

Article

Rest Grazing from the Critical Period of Soil Thawing in Alpine Meadow of Tibetan Plateau Is Conducive to the Sexual Reproduction of *Polygonum viviparum*

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Abstract: (1) Background: The most important management measure and utilization method for grassland is grazing. The suitable beginning period of spring rest grazing in the alpine meadow was selected to provide a theoretical basis for more scientific management and sustainable utilization. The experimental site is located in the cold-season pasture of an alpine meadow, which is located in the eastern part of the Qinghai Tibet Plateau. (2) Methods: We set up five treatments with the critical soil thawing period, the late soil thawing period, the grass reviving early period, the grass reviving late period with local traditional rest grazing period as the start time of rest grazing, and the grass withering period as the end time of rest grazing, recorded as P1, P2, P3, P4, and P5 (CK, control check). We studied the reproductive characteristics of the dominant plant, *Polygonum viviparum*, during different rest grazing periods. (3) Results: The results showed that, in general, *P. viviparum* was mainly involved in asexual reproduction and tended to have sexual reproduction with the rest of the grazing in advance. The biomass proportion of sexual reproduction organs and asexual reproduction organs in P1 were higher than those of other treatments, which were 704% and 20% higher than P5 (CK), respectively. The seed yields of P1 were 135%, 535%, 690%, and 1269% higher than P2–P5, respectively. The indices of *P. viviparum* seed quality in P5 were lower than those of the other treatments. The seed length, seed size, seed setting rate, and satiety grain weight ratio of P1 were higher than those of other treatments. We use the TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) analysis method to comprehensively evaluate the indicators of the five plots. (4) Conclusions: It was concluded that the rest of the grazing from the critical period of soil thawing was conducive to the growth and sexual (seed) reproduction of *P. viviparum*. Therefore, the resting grazing period of alpine meadows in spring should start with the critical period of soil thawing.

Keywords: *Polygonum viviparum*; rest grazing in spring; reproductive characteristics; alpine meadow



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1. Introduction

Alpine meadow has an important ecological barrier function and is the most widely distributed and largest grassland type in the Qinghai–Tibet Plateau. It plays a vital role in regulating East Asian climate, global climate change, water resources, and so on [1,2]. The Tibetan Plateau is named for its geographical height, climatic conditions, and ecological environment characteristics, as the most important and vulnerable ecosystem in China is seriously degraded by global warming and human disturbance. There are many measures to restore degraded grassland, but rest grazing is the simplest and most economical measure [3]. Appropriate rest grazing can slow down the rate of grassland degradation and protect the reproduction and normal growth of forage grass.

Reproduction is one of the most critical processes in the history of plant life [4]. It maintains the survival and renewal of populations and the completion of individual life history. Forage has two modes of reproduction: asexual and sexual reproduction. Asexual reproduction is conducive to reproductive security, which has obvious population statistical advantages as all genes are inherited by the offspring. It also enables plants to maintain activity, persistence, and proliferation abilities across time and space and can quickly absorb and reserve limited resources to achieve risk sharing [5]. Sexual reproduction is an important way for plants to reproduce their offspring, increase genetic diversity, and improve seed quality, allowing plants to maintain populations in complex and variable external conditions [6]. Reproduction is the most basic behavior and process of biological reproduction and population continuation, the key to population formation and development, and the basis of biological community and ecosystem succession [7]. The reproduction of plants has greatly promoted the restoration of degraded grassland. The remaining grazing measures restore degraded grasslands through seed banks and regulating buds [8]. The proportion of plant biomass allocated is of great significance for field application. Biomass allocation reflects the reproductive tendency and resource allocation of plants to a large extent, which is also the purpose of plants to make reasonable use of limited environmental resources. It reflects the reproductive strategies of the population in different environments. By studying the reproduction of plants on grassland, we can more clearly understand the process of population reproduction and renewal, predict the succession direction of the grassland community, and provide a more scientific basis for the protection and rational utilization of grassland.

Polygonum viviparum is a perennial herb in the Polygonaceae. It is sexually propagated by seeds and vegetatively propagated by bulbils. In China, it is mainly distributed in Qinghai, Gansu, Xizang, Yunnan, and other regions. It is rich in protein, soft, and juicy and is an important high-quality forage resource in high-altitude areas [9]. Previous studies on *P. viviparum* were mainly focused on the effects of different treatments on the germination rate of wild *P. viviparum* seed [9], sample extraction and chemical detection [10], genetic diversity [11], net photosynthetic rate [12], the response of leaf anatomical structure to altitude [13], differences in reproductive methods in different habitats [14], and the effect of enclosure on its reproductive strategy [15]. The response of the reproductive characteristics of *P. viviparum* to grazing rest has not been reported.

The pasture regreening period is one of the grazing prohibition periods for alpine meadows. On the one hand, the photosynthetic area of regreened seedlings is reduced after being eaten by livestock; on the other hand, the phenomena of soil freezing and thawing alternation appear before pasture regreening. Grazing before regreening damages pasture roots and affects the subsequent growth and development of the pasture. Previous studies have shown that it is beneficial for the sexual reproduction of *Kobresia humilis* [16] and *Carex capillifolia* [17] to start grazing in the critical period of soil thawing before the regreening stage of herbage. It can improve the steppe plant community and grassland productivity [18]. The grazing time should be fully utilized in the early stages of soil thawing. Therefore, it is necessary to continue to explore the suitable period of rest grazing for the alpine meadow cold-season pasture on the Tibetan Plateau. In this experiment, the alpine meadow is a cold-season pasture on the eastern part of the Tibetan Plateau. Through the observation of the soil thawing period and the grass regreening period, different beginning periods of rest grazing were determined. To study the reproductive characteristics of the dominant plant *P. viviparum* under different periods of rest grazing in spring, to understand the reproductive process of the *P. viviparum* population and the reproductive regeneration process of grassland vegetation, and to determine the best rest grazing period in the cold season of alpine grassland, so as to provide a more scientific basis for the sustainable utilization of alpine meadow. The results of this study still have a certain reference value for similar grasslands with *P. viviparum* as the dominant plant.

