 3) Whether there are differences in the seedling emergence of grasses and forbs responding to precipitation variation and trampling disturbance.

2 Materials and methods

2.1 Study area

The study was conducted in the Horqin Sandy Grassland near the Naiman Desertification Research Station, Chinese Academy of Sciences (42°54′N, 120°42′E, 360 m above sea level). Horqin Sandy Grassland is a typical semi-arid grasslands ecosystem in Inner Mongolia, as the region of water and nutrient resources is limited, and is particularly susceptible to grazing and precipitation change (Wan et al., 2015). The climate is typical of temperate semi-arid continental and monsoonal regions. The mean annual precipitation over the last 40 years has been 342 mm, 60%–80%, which occurs mainly during the growing season from May to August (Yue et al., 2016). The annual precipitation in the experiment year (2019) was 379.6 mm, which was approximately 11% higher than the mean annual precipitation. The mean annual temperature is approximately 6.4°C, with monthly mean temperatures ranging from a minimum of −13.0°C in January to a maximum of 23.7°C in July. The frost-free period averages approximately 150 days/year. The plant species are mainly annual grasses and forbs, such as *Setaria viridis*, *Corispermum macrocarpum*, *Bassia dasyphylla*, *Eragrostis pilosa, Chloris virgata, Artemisia scoparia, and Salsola collina* (Zhao et al., 2005; He et al., 2022).

2.2 Experimental design and data collection

A long-term enclosed sandy grassland with a flat terrain and uniform vegetation and soil conditions was selected as the experimental (simulation) area. In this area, we conducted a simulated trampling and precipitation experiment based on the long-term observations and investigations of precipitation and grazing intensity in this region. The simulated experiment had a multiple-factor split-plot design with four simulated trampling

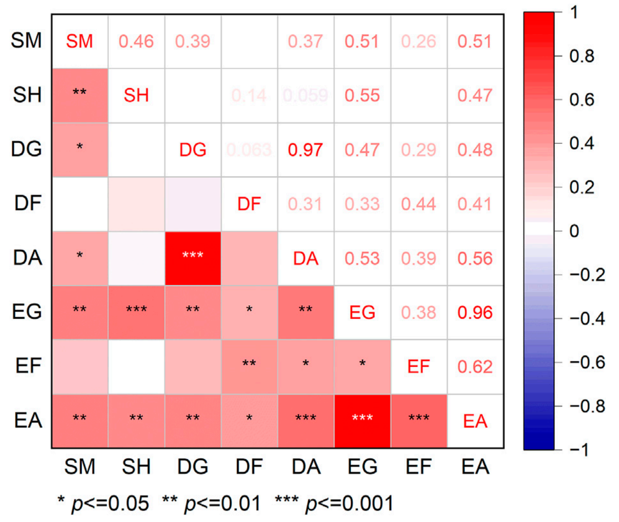

FIGURE 4
Pearson's correlation coefficients between soil moisture and seedling emergence. SM, mean soil moisture; SH, soil hardness; DG, seedling density of grasses; DF, seedling density of forbs; DA, seedling density of all annuals; EG, total seedling emergence of grasses; EF, total seedling emergence of forbs; EA, total seedling emergence of all annuals.

treatments and three precipitation treatments. These treatments were randomly arranged in the experimental area with three repetitions for each treatment. Each plot was 2 × 2 m, and there was a 2 m interval for buffering between the plots. According to the recent local grazing prohibition policy of the studied area, livestock grazing is only allowed in autumn and winter. Therefore, we conducted the simulated trampling treatments in late October of the previous year. The trampling was done by a person holding artificial hooves, which were made of wood and rubbers with grip and dynamometer to simulate the uniform trampling of adult sheep on the grassland. The simulated trampling device was made according to the hoof size and spacing of hooves of adult sheep, and the dynamometer on it was used to simulate the equivalent force of the average weight of adult sheep applying on the soil surface. Then the simulated trampling could well simulate the similar trampling effects of sheep's hooves on the soil surface (including the trampling on soil and litter aboveground). In the process of simulated trampling, the operator only walked in the buffer interval between the plots and operated the simulated trampling device outside the plot boundary for avoiding human trampling. The four trampling intensities were no-trampling (NT), light trampling (LT, 30 sheep trampling/m^2), moderate trampling (MT, 60 sheep trampling/m^2) and heavy trampling (HT, 120 sheep trampling/m^2), which is equivalent to approximately 0, 2.0, 4.0, and 6.0 sheep units/hm^2 grazing intensity, respectively, according to the standards and methods of previous studies (Zhao et al., 2005; Lin and Ren, 2009).

