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Multidimensional Response of *Stipa breviflora's* Population Stability to Different Grazing Intensities

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Abstract: Dominant species play a principal role in controlling and maintaining ecosystem stability. *Stipa breviflora* is the dominant species in desert steppe. Changes in the stability of a plant population will further affect the stability of the broader habitat, such as the desert steppe. In the desert steppe ecosystem, it is not clear what level of grazing intensity is best for improving the grazing tolerance and stability of the vegetation. And, the study of this question should involve a multi-dimensional, comprehensive analysis. This study will utilize variance analysis, plant population stability, and trade-off index to study *S. breviflora*, the dominant species in the desert steppe in Inner Mongolia, and its performance under four grazing intensities (control, CK, 0 sheep·ha^{-1}·half year^{-1}; light grazing, LG, 0.93 sheep·ha^{-1}·half year^{-1}; moderate grazing, MG, 1.82 sheep·ha^{-1}·half year^{-1}; and heavy grazing, HG, 2.71 sheep·ha^{-1}·half year^{-1}) over six scales (5 cm × 5 cm; 10 cm × 10 cm; 20 cm × 20 cm; 25 cm × 25 cm; 50 cm × 50 cm; and 100 cm × 100 cm). The characteristics of the population stability of *S. breviflora* were explored. The results showed that the response of *S. breviflora*'s stability to heavy grazing was multidimensional. Heavy grazing reduced the population stability of *S. breviflora*. Across different dimensions, base coverage was the first of the population stability metrics of *S. breviflora* to destabilize, followed by projection coverage, density, and height. Heavy grazing also affected the trade-offs of *S. breviflora*'s population stability across different dimensions. In general, the trade-off degree decreased as the grazing intensity increased, and it increased as the scale increased.

Keywords: desert steppe; grazing intensity; trade-off; population stability

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1. Introduction

Grassland accounts for more than a third of the global land area and is an important component of terrestrial ecosystems [1,2]. Due to long-term overgrazing, grasslands have been seriously degraded worldwide. This has resulted in a decrease in grassland productivity, which threatens the ability of grassland ecosystems to continue to provide human functions and services [3–5]. Therefore, ecologists are beginning to focus more on the dual effects on livestock and vegetation under grazing conditions [6,7].

In grassland ecosystems, plant population characteristics are highly sensitive to grazing [8,9]. As grazing intensity increases, in order to adapt to the environment, plants will correspondingly change their reproduction strategies and resource allocation between different organs. For example, with the interference of overgrazing, the plant height and crown width of grassland plants have been shown to decrease, leading to a trend of miniaturization [10]. To avoid self-extinction, plants induce livestock to selectively uptake specific individuals in the population [11]. Generally, dominant species show a strong resistance to grazing livestock. For example, the grazing coverage rate of dominant species with strong grazing tolerance increases significantly in mountainous grassland that experience long-term grazing [12,13]. Grazing can directly or indirectly change the plant community, its characteristics, the habitat's microclimate, and the soil's physical and chemical properties in the grassland ecosystem, thus affecting the allocation strategies of plants [14].

Grazing intensity not only changes a plant population's characteristics, but also affects the stability of broader plant populations and even entire ecosystems. Most studies have shown that a moderate grazing intensity can improve the ability of vegetation to obtain plant resources and adapt to interference, thereby increasing the stability of plant communities and ecosystems. Heavy grazing, however, is known to reduce ecosystem stability [15–17]. Then, again, in the central steppe of Argentina, heavy grazing was demonstrated to maintain the stability of the ecosystem, while mild or moderate grazing led to community changes. Thus, a relatively high grazing pressure was required to maintain community stability in this scenario [18]. In conclusion, the grazing intensity that will best maintain the stability of the ecosystem differs among different grassland types. A plant population's structure has two dimensions: vertical and horizontal. Using projection coverage alone, it is difficult to accurately describe the vertical structure of a community, so this limited method can be expanded to more comprehensively evaluate and analyze the function of a grassland plant population [19]. Plant population density is the embodiment of a plant's reproductive ability. Basal coverage is an important structural index of a population's horizontal dimension and reflects the ability of plants to obtain soil resources. Projection coverage and height are important structural characteristic indexes in the vertical dimension, and they reflect the ability of plants to occupy space on the ground after light energy is utilized [20,21]. Therefore, density, basal coverage, projection coverage, and height are important indicators that should all be considered when studying how effective grazing is at stabilizing a plant's population [22].

In Inner Mongolia, the desert steppe is located in the transition zone between grassland and desert. Due to the arid climate and poor soil environment, the structure and function of plant communities in this desert steppe are vulnerable to climate change and human disturbance [23,24]. *S. breviflora*, a perennial grass and the dominant species in desert steppe, is advantaged by its cold tolerance, drought tolerance, and trampling tolerance. The stability of its plant population has a strong keystone effect on the desert steppe. Most previous studies on *S. breviflora* have focused on the effects of different grazing intensities on the structure and function of plant communities [25–27]. However, it remains largely unknown whether grazing will affect the population stability of *S. breviflora* differently at different scales and whether this effect will change in accordance with changes in dimensions. Therefore, this paper utilizes data on *S. breviflora* taken from a long-term grazing disturbance experiment to study the quantitative characteristics (density, basal coverage, projection coverage, and height) of *S. breviflora* under different grazing intensities and scales and to answer the following two main questions: (1) As grazing intensity and scale effect increase, how will the basic quantitative characteristics of *S. breviflora* and its stability change? (2) How does the trade-off of population stability of *S. breviflora* between grazing intensity and scale effect vary across different dimensions?