2. Materials and Methods

2.1. Test Plot Overview

The experimental plot is in the eastern Qilian Mountains of the Qinghai–Tibet Plateau, with an altitude of 2960 m, and the geographical coordinates are 37°40' N, 102°32' E (Figure 1). There are two seasons each year: the warm season, June–September, and the cold season, October to May of the next year. According to the United States Department of Agriculture (USDA) soil taxonomy, the alpine meadow soil in this area was named Cryrendolls [19,20]. The grassland type of the test site belongs to an alpine meadow, which is used as a cold-season grassland. The dominant plants were *C. capillifolia*, and the dominant species were *P. viviparum*, *Elymus nutans*, and *K. humilis*.

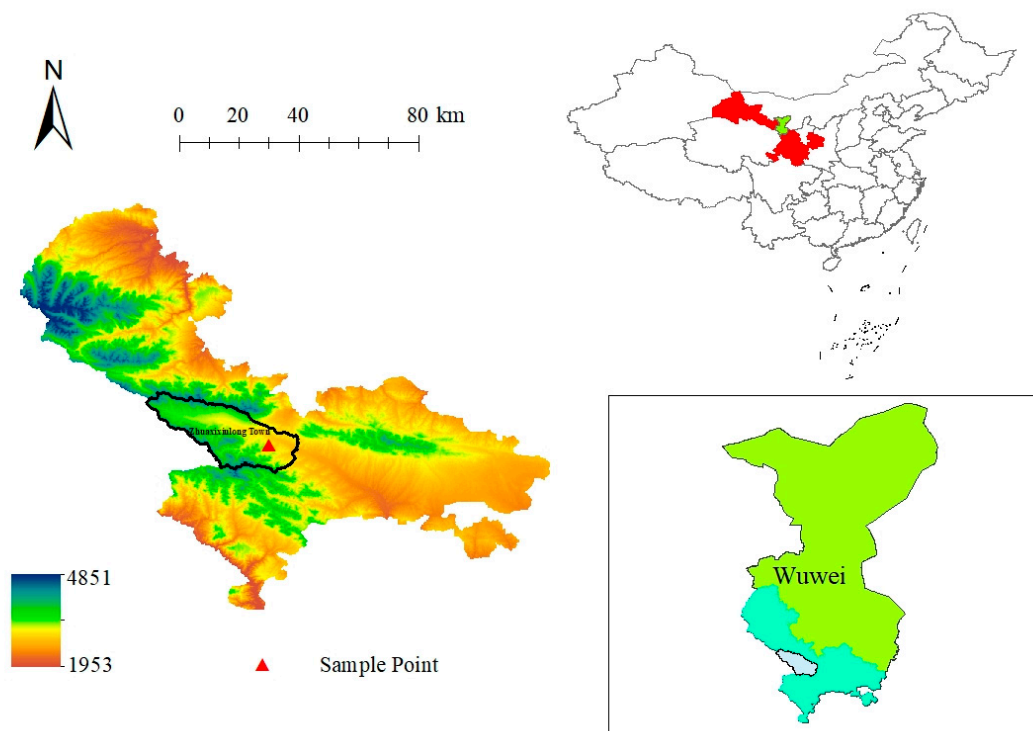


Figure 1. Geographical location map of sample plot. The digital elevation model data are obtained from the geospatial data cloud (<http://www.gscloud.cn/>, accessed on 12 December 2023) with a spatial resolution of 30 m. The administrative division data were obtained from the Resource and Environment Data Center of the Chinese Academy of Sciences (<http://www.resdc.cn>, accessed on 12 December 2023).

2.2. Plot Setting

This area has been used for experiments since 2018. The homogeneous grassland vegetation was divided into five plots by fences. The division of the five periods of rest grazing was based on soil thawing depth, grass regreening, and dominant grass height. When soil thawing depth is >0.9 cm and >10 cm, grass regreening is 30% and 70~80%, grass height reached 5 cm for each treatment of rest grazing start time, and rest grazing end time was unified for grass withered yellow period, respectively, for five plots P1–P5.

Determination of soil thawing depth: On 1 March, when the grass began to regreen, at 14:00 p.m. every day (when the thawing depth was the largest on that day), a self-made fine steel needle was slowly inserted vertically into the soil at the thawing observation point until it touched the frozen soil layer. A ruler was used to measure the depth of the steel needle inserted into the soil, that is, the depth of soil thawing, and the average value was obtained by repeated measurements eight times. Determination of the regreening period of forage grass: 1 m × 1 m quadrat was taken by the acupuncture method, and a measuring needle with a diameter of 0.2 mm was inserted vertically into the quadrat

100 times. The number of times the measuring needle touched the regreened plants during the measurement process was used as the number of regreenings.

To set the rest of the grazing period, we considered winter soil freezing and withered vegetation. As the impact of grazing was not significant, grazing began on 1 March.

In order to ensure the normal feed intake of livestock in each plot, we calculate the area according to the formula (1). Therefore, according to the specific soil thawing and grass regreening, the annual grazing time (yak and Tibetan sheep) was adjusted to make the grass utilization rate reach 80%.

$$A = \frac{(Y - F) \times D \times L}{G \times U} \quad (1)$$

where A is grassland area·m²; Y is the total amount of grass needed by livestock in a day (yak: 5.8 kg hay, Tibetan sheep: 1.7 kg hay) [21]; F is the amount of grass supplement for livestock in a day (according to field investigation, yak: 1.23 kg hay, Tibetan sheep: 0.22 kg hay); D is the number of grazing days; L represents the number of livestock grazing; G represents the grass yield of the sample plot (measured at 2895 kg·ha^{−1}); and U is the forage utilization rate (80%) (Table 1).