According to the long-term precipitation observation data and literature records, the annual and seasonal precipitation variability in studied area is approximately 25.1%–31.0% (Liu, et al., 2011; Yue et al., 2016). A simulated precipitation experiment was set up according to the three precipitation levels during the plant growth season (April to August) in 2019, which included ambient precipitation (CK), increased precipitation (+30%, relative to background ambient precipitation) and decreased precipitation (−30%, relative to background ambient precipitation). The simulated precipitation changes were performed using a precipitation alteration device. Precipitation alteration devices have been widely applied in the research of precipitation change, as they can increase or decrease of precipitation treatments synchronously with the natural precipitation and maximally ensure the accuracy of the simulation fluctuation of precipitation (Zhang et al., 2020). The precipitation alteration device reduces the rain by setting a certain proportion of rain shelter during the natural precipitation process, and the collected rain is added into the increasing precipitation plot through the rain pipe. The rain shelter was made of clear polycarbonate plastic strips with 90% transmittance, and the

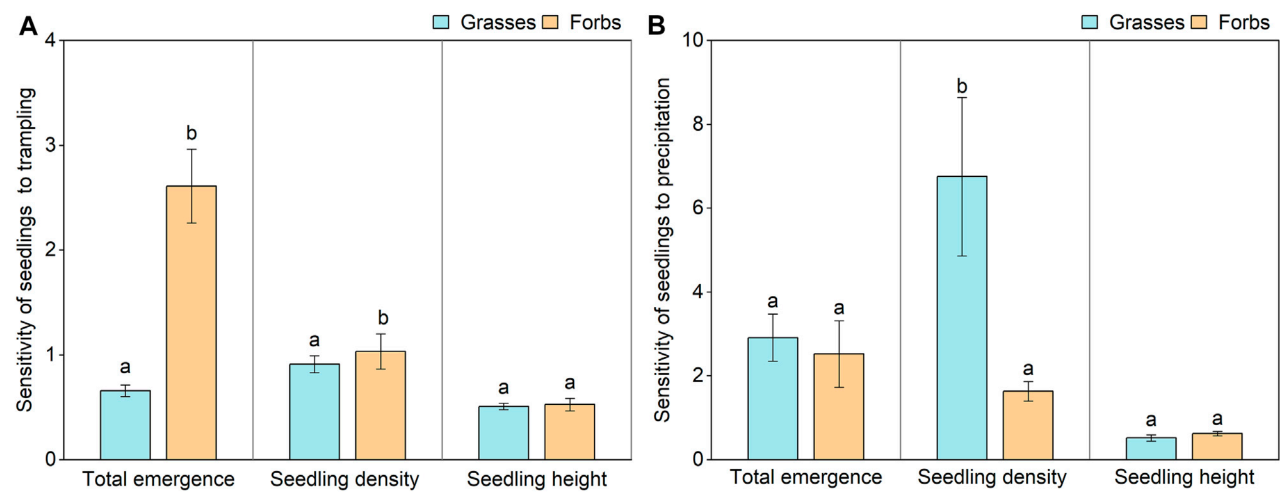

FIGURE 5
Sensitivities of total seedling emergence, seedling density and height of the grasses and forbs to trampling disturbance and precipitation variation. **(A)** Sensitivity of seedlings to trampling disturbance; **(B)** Sensitivity of seedlings to precipitation variation. Different letters indicate significant difference in sensitivity between the grasses and forbs in same groups at 0.05 level.

rain pipes was evenly distributed, which ensured the accuracy of the simulated precipitation alternation.