2. Materials and Methods

2.1. Study Site

The test site for measuring the basic quantitative characteristics of *S. breviflora* was located in the comprehensive experimental demonstration center of the Inner Mongolia Academy of Agricultural and Animal Husbandry Sciences (41°46′43.6″ N, 111°53′41.7″ E, elevation 1456 m), belonging to the Wangfu I team in the south–central Siziwang Banner of Ulanqab City. This experimental demonstration center is located in the middle-temperate, semi-arid, continental monsoon climate, with an average annual precipitation of 220 mm, and a highly uneven distribution. The vegetation is low and sparse, and species composition is relatively poor. The soil type is chestnut soil, barren and loose with low organic matter content. This region is a desert steppe; there are more than 30 common species in the experimental area, with the constructive species being *S. breviflora*. The other dominant species include *Artemisia frigida* and *Cleistogenes songorica*, while the common species include *Convolvulus armanii*, *Kochia protata*, *Neopallasia spectata*, and *Heteropappus alticus*.

2.2. Experimental Design

The experiment with varying intensities of long-term grazing was established in 2004, over a total area of about 50 ha. Using a completely randomized block design, twelve fenced grazing plots were divided into three blocks (see Figure 1). Four treatments representing the different grazing intensities were randomly arranged in each group: control CK (0 sheep·ha^{-1}·half year^{-1}), light grazing LG (0.93 sheep·ha^{-1}·half year^{-1}), moderate grazing MG (1.82 sheep·ha^{-1}·half year^{-1}), and heavy grazing HG (2.71 sheep·ha^{-1}·half year^{-1}). The actual number of grazing sheep applied in the light, moderate, and heavy treatments were four, eight, and twelve, respectively. The grazing season ran during summer and autumn, and winter and spring were the rest seasons. Throughout the grazing season, the livestock were introduced to the grazing plots daily and allowed to feed freely (water was drunk before arriving at the plots) before being returned to the livestock ring in the evening (where they were administered drinking water and salt supplements). The livestock grazed from six a.m. to six p.m. each day.

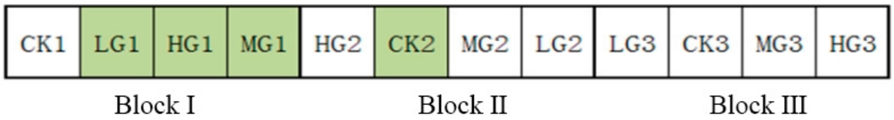

Figure 1. Schematic diagram for the grazing experiment's plot layout. The colored plots were sampled. The grazing experiment plots (each ca. 4.4 ha) were arranged in a completely randomized block design that included four grazing intensity treatments repeated three times each.

2.3. Vegetation Sampling

The CK treatment in block II was selected for sampling to measure the quantitative characteristics of the *S. breviflora* population in the desert steppe, as shown in Figure 1, in order to avoid any margin effects experienced by the CK treatment in block I. In each sample plot, for all the grazing intensities, a representative area with consistent terrain (5 m × 5 m) was selected. A 1 m × 1 m sample frame was delineated; each 1 m × 1 m sample was subdivided into 400 5 cm × 5 cm small samples, creating 25 squares according to the order of the snake matrix, and the accurate spatial position of *S. breviflora* in the sample frame was demarcated by tape. The origin of the coordinates in each sample was defined as the upper left corner of the sample plot. In this experiment, the density (cluster), radius of base coverage (cm) and projection coverage (cm), and height (cm) of the *S. breviflora* population were all measured outdoors on 15 August 2019, and the area of base coverage and projection coverage were calculated indoors later. The average precipitation in 2019 was 249.2 mm, and the average temperature from June to September was 13.98 °C. This experiment lasted for about 7 days (see Figure 2).

(**a**) (**b**)

Figure 2. A photo of the desert steppe in the CK (**a**) and HG (**b**) treatments was taken on the 15th of August 2019.

2.4. Data Analysis

For each of the grazing intensities, the density (cluster), base coverage (cm^2), and projection coverage (cm^2) of *S. breviflora* were transformed by the square root (height (cm) data did not need to be transformed), so that all the data would be normally distributed. The sample area of 5 m × 5 m was sub-divided into grids with squares of size 5 cm × 5 cm, 10 cm × 10 cm, 20 cm × 20 cm, 25 cm × 25 cm, 50 cm × 50 cm, and 100 cm × 100 cm. Variance analysis was used to compare the effects of grazing intensity and scale on the quantitative characteristics of *S. breviflora*, and contour plots were used to compare the changes in the quantitative characteristics of *S. breviflora* under the different grazing intensities and scales. The base coverage and projection coverage were calculated as follows:

$$S = \pi \times r^2 \tag{1}$$

where S is the plot of base coverage or projection coverage and r is the radius of base coverage or projection coverage.