Table 1. Design of rest grazing period and sample area.

Treatments	Rest Grazing Settings	Actual Rest Grazing Period	Actual Grazing Period	Number of Grazing Livestock (Adults)	Sample Area (m ²)
P1	Critical period of soil thawing–plant withering period	19 March~28 February of the following year	1 March~18 March	4 (Yaks + Tibetan Sheep)	1881
P2	Late period of soil Thawing plant withering period	2 April~28 February of the following year	1 March~1 April	4 (Yaks + Tibetan Sheep)	3344
P3	Early period of grass revival–plant withering period	16 April~28 February of the following year	1 March~15 April	4 (Yaks + Tibetan Sheep)	4807
P4	Late period of grass revival–plant withering period	2 May~28 February of the following year	1 March~1 May	4 (Yaks + Tibetan Sheep)	6478
P5(CK)	Period of local traditional rest grazing–plant withering period	21 May~28 February of the following year	1 March~20 May	16 (Yaks + Tibetan Sheep)	33,855

2.3. Determination Indices and Methods

P. polygonum has no branches. The top of the plant is spike-shaped, the upper part of the spike has flowers, and the lower part has bulbils (Figure 2). Seeds are encapsulated in perianths and are dark brown oval triangular achenes [22].

During the spring rest grazing period, reduce the impact of humans on the fallow grassland as far as possible to make it close to the natural recovery state. In late August 2022, we randomly selected 30 *P. polygonum* plants from each sample plot and measured the plant height, panicle length (measuring spike length of flower and bulbil separately, denoted as the length of flower spike and length of bulbil spike, respectively), panicle basal diameter, and number of flowers and bulbils per plant. Then, the single plant was divided into five parts: flower, bulbil, stalk, leaves, and root. The plant components were placed in an oven (Shanghai Yuejin Medical Equipment Co., Ltd., Shanghai, China), heated to a constant weight at 65 °C, and then weighed with a precision (0.0001 g) electronic balance. Next, the proportion of flower number and bulbil number, the proportion of flower biomass and bulbil biomass, flower size, and bulbil size were calculated [12].



Figure 2. Two propagation methods of *P. viviparum*. (*P. viviparum* was propagated with seeds and bulbils, and the weight of an air-dried single seed was between 0.18 and 2.21 mg, and the mass of a dried single bulbil was between 0.88 and 7.01 mg).

Resource investment efficiency calculation [23]: flowers were used as sexual reproduction structures, and bulbils were used as asexual reproduction structures. The sum of the biomass of flowers, bulbils, stalks, and leaves is the aboveground biomass, and the root biomass is the underground biomass. The biomass ratio and root–shoot ratio of each part are calculated.

$$\text{Proportion of spike length} = \frac{\text{length of flower spike}}{\text{height}} \times 100\% \quad (2)$$

$$\text{Proportion of bulbil length} = \frac{\text{length of bulbil spike}}{\text{height}} \times 100\% \quad (3)$$

$$\text{Proportion of flower number} = \frac{\text{flower number}}{\text{flower number} + \text{bulbil number}} \times 100\% \quad (4)$$

$$\text{Proportion of bulbil number} = \frac{\text{bulbil number}}{\text{flower number} + \text{bulbil number}} \times 100\% \quad (5)$$

$$\text{Flower size} = \frac{\text{flowers biomass}}{\text{flower number}} \quad (6)$$

$$\text{Bulbil size} = \frac{\text{bulbils biomass}}{\text{bulbils number}} \quad (7)$$

$$\text{Biomass proportion of asexual reproduction organs} = \frac{\text{bulbils biomass}}{\text{total biomass}} \times 100\% \quad (8)$$

$$\text{Biomass proportion of sexual reproduction organs} = \frac{\text{flowers biomass}}{\text{total biomass}} \times 100\% \quad (9)$$

$$\text{Proportion of underground biomass} = \frac{\text{root biomass}}{\text{total biomass}} \times 100\% \quad (10)$$

$$\text{Proportion of aboveground biomass} = \frac{(\text{flower} + \text{stalk} + \text{bulbil} + \text{leaf}) \text{ biomass}}{\text{total biomass}} \times 100\% \quad (11)$$

$$\text{Root – crown ratio} = \frac{\text{aboveground biomass}}{\text{underground number}} \quad (12)$$

In late September of the same year, we set up 10 quadrants (1 m × 1 m) for each treatment to measure plant density and collect seeds. Thirty ears were randomly selected from each treatment group. After drying, the seeds on each ear were collected, and the number of unfruited florets was counted. The seeds were divided into satiety and shriveled grains, counted, and weighed. The number of seeds per ear, seed setting rate, single grain weight, satiety seed number ratio, and satiety seed weight ratio were calculated. The length and edge length of 50 seeds were measured randomly in each plot, and the volume was calculated.

$$\text{Seed number per ear} = \text{satiety seed number} + \text{shriveled seed number} \quad (13)$$

$$\text{Seed setting rate} = \frac{\text{satiety seed number} + \text{shriveled seed number}}{\text{satiety seed number} + \text{shriveled seed number} + \text{unfruited floret number}} \times 100\% \quad (14)$$

$$\text{Satiety seed number} = \frac{\text{satiety seed number}}{\text{seed number per ear}} \quad (15)$$

$$\text{Satiety seed weight ratio} = \frac{\text{satiety seed weight}}{(\text{satiety seed weight} + \text{shriveled seed weight})} \times 100\% \quad (16)$$

$$\text{Single - grain weight} = \frac{\text{satiety seed weight} + \text{shriveled seed weight}}{\text{seed number per ear}} \quad (17)$$

$$\text{Seed size}(\text{mm}^3) = \text{Seed length} \times \text{Seed edge length}^2 \times 0.6495 \quad (18)$$

2.4. Data Analysis

We use Microsoft Excel 2019 software to organize, summarize, plot, and tabulate the data and finally calculate the comprehensive evaluation value. The experimental data were analyzed using SPSS 19.0 software. Duncan's method was used to compare the measured data, and the mean value and standard error were used to represent the measurement results. Linear regression analysis linear regression program in SPSS. The correlation analysis of seed traits was performed using the Correlate–Bivariate program in Origin 2021. TOPSIS is a comprehensive analysis of all indicators.