The seedling emergence investigation began in mid-April, once every 15 days, and ended in mid-June when seedling density reached its peak according to our previous vegetation investigation (unpublished data). We divided the 2 × 2 m plots into 0.5 × 0.5 m little quadrats and selected paired small quadrats in each plot as fixed observation quadrats for seedling observation. One was used for fixed monitoring of the total seedling emergence (TE, the cumulative seedling emergence during the experimental period) using the seedling removal method (He et al., 2022), where the emerged seedlings were identified and counted, and then moved at each time point. The other was used to investigate the species number, density, and height of the seedlings that survived until the end of the experiment at the species level. Species identification of seedlings was based on our previous vegetation investigation. All the plants that emerged from the soil but did not have differentiated reproductive organs were defined as seedlings for annuals. We classified all observed annual plant species into two functional groups, grass species and forb species groups, during the experiment. The species percentage of each functional group (grass species or forb species) was the species number of grasses/forbs divided by the total annual species number observed during the experiment. The seedling percentage of each functional group (grass species or forb species) was the number of seedlings from grasses or forbs divided by the total number of all annual seedlings. Soil hardness on the soil surface, which is related to trampling intensity, was measured in each quadrat in triplicate using a soil hardometer (SC-900, Spectrum, United States). The soil moisture content (0–20 cm soil depth), which is related to precipitation, was measured in triplicate (in each quadrat) using a soil moisture meter (TDR 300, Spectrum, United States).

2.3 Data analysis

The effects of precipitation variation on seedling emergence (total seedling emergence, density, and height, and functional composition percentage) under each trampling treatment were test with One-way ANOVA. The differences of seedling emergence among precipitation conditions and among trampling treatments were analyzed using Tukey's test at a significance level of 0.05. A Pearson's correlation analysis was used to examine the relationship between seedling emergence, mean soil moisture content and hardness. All data analysis and illustrations were performed using IBM SPSS (version 22.0, SPSS Inc., Chicago, IL, United States) and Origin (version 22.0, OriginLab, United States).

Sensitivity was calculated as the relative change in precipitation or trampling manipulation plots compared with that of the control plot (no trampling and ambient precipitation treatment) as follows by referring the previous studies (Luo et al., 2018; Zhang et al., 2020).

$$\text{Sensitivity} = \left|\text{Emergence}_{tr} - \text{Emergence}_{ctrl}\right| / \text{Emergence}_{ctrl}$$

where Emergence_{tr} and Emergence_{ctrl} represent seedling emergence (including total seedling emergence, density, and height) in the treatment and control plots (no trampling with ambient precipitation), respectively. The higher the sensitivity value, the higher the sensitivity of seedling emergence to changes in precipitation or trampling disturbances.

3 Results

3.1 Total seedling emergence

Overall, the total seedling emergence (TE) of grasses, forbs, and annuals all increased with increasing precipitation, whether trampled or not, although no significant difference was detected between −30% precipitation and CK. However, the TE of grasses, forbs, and all annuals was higher under no-trampling treatment than under the trampling treatments (including LT, MT, and HT) with +30% precipitation, while no significant difference was observed among the trampling treatments with −30% precipitation (Figure 1). Specifically, under trampling conditions (LT, MT, and HT), +30% precipitation significantly ($p < 0.05$) improved TE of grasses by 3.5–3.6 times compared to CK, but the increase was not significant ($p > 0.05$) under the no-trampling treatment (Figure 1A). The TE of forbs markedly ($p < 0.05$) improved under the +30% precipitation conditions in the no-trampling treatment (NT) but not under the trampling treatments (LT, MT, and HT), while −30% precipitation resulted in a significant decrease in the TE of the forbs compared to that of CK under the HT treatment (Figure 1B). Changes in the TE of all annuals were similar to those of the grasses, and +30% precipitation markedly improved the TE of all annuals, with or without trampling treatment (Figure 1C).