Secondly, the effects of the increased grazing intensity and scale on the stability of *S. breviflora*'s population were analyzed in different dimensions. The plant population stability is represented by the reciprocal (ICV) of the coefficient of variation (CV) of the basic quantitative characteristics of the species' population (density (cluster), base coverage (cm^2), projection coverage (cm^2), and height (cm)) [28,29]:

$$ICV = \frac{\mu}{\delta} \tag{2}$$

In the formula, μ is the average value of a certain index of *S. breviflora* in the sample, and δ is the standard deviation of the same index of *S. breviflora* in the sample. The smaller the value of ICV, the lower the stability of the plant's population; conversely, a higher ICV indicates a greater stability in the plant's population.

Finally, under the various grazing intensities and scales, the population stability of *S. breviflora* was analyzed under different dimensions (density (cluster), base coverage (cm^2), projection coverage (cm^2), and height (cm)) and overall dimensions to calculate the trade-off value [30,31].

The trade-off model is described as follows: the trade-off of research object A refers to the relative deviation between its observed value and the average value. First, the relative equity B_A of an object of study is defined, and then the relative equity of each index observation value (x axis or y axis) can be calculated using the following formula:

$$B_A = \frac{A_{OBS} - A_{Min}}{A_{Max} - A_{Min}} \tag{3}$$

Among these variables, A_{OBS} is the observed value of the index, and A_{Max} and A_{Min} are the maximum and minimum values of the index of all observed values. The observed value of each indicator corresponds to an equity value B_A, which ranges from zero to one and can be conceptualized as the proportion of possible benefits of object A.

The obtained equity values of the x-axis and y-axis indexes are reflected on the two-dimensional coordinate axis. By calculating the distance from this point to the zero trade-off line (1:1 line), the trade-off of the x-axis or y-axis indexes can be obtained. In this model, if the point falls on the zero trade-off line, it is regarded that there is zero trade-off; if the point falls above the zero trade-off line, it represents that the y-axis benefits more from the trade-off than the x-axis; if the point falls below the zero trade-off line, it represents that the x-axis benefits more from the trade-off than the y-axis; and the distance of the point offline indicates the degree of trade-off (Figure 3). This method effectively quantifies the relationship between the x-axis and y-axis indicators.

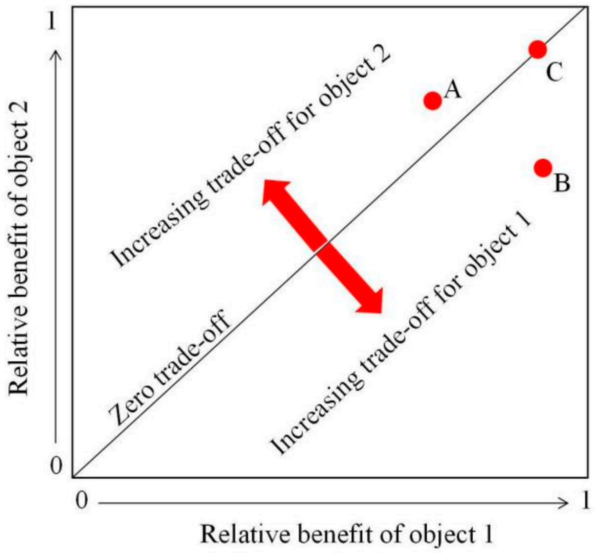

Figure 3. Illustration and example of trade-offs between two objects. The trade-off degree increases as the distance from the zero trade-off line increases. At the zero trade-off line, the interest of object 1 is equal to that of object 2. The trade-off order of points A, B, and C is B > A > C.

The SAS 9.4 (SAS Institute Inc., Cary, NC, USA) software was used for the data processing of the variance analysis in this paper and was performed at the significance level of $p < 0.05$. The assembly process and rendering of graphics were completed in Sigmaplot 14.0 (Systat Software Inc., San Jose, CA, USA).

This article first conducts a variance analysis on the basic quantitative characteristics of *S. breviflora* under the different grazing intensities and scales, using contour maps to study the changes in the basic quantitative characteristics of *S. breviflora* under the different grazing intensities and scales. Secondly, based on the calculated stability values, this article explores the changes in the population stability of *S. breviflora* under the different grazing intensities and scales. Finally, based on the calculated trade-off values, this article explores the trade-off characteristics of the *S. breviflora* population in different dimensions. The data processing of ANOVA in this study was conducted using the SAS 9.4 (SAS Institute Inc., Cary, NC, USA) software at a significance level of $p < 0.05$. The assembly process and graphic drawing were completed in Sigmaplot 14.0 (Systat Software Inc., San Jose, CA, USA), and the table production process was completed in the Excel 2019 software.

3. Result

The responses of *S. breviflora* population's basic quantitative characteristics to the grazing intensity and scale effects are discussed in the following sections.