3. Results

3.1. Effects of Different Periods of Rest Grazing on the Biomass of Each Component of *P. viviparum*

3.1.1. Aboveground Biomass and Underground Biomass

In each treatment, the biomass of each component of *P. viviparum* in P5 was lower than in other plots (Table 2). The *p*-value of flower biomass and culm biomass among different plots was 0.000. The flower biomass of P1 was 19.44 mg/per plant, which was significantly higher than other plots ($p < 0.05$), 141.79% higher than P2, 511.32% higher than P3, 787.67% and 862.38% higher than P4 and P5, respectively. The bulbil biomass of P1 was 153.93 mg/per plant, which was significantly different from that of P4 and P5 ($p < 0.05$). The bulbil biomass of P1 was higher than that of other plots, which was 13.71%, 30.5%, and 36.98% higher than P3, P4, and P5, respectively. The stalk biomass of P1 was significantly higher than other plots ($p < 0.05$), which was 119.82 mg/per plant, 56.00% higher than P5. The leaf biomass of P1 was 13.35% and 32.19% higher than that of P4 and P5, respectively. The root biomass of P2 was higher than that of other plots, which was 574.52 mg/plant. There was no significant difference in *P. viviparum* root biomass among different plots.

Table 2. Comparison of different modular biomass for *P. viviparum* among different periods of rest grazing.

Treatments	Biomass of Flowers/mg	Biomass of Bulbils/mg	Biomass of Stalks/g	Biomass of Leaves/mg	Underground Biomass/mg
P1	19.44 ± 3.18 a	153.93 ± 9.15 a	119.82 ± 8.64 a	198.23 ± 10.57 a	553.00 ± 50.41 a
P2	8.04 ± 2.37 b	143.82 ± 10.40 ab	115.62 ± 6.04 ab	193.95 ± 10.27 a	574.52 ± 61.34 a
P3	3.18 ± 1.05 bc	135.37 ± 9.65 abc	109.24 ± 3.61 ab	186.39 ± 12.96 a	564.68 ± 64.90 a
P4	2.19 ± 0.82 c	117.94 ± 9.24 bc	100.68 ± 6.52 b	174.89 ± 11.26 ab	563.37 ± 51.88 a
P5(CK)	2.02 ± 0.62 c	112.37 ± 10.33 c	76.81 ± 4.16 c	149.96 ± 8.10 b	549.55 ± 44.81 a
<i>p</i> -value	0.000	0.019	0.000	0.014	0.998

Note: Different lowercase letters in the same column in the table indicate that the index is significantly different at the 0.05 level under different grazing time treatments. The *p*-value indicates the difference in each index between the different treatments.

3.1.2. The Relationship between Individual Size and Reproductive Investment

In each treatment with a different rest grazing period, the reproductive allocation of *P. viviparum* was basically maintained within a certain range, and its reproductive investment and aboveground biomass showed a positive correlation (Figure 3); that is, the greater the aboveground biomass, the more the reproductive investment, and the correlation between reproductive input and aboveground biomass was extremely significant ($p < 0.01$).