3.2 Functional composition

The functional composition percentage of species and seedlings did not significantly change with precipitation variation under NT, but was significantly different under the trampling treatments (LT, MT, and HT). In particular, the percentage of grass species significantly increased by 30.6% ($p < 0.05$), whereas the percentage of forb species significantly decreased by 30.6% with a precipitation decrease of −30% compared to CK under LT (Table 1). The percentage of grass seedlings was significantly ($p < 0.05$) improved by 61.4, 34.8, and 29.0% under +30% precipitation conditions in LT, MT, and HT treatments, respectively, compared to those under CK, whereas the percentage of forb seedlings decreased accordingly (Table 1).

The percentage of grass species under MT was significantly ($p < 0.05$) higher than that under NT and other trampling treatments under +30% precipitation, and the percentage of forb species under NT and LT was significantly ($p < 0.05$) higher than that under the other trampling treatments (MT and HT) under +30% precipitation (Table 1). The percentage of grass seedlings under NT was significantly ($p < 0.05$) lower than that under other trampling treatments (LT, MT, and HT) under +30% precipitation, while the percentage of forb seedlings under NT was significantly higher than that under other trampling treatments under +30% precipitation (Table 1). There was no significant difference ($p > 0.05$) in the functional composition percentage of species and seedlings among the trampling treatments under −30% precipitation conditions.

3.3 Emergence dynamics and seedling density

Seedling emergence of the grasses and forbs both peaked at the beginning of June, and many seedlings emerged during June, while some differences in the seedling emergence dynamics were found between grasses and forbs, and among different trampling intensities (Figures 2A, B). A certain number of forbs seedlings emerged from mid-April to the beginning of June, while fewer grass seedlings emerged before June. The peak value of seedling emergence increased with the increase in precipitation under the NT treatment, but the peak value of seedling emergence was higher under the −30% precipitation condition than under CK in the LT and MT treatments for both the grasses and forbs. The seedling emergence dynamics of all annuals were similar to those of the grasses (Figure 2C).

Precipitation effects on seedling density and height shifted from different trampling treatments. The +30% precipitation condition markedly increased seedling density of grasses by 2.4, 20.2, 15.4, and 4.1 times, respectively, in contrast to CK under NT, LT, MT, and HT, while no significant difference ($p > 0.05$) was found in seedling density of grasses between −30% precipitation and CK (Figure 3A). Seedling density of forbs showed an increasing trend with precipitation, it increased under NT and LT but decreased under the MT and HT treatments (Figure 3C). The seedling density of all annuals increased with precipitation increasing and the changes were similar to that of grasses (Figure 3E).

The seedling density of grasses and all annuals were improved under the trampling treatment in −30% precipitation conditions, and was significantly higher ($p < 0.05$) under HT. The highest value of seedling density of grasses and all annuals was found under MT in +30% precipitation conditions, and the highest seedling density of forbs was found under NT in +30% precipitation conditions. There was no significant difference detected in seedling height of grasses, forbs, and annuals among the precipitation and trampling treatments, although seedling height of forbs and all annuals changed with a trend of first increasing and then decreasing (Figure 3B, D, F).

3.4 Sensitivities of seedling emergence to precipitation and trampling

Pearson's correlation analysis showed that the total seedling emergence, seedling density of grasses and all annuals were significantly correlated with soil moisture, and the total seedling emergence of the grasses and all annuals was significantly correlated with soil hardness (Figure 4). Furthermore, the sensitivities of total seedling emergence and density in response to trampling and precipitation varied between the grasses and the forbs. The total seedling emergence and density of the forbs were more sensitive to trampling disturbances than those of the grasses (Figure 5A). The total seedling emergence and density of the grasses were likely more sensitive to precipitation variation than those of the forbs (Figure 5B), but no significant difference ($p > 0.05$) was found between the grasses and the forbs in the sensitivity of seedling height to trampling disturbance and precipitation variation (Figures 5A, B).