After the square root transformation of the density, base coverage, and projection coverage metrics of the *S. breviflora* population (height did not need a square root transformation), all the data representing the basic quantitative characteristics of the *S. breviflora* population followed a normal distribution, and a variance analysis could be performed. The results showed that the grazing intensity had significant effects on the height of the *S. breviflora* plant population and that the scale effect had significant effects on the density, base coverage, projection coverage, and height (Table 1, $p < 0.05$). The *SS*, *MS*, and *F* values of the scale effect were larger than those of the grazing intensity factors, and their variance contribution rate was more than 85%, which indicates that the basic quantitative characteristics of the *S. breviflora* population responded more strongly to the scale effects than to the grazing effects.

Table 1. The effects of grazing intensity and scale on the basic quantitative characteristics of *S. breviflora*.

Variable	Factors	*df*	*SS*	*MS*	*F* Value	*Pr* > *F*	Variance Contribution	Data Transformed
Density (cluster)	Grazing intensity	3	1.58	0.53	5.87	0.0074	1.12%	Yes
	Scale	5	138.03	27.61	308.79	<0.0001	97.93%	
Base coverage (cm^2)	Grazing intensity	3	58.47	19.49	5.83	0.0076	6.03%	Yes
	Scale	5	860.77	172.15	51.48	<0.0001	88.79%	
Projection coverage (cm^2)	Grazing intensity	3	184.65	61.55	5.86	0.0074	5.12%	Yes
	Scale	5	3267.25	653.45	62.19	<0.0001	90.52%	
Height (cm)	Grazing intensity	3	9.21	3.07	8.04	0.002	8.40%	No
	Scale	5	94.64	18.93	49.57	<0.0001	86.37%	

Notes: *SS*: Stdev square; *MS*: Mean square.

The basic quantitative characteristics of *S. breviflora*, as the grazing intensity and scale varied, are shown in Figure 4. As the spatial scale increased, the density, base coverage, projection coverage, and height of *S. breviflora* all showed an increasing trend, and the increase was greater in the scales ranging from 25 cm × 25 cm to 100 cm × 100 cm. However, as the grazing intensity increased, the density of *S. breviflora* peaked in the HG treatment (Figure 4A), and the base coverage and projection coverage of *S. breviflora* showed an overall upward and then downward trend, peaking in the MG treatment (Figure 4B,C). The change in *S. breviflora*'s height, with the variation in grazing intensity and scale, is shown in Figure 4D. As the grazing intensity and scale increased, the height of *S. breviflora* showed a more obvious trend of rising and then falling, with the peak value being recorded in the LG treatment. Overall, the basic quantitative characteristics of *S. breviflora* changed little in the small scale, but differed significantly in the larger scales. As the grazing intensity increased, the density of *S. breviflora* increased, and the other quantitative indexes first increased and then decreased.

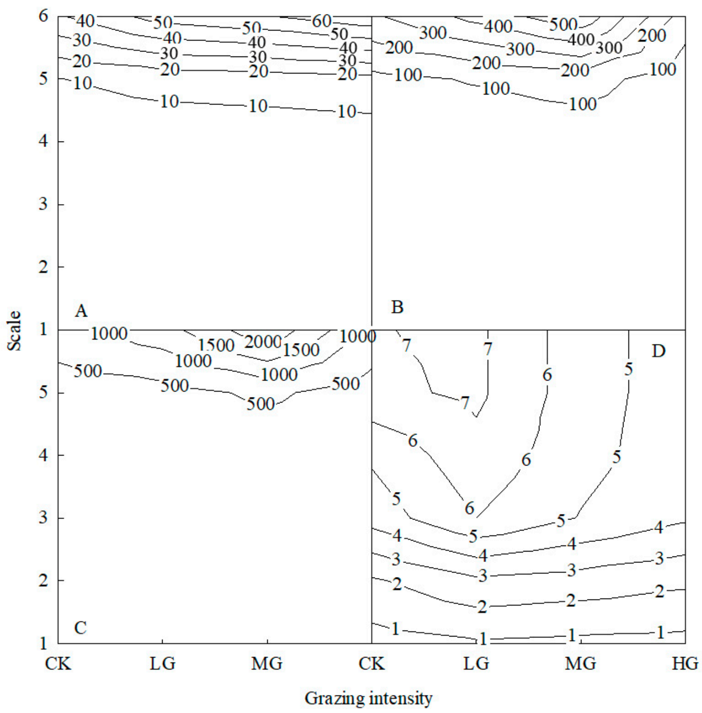

Figure 4. Variation in the basic population characteristics of *S. breviflora* in the varying treatments of grazing intensity and scale. (**A**) density, (**B**) base coverage, (**C**) projection coverage, and (**D**) height of *S. breviflora*. CK, control; LG, light grazing; MG, moderate grazing; and HG, heavy grazing. (1) 5 cm × 5 cm; (2) 10 cm × 10 cm; (3) 20 cm × 20 cm; (4) 25 cm × 25 cm; (5) 50 cm × 50 cm; and (6) 100 cm × 100 cm.