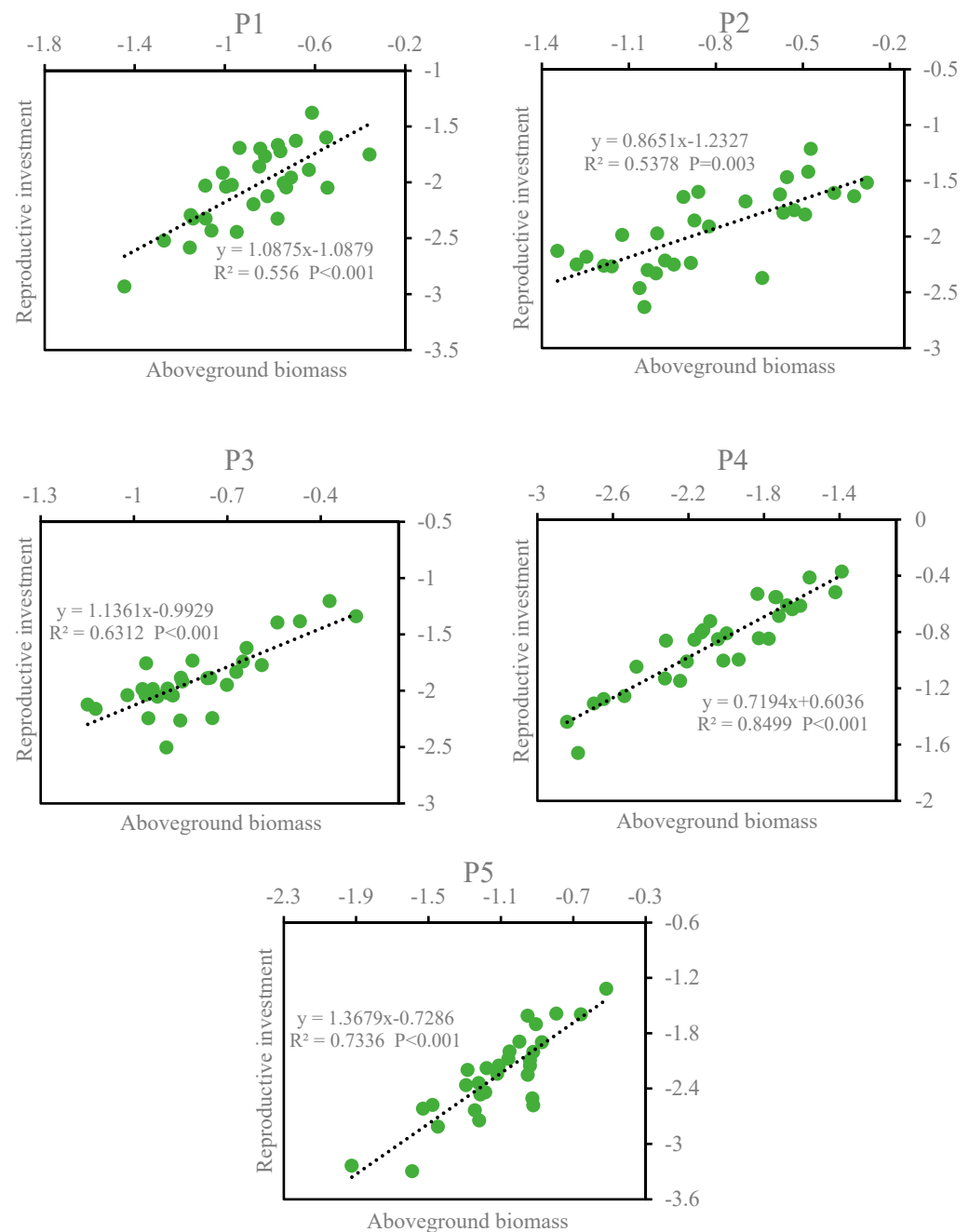


Figure 3. The regression relationship between aboveground biomass (x) and reproductive input (y) of *P. viviparum* in different grazing rest plots (x and y are transformed into natural logarithms).

3.1.3. The Plant Biomass Allocation Ratio

From Table 3, the difference in the biomass ratio of sexual reproductive organs among different places is 0.000. With the advance of grazing time, the biomass ratio of asexual reproductive organs first increased and then decreased. The biomass of P1 was 15.68%

higher than that of other plots and 19.51% higher than that of P5. With the start of grazing earlier, the proportion of biomass in sexual reproductive organs increased gradually. The biomass of P1 was 1.93%, which was significantly higher than other plots ($p < 0.05$), 153.95% higher than P2, 484.85% higher than P3, 614.81% higher than P4, and 704.17% higher than P5. There was no significant difference between P2, P3, P4, and P5. With the start of grazing time earlier, the proportion of aboveground biomass of *P. viviparum* increased first and then decreased, and the proportion of aboveground biomass of P3 was higher than that of other plots, which was 48.65%. There was no significant difference between P1, P2, and P4, and P5 was 40.16%, which was lower than other plots. P3 was 21.14% higher than P5. With the advance of grazing rest time, the proportion of underground biomass of *P. viviparum* showed a trend of decreasing first and then increasing. There was no significant difference among P1, P2, and P4. The proportion of underground biomass in P5 was higher than that of other plots, which was 59.84%, 11.39% higher than in P1. The root–shoot ratio of P5 was 1.81, which was higher than that of other plots. P3 was lower than other plots, 1.31; there was no significant difference among the five plots in the root–shoot ratio of *P. viviparum*.

Table 3. Effects of different periods of rest grazing on biomass allocation proportion of *P. viviparum*.

Treatments	Biomass Proportion of Asxexual Reproduction Organs (%)	Biomass Proportion of Sexual Reproduction Organs (%)	Proportion of Aboveground Biomass (%)	Proportion of Underground Biomass (%)	Root–Crown Ratio
P1	15.68 ± 1.11 a	1.93 ± 0.34 a	46.28 ± 2.63 ab	53.72 ± 2.63 ab	1.39 ± 0.15 a
P2	15.21 ± 1.30 a	0.76 ± 0.22 b	47.22 ± 2.56 ab	52.78 ± 2.56 ab	1.36 ± 0.17 a
P3	14.54 ± 1.16 a	0.33 ± 0.12 b	48.65 ± 2.79 a	51.35 ± 2.79 b	1.31 ± 0.16 a
P4	12.82 ± 1.04 a	0.27 ± 0.11 b	45.96 ± 2.74 ab	54.04 ± 2.74 ab	1.48 ± 0.19 a
P5	13.12 ± 1.33 a	0.24 ± 0.08 b	40.16 ± 2.42 b	59.84 ± 2.42 a	1.81 ± 0.20 a
<i>p</i> -value	0.179	0.000	0.199	0.199	0.271

Note: Different lowercase letters in the same column in the table indicate that the index is significantly different at the 0.05 level under different grazing time treatments. The *p*-value indicates the difference in each index between the different treatments.

3.2. Effects of Rest Grazing at Different Periods on Reproductive Characteristics of *P. viviparum*

3.2.1. The Flower and Bulbil Related Indicators

It can be seen from Table 4 that the flower spike length, flower spike length ratio, bulbous spike length, flower number, flower number ratio, bulbil number, flower size, and bulbil size of P1 were higher than other plots, among which the flower spike length, flower number, flower size, and bulbil size were significantly higher than other plots ($p < 0.05$). The difference between the length of the flower spike, the proportion of flower spike length per plant, the number of flowers, the proportion of flower number per plant, and the proportion of bulbil number per plant was 0.000. The flower spike lengths of P2–P5 and P1 were 141.24%, 384.47%, 387.5%, and 532.43% higher than P1, respectively. The flower number in P1 was 729.13% higher than that of P5, and there was no significant difference between P2 and P5. The flower size of P1 was 0.47 mg, which was significantly larger than other plots, which were 135.00%, 339.25%, 176.47%, and 347.62% larger than that of P2–P5, respectively. The bulbil size of P1 was 3.39 mg, which was significantly larger than that of the other four plots ($p < 0.05$). The bulbil size of P5 was significantly smaller than that of other plots ($p < 0.05$), which was 91.53%, 66.67%, 35.59%, and 31.07% smaller than that of P1–P4, respectively.