Specifically, the sensitivity of the forbs in terms of the total seedling emergence and density to precipitation variation was significantly higher ($p < 0.05$) than those of the grasses under NT (Figures 6A, B). However, the sensitivity of the grasses in the total seedling emergence and density to precipitation variation was clearly higher than those of the forbs under trampling treatments (LT, MT, and HT), except for the sensitivity of total seedling emergence, which did not significantly differ between forbs and grasses under LT.

4 Discussions

4.1 Effects of precipitation and trampling on seedling emergence

Precipitation change and water availability are key factors affecting seedling emergence in the semi-arid regions (Perkins and Owens, 2003). Our results found that the TE of grasses, forbs, and annuals increased with the increasing of precipitation under all tramping treatments, particularly at +30% precipitation. This result agreed with the findings from previous studies that precipitation and soil water greatly influence seedling emergence, there were fewer seedlings under drier conditions (Van der Waal et al., 2009; Kardol et al., 2010). It should be noted that the total seedling emergence under −30% precipitation did not significantly differ from that under CK, which may be due to high ambient precipitation in the experiment year (11% higher than the average), and −30% precipitation might not cause a significant deficit in soil moisture. This result was consistent with a previous study showing that +20% precipitation significantly increased seedling emergence and survival, whereas a decrease in precipitation amounts did not significantly lower seedling emergence (Wang et al., 2019).

Our results also suggested that the response of seedling emergence to precipitation changes varies with functional types and trampling intensity. This supports the findings of previous studies that different species respond to precipitation changes and grazing disturbance in a unique pattern, and seedling emergence and establishment of forbs differed and were influenced by seedlings from dominant grasses (Classen et al., 2010; Dickson and Busby, 2010). In this study, for grasses, the TE and density of seedlings were clearly established, and both were significantly promoted by precipitation increase under the trampling treatments, while increased precipitation markedly improved TE and seedling density of forbs only under the no-trampling treatment, and caused a decreasing trend in seedling density under MT and HT. This indicates that seedling emergence of grasses and forbs responded differently to trampling and rainfall, and the effects of precipitation on the seedling emergence of forbs might interfere with trampling disturbance more than that on grasses. Previous studies also reported that trampling affected plant density and particularly influenced the density of forbs obviously (Rupp et al., 2001). The newly emerged forb seedlings with taproot systems have difficulty to penetrate the compacted soil and absorb sufficient moisture and nutrient supporting seedling development and growth, which may be the reason for why trampling influenced seedling emergence and caused the decline of forbs seedling density (Tjelele et al., 2015; Cambi et al., 2018).

Trampling disturbance has been suggested to have profound effects on seedling emergence. First, it changes seed distribution, and presses surface seeds into the soil and compacts the soil (Eichberg and Donath, 2017; Klv et al., 2020). Changes in soil