3.1. Characteristics of and Variation in S. breviflora's Population Stability

The stability of the *S. breviflora* population varies with the grazing intensity and scale (Table 2). The reciprocal (*ICV*) analysis results of the variation coefficient of the *S. breviflora* plant population in different dimensions showed that the stability of *S. breviflora* increased as the scale increased, in both the different dimensions (density, base coverage, projection coverage, and height) and overall dimensions. As the grazing intensity increased in the dimension of *S. breviflora*'s density, the stability of *S. breviflora* increased and the density peaked in the HG treatment. In the dimension of *S. breviflora*'s base coverage in the 100 cm × 100 cm scale, the stability of *S. breviflora* was highest in the HG treatment, though the stability peaked in the MG treatment for all the other scales. As the grazing intensity increased in the dimension of *S. breviflora*'s projection coverage, the stability of *S. breviflora* increased. The projection coverage peaked in the MG treatment, and the stability of *S. breviflora* decreased in the HG treatment. In the dimension of *S. breviflora*'s height in the 5 cm × 5 cm scale, the stability of *S. breviflora* peaked in the HG treatment, though it peaked in the MG treatment at all the other scales. As the grazing intensity increased in the overall dimension of *S. breviflora*, the stability of *S. breviflora* first increased and then decreased, with the peak value being recorded in the MG treatment. Therefore, depending on the grazing conditions, *S. breviflora* had different stability maintenance mechanisms for different dimensions. Summarizing the multiple dimensions, the stability of *S. breviflora* tended to increase with the increase in grazing intensity up until moderate grazing, before decreasing under heavy grazing.

Table 2. Effects of grazing intensity and scale on the stability of the *S. breviflora* population in the different dimensions.

Dimension	Grazing Intensity	Scale					
		1	2	3	4	5	6
Density (cluster)	CK	0.030	0.537	0.959	1.072	1.563	1.926
	LG	0.361	0.704	1.373	1.606	2.385	2.725
	MG	0.392	0.819	1.598	2.003	3.632	5.349
	HG	0.415	0.834	1.628	1.884	3.738	5.866
Base Coverage (cm^2)	CK	0.215	0.414	0.792	0.941	1.543	2.215
	LG	0.318	0.627	1.188	1.392	1.994	2.272
	MG	0.324	0.670	1.230	1.515	2.601	3.279
	HG	0.318	0.625	1.181	1.362	2.303	2.940
Projection Coverage (cm^2)	CK	0.241	0.458	0.857	0.998	1.622	2.169
	LG	0.293	0.570	1.097	1.275	1.865	2.163
	MG	0.347	0.708	1.315	1.582	2.410	2.856
	HG	0.271	0.530	0.945	1.058	1.442	1.564
Height (cm)	CK	0.284	0.569	1.169	1.441	2.986	4.564
	LG	0.352	0.739	1.845	2.657	5.724	6.825
	MG	0.392	0.894	2.676	4.699	11.443	16.816
	HG	0.405	0.890	2.387	3.159	4.663	4.830
Total	CK	0.192	0.495	0.944	1.113	1.929	2.719
	LG	0.331	0.660	1.376	1.733	2.992	3.496
	MG	0.364	0.773	1.705	2.450	5.021	7.075
	HG	0.353	0.720	1.535	1.866	3.037	3.800

Abbreviations: CK, control; LG, light grazing; MG, moderate grazing; and HG, heavy grazing. (1) 5 cm × 5 cm; (2) 10 cm × 10 cm; (3) 20 cm × 20 cm; (4) 25 cm × 25 cm; (5) 50 cm × 50 cm; and (6) 100 cm × 100 cm.

3.2. Balance of S. breviflora's Population Stability in Different Dimensions

Under the different grazing intensities, the trade-offs of *S. breviflora*'s population stability varied in the different dimensions (Figure 5). With base coverage as the index, the trade-off between the base coverage and density, overall dimension, and height favored the base coverage in the stability of *S. breviflora* (Figure 5a–c). The trade-off degrees were ordered LG > CK > MG, from largest to smallest. The HG treatment was relatively special, with the trade-off between the base coverage and the density being nearly zero. The trade-off degree was largest between the base coverage and the overall dimension and height. Between the base coverage and the projection coverage (Figure 5d), only the HG treatment showed a trade-off favoring the base coverage, whereas the other processing regions showed zero trade-off.