Table 4. Comparison of related indexes of two reproductive modes of *P. viviparum* under different periods of rest grazing treatment.

Treatments	Length of the Flower Spike(cm)	Proportion of Flower Spike Length per Plant (%)	Length of Bulbous Spike (cm)	Proportion of Bulbils Spike Length per Plant (%)	Number of Flowers	Proportion of Flower Number per Plant (%)	Number of Bulbils	Proportion of Bulbil Number per Plant (%)	Flower Size (mg)	Bulbil Size (mg)
P1	2.34 ± 0.27 a	8.62 ± 0.99 a	5.46 ± 1.27 a	10.70 ± 0.89 b	48.67 ± 7.67 a	39.76 ± 4.63 a	49.73 ± 2.17 a	60.24 ± 4.63 c	0.47 ± 0.14 a	3.39 ± 0.14 a
P2	0.97 ± 0.20 b	3.61 ± 0.75 b	5.25 ± 1.67 a	15.50 ± 0.92 b	17.10 ± 4.25 b	21.14 ± 4.59 b	49.50 ± 3.10 a	78.86 ± 4.59 b	0.20 ± 0.05 b	2.95 ± 0.13 ab
P3	0.48 ± 0.14 bc	1.32 ± 0.41 b	4.03 ± 0.21 a	17.30 ± 4.64 b	8.03 ± 2.48 b	13.00 ± 3.49 bc	45.87 ± 2.23 a	87.00 ± 3.49 ab	0.107 ± 0.03 b	2.40 ± 0.12 ab
P4	0.48 ± 0.13 bc	2.86 ± 1.09 b	3.42 ± 0.23 a	25.73 ± 6.36 b	6.37 ± 1.79 b	12.20 ± 3.44 bc	45.43 ± 3.14 a	87.91 ± 3.44 ab	0.17 ± 0.04 b	2.32 ± 0.10 ab
P5	0.37 ± 0.11 c	3.42 ± 1.40 b	2.76 ± 0.20 a	49.32 ± 5.10 a	5.87 ± 2.20 b	8.95 ± 2.81 c	43.80 ± 3.22 a	91.06 ± 2.81 a	0.105 ± 0.03 b	1.77 ± 0.12 b
<i>p</i> -value	0.000	0.000	0.209	0.005	0.000	0.000	0.482	0.000	0.003	0.083

Note: Different lowercase letters in the same column in the table indicate that the index is significantly different at the 0.05 level under different grazing time treatments. The *p*-value indicates the difference in each index between the different treatments.

3.2.2. The Seed Yield and Its Components

As shown in Table 5, the difference in height, length of flower spike, seed number per ear, and seed yield was 0.000. The difference in plant density was 0.001. The seed yield and related indicators of P1 were higher than other treatments. Among them, flower spike length, plant density, seed number per plant, and seed yield were significantly higher than other treatments ($p < 0.05$). The plant height of P1 was 40.59% greater than P5. Flower spike lengths of P1 were 141.24%, 384.47%, 387.50%, and 532.43% longer than those of P2, P3, P4, and P5, respectively. Seed number per ear of P1 was 81.54%, 92.53%, and 100.37% higher than P3, P4, and P5, respectively. Single grain weights of P1 were 62.22%, 108.57%, 135.48%, and 170.37% higher than P2, P3, P4, and P5, respectively. Plant densities of P1 were 48.48%, 81.48%, and 148.10% higher than P3, P4, and P5, respectively. Seed yield was 135.11%, 535.05%, 689.74%, and 1268.89% higher than P2, P3, P4, and P5, respectively.

Table 5. The changes in seed yield and yield components of *P. viviparum* under different periods of rest grazing treatment.

Treatments	Height (cm)	Length of Flower Spike (cm)	Panicle Basal Diameter (mm)	Seed Number per Ear	Single Grain Weight (mg)	Plant Density (m ²)	Seed Yield (kg·hm ^{−2})
P1	26.81 ± 0.75 a	2.34 ± 0.27 a	2.00 ± 1.48 a	21.64 ± 2.56 a	0.73 ± 0.37 a	39.20 ± 3.57 a	6.16 ± 0.14 a
P2	26.59 ± 0.64 a	0.97 ± 0.20 b	1.06 ± 0.03 a	16.00 ± 1.13 ab	0.45 ± 0.03 a	36.80 ± 4.04 ab	2.62 ± 0.41 ab
P3	26.32 ± 1.21 a	0.483 ± 0.14 bc	1.02 ± 0.04 a	11.92 ± 2.20 b	0.35 ± 0.03 a	26.40 ± 4.46 bc	0.97 ± 0.10 b
P4	24.11 ± 1.12 a	0.48 ± 0.13 bc	0.94 ± 0.04 a	11.24 ± 2.40 b	0.31 ± 0.03 a	21.60 ± 2.73 c	0.78 ± 0.21 b
P5 (CK)	19.07 ± 1.20 b	0.37 ± 0.11 c	0.70 ± 0.06 a	10.80 ± 0.42 b	0.27 ± 0.02 a	15.80 ± 3.77 c	0.45 ± 0.11 b
<i>p</i> -value	0.000	0.000	0.685	0.000	0.329	0.001	0.000

Note: Different lowercase letters in the same column in the table indicate that the index is significantly different at the 0.05 level under different grazing time treatments. The *p*-value indicates the difference in each index between the different treatments.