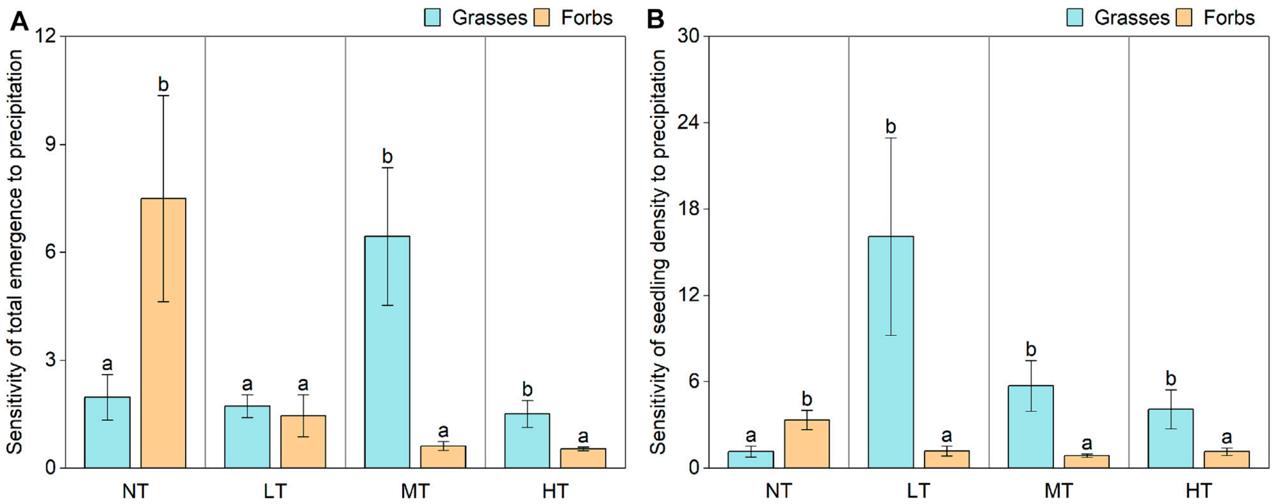

FIGURE 6
Sensitivities of total seedling emergence and seedling density of the grasses and forbs to precipitation variation under different trampling treatments. **(A)** Sensitivity of total seedling emergence to precipitation variation; **(B)** Sensitivity of seedling density to precipitation variation. Different letters indicate significant difference in sensitivity between the grasses and forbs in same groups at 0.05 level.

compaction and a reduction in soil permeability caused by trampling is generally influenced precipitation infiltration and redistribution (Chai et al., 2019), which further affects the soil moisture environment of seedling emergence and growth. These results indicated that TE was lower under the trampling treatments compared to that under the no-trampling treatment, and seedling emergence number, emergence dynamics, and seedling density with precipitation changes, differed among different trampling treatments. Previous studies have reported that precipitation was a positive force that could buffer the impacts caused by grazing, and the negative effect of grazing might be blurred by larger amounts of precipitation (Marone and Pol, 2021). Our results showed that +30% precipitation improved the seedling density of grasses and annuals, regardless of the trampling intensity. The TE of forbs markedly decreased in the −30% precipitation condition under the heavy trampling treatment. These results indicated that trampling disturbance had strong effects on the seedling emergence of forbs, and even interfered with the positive effects of increasing precipitation. In addition, heavy trampling disturbance and precipitation reduction were unfavorable for forb seedling emergence. The trampling disturbance, rather than precipitation variation, might be a crucial factor for influencing the seedling dynamics of forbs in the semi-arid grazing grasslands. Then given trampling disturbance could influence the effects of precipitation on the emergence and establishment of annual seedlings, the effects might depend on the functional groups (Sun, 2010; Marone and Pol, 2021).

4.2 Effects of trampling and precipitation on seedling functional composition

Grazing and precipitation plays important roles in affecting vegetation growth and community structure in grasslands (Perkins and Owens, 2003; Herrero-Jáuregui and Oesterheld, 2018; Shan et al., 2018). Most studies have suggested that grazing has a strong influence on species composition, but this effect may be exceptionally complicated (Milchunas and Lauenroth 1993; Kladivová and Münzbergová, 2016). The results that a higher percentage of forb seedlings developed under NT, whereas a higher percentage of grass seedlings developed under trampling treatments in this study indicated that livestock trampling, even in the short-term, potentially influenced and caused changes in the functional composition of the seedling community (Winkel et al., 1991; Roundy et al., 1992), and the effects were closely related to the trampling intensity. Medium trampling was beneficial for the development of the grass seedlings, whereas NT favored the development of forb seedlings.

Precipitation variation also significantly influenced the functional composition of seedlings in this study, and the effects varied with trampling intensity. This was similar to the results of previous research showing that changes in vegetation composition were dramatically influenced by precipitation variation with high precipitation promoting grasses, and the change pattern with precipitation variability shifted in grazing conditions (Fynn and O'Conno, 2000). In this study, increased precipitation (+30%) significantly improved grasses seedling proportion but led to a decrease in forbs seedling proportion under the trampling treatments, with a particularly large proportion change in the LT and MT conditions (61.4% and 34.8%, respectively). This indicated that precipitation variation had a potential influence under LT and MT conditions in changing the seedling community composition in the semi-arid grassland. The slight effect on community structure and composition over a short period might accrue over time to manifest as a marked impact on the species (Milchunas and Lauenroth, 1993; Herrero-Jáuregui and Oesterheld, 2018). Thus, the changes in seedling community structure influenced by trampling disturbance and precipitation variation might be the beginning of the change in vegetation composition caused by long-term grazing and climate change. It is necessary to pay more attention to changes in the community structure of the seedlings in future studies.