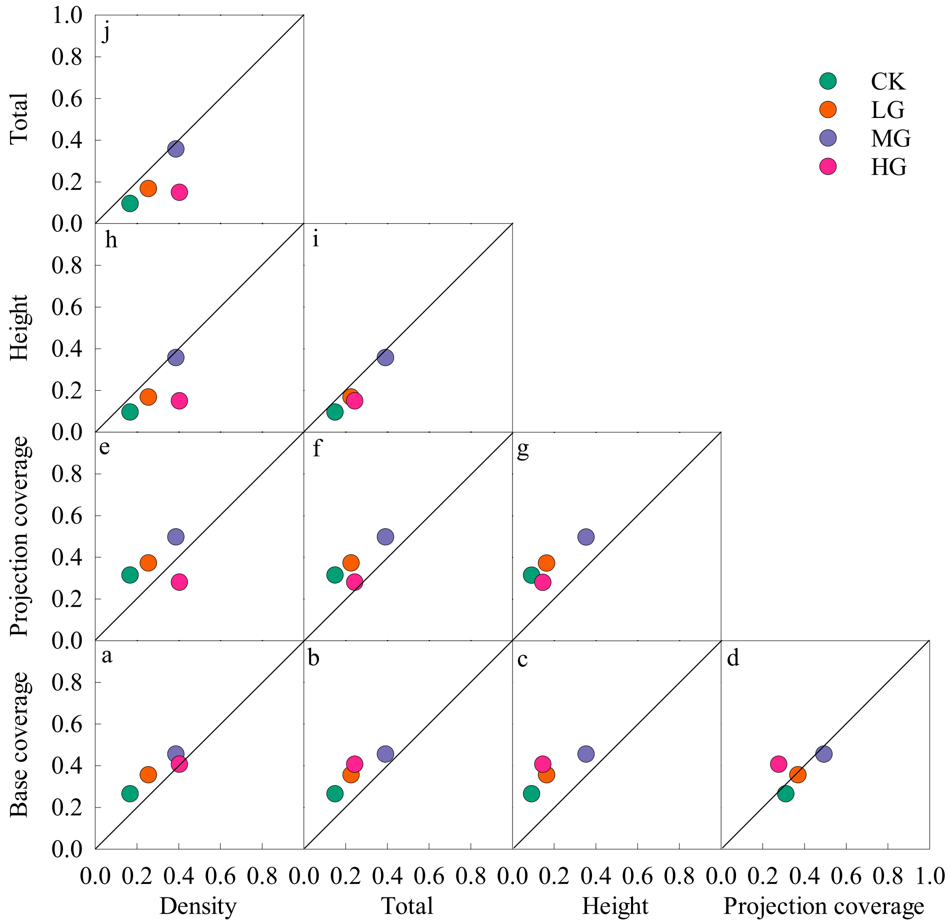

Figure 5. Trade-off of *S. breviflora* population in multiple dimensions under the different grazing intensities. CK, control; LG, light grazing; MG, moderate grazing; and HG, heavy grazing. (**a**) The trade-off between the base coverage and density of *S. breviflora* population; (**b**) The trade-off between the base coverage and overall dimension of *S. breviflora* population; (**c**) The trade-off between the base coverage and height of *S. breviflora* population; (**d**) The trade-off between the base coverage and projection coverage *S. breviflora* population; (**e**) The trade-off between the projection coverage and density of *S. breviflora* population; (**f**) The trade-off between the projection coverage and overall dimension of *S. breviflora* population; (**g**) The trade-off between the projection coverage and height of *S. breviflora* population; (**h**) The trade-off between the height and density of *S. breviflora* population; (**i**) The trade-off between the height and overall dimension of *S. breviflora* population; (**j**) The trade-off between the overall dimension and density of *S. breviflora* population.

Projection coverage was used as an indicator to study the trade-off degree under the different dimensions (Figure 5e–g). Under the moderate grazing condition, the stability of *S. breviflora* was characterized by the trade-off favoring the projection coverage, and the trade-off degree decreased as the grazing intensity increased. The difference was that, under the HG treatment, the trade-off between the projection coverage and the density tended to favor the density, while the trade-off between the projection coverage and overall dimension was zero, and the minimum trade-off was between the projection coverage and the height.

The trade-off degree under the different dimensions was studied with the height as an indicator (Figure 5h,i). In the trade-off between the height and the density, the stability of *S. breviflora* tended to favor the density. Under the moderate grazing conditions, the trade-off degree decreased as the grazing intensity increased, and it tended toward zero trade-off. The trade-off degree was highest in the HG treatment. In the trade-off between the height and the overall dimension, the stability of *S. breviflora* tended to favor the overall dimension. The trade-off degree was highest in the HG treatment and tended to be zero under the moderate grazing conditions.

In the trade-off between the overall dimension and the density (Figure 5j), the stability of *S. breviflora* depended most strongly on the trade-off between the density and the direction. The trade-off degree decreased as the grazing intensity increased, and it tended to be zero in the MG treatment. The trade-off degree was largest in the HG treatment. In short, the response mechanisms of trade-off performance varied in the different treatments under the different dimensions. Under the moderate grazing conditions, the degree of trade-off decreased as the grazing intensity increased, and the degree even tended toward zero trade-off. However, the trade-off changes were special in the different dimensions of the HG treatment and so a specific analysis was performed in the different dimensions.

At the different scales, the trade-offs of *S. breviflora*'s population stability varied with the dimension (Figure 6). With base coverage as the index, the stability of *S. breviflora* favored the base coverage in the trade-off between the base coverage and density, overall dimension and height (Figure 6a–c), and the trade-off degree increased as the scale increased. In the trade-off between the base coverage and the projection coverage (Figure 6d), only the 100 cm × 100 cm scale favored the base coverage in the trade-off. There was zero trade-off in all the other scales.