3.2.3. The Seed Yield and Related Indexes of *P. viviparum*

The correlation analysis of seed yield and related indexes in *P. viviparum* under different rest grazing periods showed that each index was positively correlated with seed yield. The order from largest to smallest was single grain weight (0.9971) > flower spike length (0.9968) > seed number per ear (0.9942) > panicle basal diameter (0.9687) > plant density (0.8545) > plant height (0.5766) (Figure 4). Among them, the flower spike length was significantly positively correlated with the diameter of the spike base and the number of seeds per ear ($p < 0.01$) and was highly significantly positively correlated with the single-seed weight ($p < 0.001$). The basal diameter was significantly positively correlated with the seed number per plant ($p < 0.05$), and the basal diameter of the panicle was significantly positively correlated with single grain weight ($p < 0.01$). Seed number per plant was positively correlated significantly with single grain weight ($p < 0.01$) and planting density ($p < 0.05$). Flower spike length, single-seed weight, seed number per plant, and

seed yield were significantly positively correlated ($p < 0.001$), and the spike basal diameter was significantly positively correlated with seed yield ($p < 0.01$).

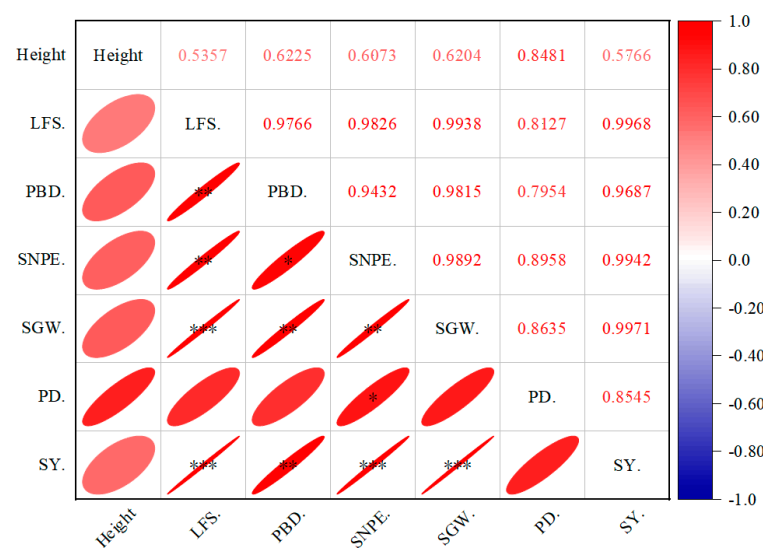


Figure 4. Correlation analysis of seed yield and yield components of *P. viviparum* under rest grazing in different periods. LFS: length of flower spike; PBD: panicle basal diameter; SNPE: seed number per ear; SGW: single grain weight; PD: plant density; SY: seed yield *** was significantly correlated at the 0.001 level, ** was significantly correlated at the 0.01 level, and * was significantly correlated at the 0.05 level.

3.2.4. Effects of Different Periods of Rest Grazing on Seed Quality of *P. viviparum*

As shown in Table 6, the difference in seed setting rate was 0.003. The difference in seed length was 0.029. The indicators of P5 were lower than those of other treatments. The seed edge length, size, and satiety grain number ratio of P1 were higher than those of the other treatments, and the seed setting rate and satiety grain weight ratio were significantly higher than other treatments ($p < 0.05$). The seed setting rates of P1 were 25.26%, 54.15%, 54.34%, and 82.79% higher than those of P2–P5, respectively. The ratio of satiety grain number in P1 was 13.57% higher than in P5, and the satiety grain weight ratio in P1 was 20.37%, 24.98%, 85.78%, and 137.92% higher than that in P2–P5, respectively.

Table 6. Comparison of seed quality of *P. viviparum* under rest grazing in different periods.

Treatments	Seed Length/mm	Seed Edge Length/mm	Seed Size/mm ³	Seed Setting Rate/%	Plump Grain Weight Ratio/%	Plump Grain Number Ratio/%
P1	2.89 ± 0.04 a	1.43 ± 0.04 a	3.85 ± 0.19 a	61.49 ± 2.72 a	33.81 ± 1.78 a	31.62 ± 9.93 a
P2	2.90 ± 0.05 a	1.40 ± 0.03 a	3.71 ± 0.24 a	49.09 ± 2.94 ab	33.17 ± 0.94 a	26.27 ± 1.03 ab
P3	2.70 ± 0.05 b	1.40 ± 0.03 a	3.44 ± 0.17 a	39.89 ± 4.18 bc	32.98 ± 5.05 a	25.30 ± 1.32 ab
P4	2.83 ± 0.07 ab	1.39 ± 0.03 a	3.58 ± 0.16 a	39.84 ± 7.54 bc	31.22 ± 7.21 a	17.02 ± 3.83 ab
P5 (CK)	2.77 ± 0.04 ab	1.38 ± 0.03 a	3.44 ± 0.18 a	33.64 ± 2.90 c	29.77 ± 4.72 a	13.29 ± 1.90 b
<i>p</i> -value	0.029	0.842	0.411	0.003	0.969	0.095

Note: Different lowercase letters in the same column in the table indicate that the index is significantly different at the 0.05 level under different grazing time treatments. The *p*-value indicates the difference in each index between the different treatments.

3.3. Comprehensive Evaluation of *P. viviparum* Traits under Different Periods of Rest Grazing Treatments

The TOPSIS comprehensive analysis method was carried out on the biomass distribution and proportion of *P. viviparum*, the related indexes of the two reproductive methods, the seed yield and its related indicators, and the seed quality. We comprehensively evaluated 32 indexes, such as leaf biomass, stem biomass, bulbil biomass, and flower size, in

different grazing rest plots. As shown in Figure 5, the comprehensive score indexes of all evaluation indexes of *P. viviparum* were calculated by the TOPSIS method. The comprehensive evaluation values of rest grazing in the critical period of soil thawing, rest grazing in the late stage of soil thawing, rest grazing in the early stage of regreening, rest grazing in the late stage of regreening, and traditional rest grazing were 0.877, 0.511, 0.328, 0.256, and 0.201, respectively. According to the results of the comprehensive analysis, traditional rest grazing is not conducive to the reproduction and root growth of *P. viviparum*. In the critical period of soil thawing, the reproduction of *P. viviparum* was most affected.