4.3 Sensitive of seedling emergence to precipitation and trampling

Soil moisture from precipitation is a vital factor that controls seedling emergence (Classen et al., 2010; Tjelele et al., 2015). The correlation analysis results in this study suggested that total seedling emergence and seedling density of grasses were closely related to soil moisture, and the seedling density of grasses correlated with soil hardness, which is associated with trampling. This conclusion is consistent with the results for the seedling sensitivity to precipitation and trampling. These results indicated that seedling emergence and density of grasses were more dependent on precipitation than those of forbs. Moreover, appropriate trampling, such as LT and MT, could facilitate the emergence and establishment of grass seedlings when there is adequate precipitation. This result agrees with the conclusions of other studies, which also showed that more grass seedlings were observed in light-grazed areas in semi-arid land in Africa (Solomon et al., 2006). It may be that more grass seeds on the surface entered the soil layer suitable for emergence under light and moderate trampling disturbance, and sufficient precipitation promoted its emergence and settlement. However, the seedling emergence of forbs was more sensitive to trampling and had higher sensitivity to precipitation under the no-trampling treatment. It is possible that the seeds of forbs in the studied area were suitable for no burial or shallow soil burial depth, and the seeds could not emerge when the seed burial depth exceeded a certain depth. For example, germination and emergence of the forb species *Bassia dasyphylla* were highest with no burial (He et al., 2013). Previous studies have suggested that the influence of trampling disturbance on the soil seed bank due to overgrazing is also considered a disruptive force on the size and structure of the soil seed bank (Marone and Pol, 2021). Extensive livestock trampling always changes the seed distribution and leads to more surface-lying seeds being buried under the biological limit, which causes obstacles in seed germination and a decline in seedling emergence (Winkel et al., 1991; Eichberg and Donath, 2017; Zhang et al., 2017). The reduction in soil seed banks in the grazing areas is mainly due to the decline in forbs (Zhao et al., 2001; Pol et al., 2014). This suggests that enclosure and reducing trampling disturbance might be necessary measures to promote the vegetation restoration of those plant communities dominated by forbs, and that different management measures should be considered for plant communities dominated by grasses or forbs with precipitation changes.

5 Conclusion

This study investigated the response of annual plant seedling emergence to precipitation variation and trampling disturbances in a semi-arid grassland. First, the results showed that increasing precipitation tended to increase the total seedling emergence of grasses, forbs, and all annuals, and the effects varied with the functional groups and trampling intensities. Second, precipitation variation and trampling disturbance changed the functional composition of species and seedlings from grasses and forbs. Third, the seedling emergence of grasses was more sensitive to precipitation than that of forbs, in particularly under the trampling treatments, and the seedling emergence of forbs was more sensitive to trampling and had higher sensitivity to precipitation under the no-trampling treatment. Thus, it appears that light and moderate trampling with precipitation increase could promote seedling emergence of grasses, and no trampling with precipitation increase could improve the seedling emergence of forbs. These findings suggested that targeted grazing management measures should be implemented for plant communities dominated by grasses or forbs under the background of precipitation change, thus, promoting the vegetation restoration in semi-arid grasslands.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization, XL and YH; methodology, YH, LC, HH, and XL; validation, XL and YH; formal analysis, YH, LC, HH, and YX; investigation, XL, LC, and HH; resources, XL; data curation, YH, LC, HH, and YX; writing—original draft preparation, XL and YH; writing—review and editing, YH and XL; visualization, XL and YH; Supervision, XL; project administration, YH and XL; funding acquisition, YH and XL All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Publisher's note

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