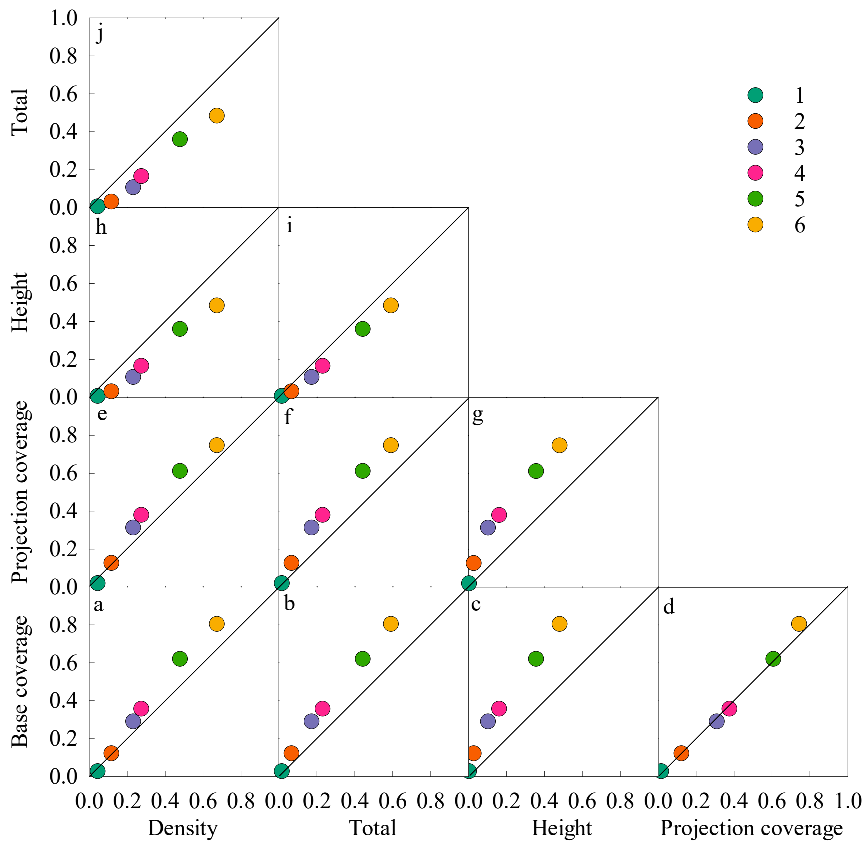

Figure 6. Trade-off of population stability of *S. breviflora* at the different scales in multiple dimensions. (1) 5 cm × 5 cm; (2) 10 cm × 10 cm; (3) 20 cm × 20 cm; (4) 25 cm × 25 cm; (5) 50 cm × 50 cm; and (6) 100 cm × 100 cm. (**a**) The trade-off between the base coverage and density of *S. breviflora* population; (**b**) The trade-off between the base coverage and overall dimension of *S. breviflora* population; (**c**) The

trade-off between the base coverage and height of *S. breviflora* population; (**d**) The trade-off between the base coverage and projection coverage *S. breviflora* population; (**e**) The trade-off between the projection coverage and density of *S. breviflora* population; (**f**) The trade-off between the projection coverage and overall dimension of *S. breviflora* population; (**g**) The trade-off between the projection coverage and height of *S. breviflora* population; (**h**) The trade-off between the height and density of *S. breviflora* population; (**i**) The trade-off between the height and overall dimension of *S. breviflora* population; (**j**) The trade-off between the overall dimension and density of *S. breviflora* population.

With projection coverage as the index, the trade-off degree under the different dimensions varied mostly for 100 cm × 100 cm, as shown in Figure 6e–g. It can be seen that the stability of *S. breviflora* was represented by the trade-off of projection coverage. Taking height as the index, the trade-off degree of the different dimensions varied mostly for 100 cm × 100 cm (Figure 6h,i). It can be seen that the stability of *S. breviflora* is characterized by the trade-off between the density and the overall dimension. In the trade-off between the overall dimension and the density, the stability of *S. breviflora* was shown as the trade-off between the density and the direction (Figure 6j).

In short, across the different dimensions, the trade-off degree of *S. breviflora*'s population stability increased as the scale increased, and it followed a logarithmic curve. However, the slope (inflection point) of the curve differed under the different dimensions.

4. Discussion

Grazing is the most frequently observed pattern of land use in grasslands. Plant population and community composition change as a direct response to grazing, but can also be affected by environmental conditions and grassland types, as well as whether the dominant species changes over time [32–34].

In this experiment, as the grazing intensity increased, the density of *S. breviflora* increased, and the height, base coverage, and projection coverage increased at first and then decreased. This change was obvious on a large scale. This reveals that, in the face of grazing disturbance, *S. breviflora*, the dominant species in this desert steppe, has formed a unique survival strategy for coping with long-term coexistence with livestock [35]. This can be explained by the following factors: Firstly, the changes of *S. breviflora* are obvious at the large scales and there is almost zero change at the small scales. Herbivore activities can affect habitat heterogeneity differently at different scales, which, thus, translates into the differential effects of grazing on species' diversity at different scales [36–39]. Secondly, although the density of *S. breviflora* increased as the grazing intensity increased, the height of *S. breviflora* peaked in the LG treatment. The increased grazing intensity reduced the height of *S. breviflora* because plants usually adopt dwarfing strategies to adapt to harsh soil conditions and high-intensity trampling by livestock [40]. Finally, as the grazing intensity increased, the phenotypic characteristics of the plants were altered through changing the resource allocation mode and reproductive distribution strategy of different organs above and below the ground. Ultimately, this improved population fitness [41]. *S. breviflora* is a densely clustered grass. The tillering node is located on the ground, so it is easily affected by livestock feeding behavior, as demonstrated by the resulting fragmentation of plant clusters and the decreases in cluster size [42]. For this reason, the base coverage and projection coverage of *S. breviflora* peaked in the MG treatment and decreased in the HG treatment. Further, plants may sacrifice their organs selectively. In general, herbivores like to eat the most delicious parts of plants (young leaves, fruits, and seeds), and so mature plants may sacrifice parts of themselves to protect immature individuals [43,44].

In grassland ecosystems, grazing usually produces more stable vegetation patterns than non-grazing would [45,46]. The resistance and resilience of plants to grazing disturbance can also be reflected in the stability of plant populations [47]. For example, semi-arid grasslands need a certain degree of grazing to maintain ecosystem stability [48]. In this study, *S. breviflora* was found to have different stability maintenance mechanisms under different grazing conditions. The density of *S. breviflora* had the highest stability in the HG treatment, and the base coverage, projection coverage, and height of *S. breviflora* had the highest stability in the MG treatment. As a dominant species, *S. breviflora* maintained the stability of the plant community in multiple states. Therefore, combined with multiple dimensions, under moderate grazing, the stability of *S. breviflora* increased as the grazing intensity increased, and heavy grazing reduced the stability of *S. breviflora*. An optimal grazing intensity can maintain the structure and function of the grassland ecosystem, while a low grazing intensity may lead to component changes and species invasion, and a high grazing intensity may reduce biodiversity and productivity [49,50].

Due to the limitation of resources, there is always competition and some trade-off between the functional traits of plants and the growing process. According to the optimal allocation theory, in order to adapt to environmental changes to the maximum extent possible, plants tend to allocate more resources to structures or organs that maximize access to the resources needed for survival, growth, and reproduction. These resources include water, nutrients, and light [51,52]. In this study, in different dimensions, the trade-off of the population stability of *S. breviflora* was first inclined to favor the base coverage, followed by the projection coverage, density, and height. The base coverage and the projection coverage directly or indirectly reflected the growth status of the plants and the relative spatial range of living resources, such as sunlight, soil moisture, and nutrients, accessible to them. These metrics represent the effective photosynthetic area of plant populations [53,54]. In addition, plants always avoid mutual occlusion as much as possible, and they obtain sunlight with the largest base diameter area and crown area [55]. This reflects the competitive relationship between plants [56,57]. Under moderate grazing intensity, the trade-off degree of the population stability of *S. breviflora* decreased as the grazing intensity increased, and it showed special properties under heavy grazing. This also further explained the reason why the maximum stability of *S. breviflora* appeared in the MG treatment (Table 2). In the different dimensions, the trade-off degree of the population stability of *S. breviflora* increased as the scale increased, following a logarithmic curve. The stability of the *S. breviflora* population showed multidimensional characteristics, indicating that grazing can change the distribution strategy of plants and cause them to develop in a way that improves population fitness [58].

The resistance or resilience of plants to grazing disturbance also depends on the local environment [59]. In arid and semi-arid desert steppe, water is the main limiting factor that determines the grazing resistance and resilience of plant communities. Studies have shown that compensatory growth occurs in plants under sufficient precipitation conditions, but no compensatory growth occurs in drought years [27]. Therefore, in order to better explore the changes in plant population stability under grazing disturbance, further studies should account for the changes in trade-offs regarding the internal mechanism of the plant population in combination with the habitat's conditions, the physiological characteristics of plants, and other factors.

5. Conclusions

This study concluded that the response of *S. breviflora*'s population stability to grazing was multi-dimensional. The results of this study showed that, as the grazing intensity increased, the density of *S. breviflora* also increased. The base coverage, projection coverage, and height of *S. breviflora* first increased and then decreased, and this change was obvious on a large scale. Under moderate grazing, the stability of *S. breviflora* increased as the grazing intensity increased, while heavy grazing decreased the stability of *S. breviflora*. In the different dimensions, the balance of population stability of *S. breviflora* first favored the base coverage, followed by the projection coverage, the density, and the height. The trade-off degree of *S. breviflora*'s population stability decreased in the different dimensions as the grazing intensity increased (except for the HG treatment), and it increased as the scale increased. The multi-dimensionality of *S. breviflora*'s population stability under heavy grazing may further play into the ecosystem stability and sustainability of the desert steppe.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13102657/s1, Table S1: Stocking rate data.

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