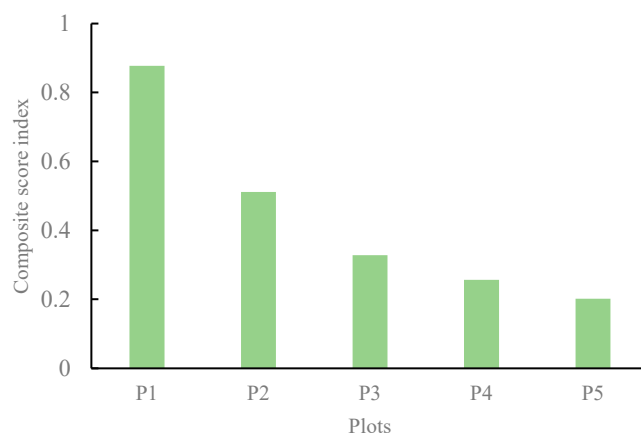


Figure 5. TOPSIS comprehensive evaluation of each index of *P. viviparum* under different grazing rest periods.

4. Discussion

4.1. Effects of Rest Grazing at Different Stages on Biomass of Each Component of *P. viviparum*

In the case of limited resources, to maintain genetic characteristics and population size, plants allocate and balance energy among different tissues and organs to maximize reproductive capacity [24]. The findings of this study demonstrated that root biomass and its proportion were higher than those of other parts, which indicated that the material and energy required for the life cycle, such as growth and reproduction of *P. viviparum*, were mainly provided by underground organs. The experimental site is situated in an alpine region characterized by a cold climate and a short growing season. To survive, plants allocate resources more reasonably among the components, increase the underground biomass to obtain more nutrients, and ensure the normal growth and reproduction of the aboveground part so as to adapt to the environment.

According to a comparison of the biomass of each component of the plant and the proportion of biomass, the main reproduction mode can be more intuitively shown. The flower and bulbil biomasses of P1 were higher than those of other treatments, and the flower and bulbil spike lengths, number of flowers and bulbils, and biomass proportion of sexual and asexual reproductive organs were higher than those of other treatments. P2 flower, bulbil biomass, the biomass proportion of sexual and asexual reproductive organs, flower spike length, and other indicators followed, indicating that *P. viviparum* allocated resources to reproduction to the greatest extent under conditions of limited environmental resources. The P3 plot began to rest grazing in the early stage of grass regreening, and the biomass proportion of sexual and asexual reproductive organs was lower than P1. The number of flowers and bulbils was also less than P1, while the proportion of aboveground nutrition and support structure was greater than P1. Stalk and leaf input can support plants, and more photosynthetic products will be transported to reproductive and underground storage organs for the season or subsequent growth energy accumulation to ensure population reproduction. The biomass of each part of P4 and P5 was smaller than that of P1–P3, but the growth effort of the underground roots was larger than that of P1–P3, indicating that they tended to store nutrients underground. P5 was affected by grazing for the longest time,

and the aboveground biomass was reduced to a minimum owing to livestock grazing. The underground part shared interference with the growth and survival of the aboveground part, so the underground growth effect of P5 was greater than that of other treatments.

The findings of this study show that *P. viviparum* ensured the dominance of the population in the grassland community by reducing the input of underground roots, maintaining vegetative reproduction, and increasing sexual reproduction. Compared with P5, the underground root input of P1 decreased by 19.04%, and the vegetative reproductive effort of sexual reproduction increased by 704.17% and 19.51%, respectively. In a study by Peng et al. [17], the growth effort and sexual reproductive efforts of *C. capillifolia* increased by 8.70% and 64.26%, respectively, and the vegetative reproductive effort decreased by 35.63%. In a study by Bai et al. [16], the growth efficiency of *K. humilis* decreased by 3.53%, and the investment in sexual and asexual reproduction efforts increased by 13.33% and 28.46%, respectively. The heights of the three plants were as follows: *C. capillifolia* > *P. viviparum* > *K. humilis*, and the underground growth effect showed that *K. humilis* > *C. capillifolia* > *P. viviparum*. *P. viviparum* is a broad-leaved plant with a high plant height, which can obtain sufficient energy through leaves after reducing the input of underground roots, whereas *C. capillifolia* and *K. humilis* are narrow-leaved plants, and *K. humilis* has low leaves. The energy absorbed by the leaves is limited, and sufficient root absorption and storage of nutrients are necessary to ensure normal plant growth and reproduction. The biomass allocation of the three plants was different when they responded to the change in rest grazing time, indicating that the plants adapted to changes in the external environment in different ways. The sexual reproduction effort of *P. viviparum* was the most obvious response to the advance of the rest of the grazing period, followed by *C. capillifolia* and *K. humilis*, which may lead to an improvement in the competitiveness of *P. viviparum* and the weakening of *K. humilis*. In the long run, further research is needed. With the advance of rest grazing, livestock feed on less germinated plants, and the smaller the impact on *P. viviparum*, the more material and energy can be used for plant growth. The advantages of broad leaves and plant height make it easier for *P. viviparum* to obtain resources. In the biomass allocation of each component of the plant, more resources can be allocated to florets that breed seeds to enhance sexual reproduction.

The proportion of reproductive organ biomass exhibited a strong positive correlation with the aboveground biomass of *P. viviparum* in different treatments at different grazing rest periods. The investment of *P. viviparum* in reproductive organs depended on the individual aboveground biomass. Some *P. viviparum* have large biomass per plant, developed rhizomes, many fibrous roots, and a strong ability to obtain water and nutrients. Larger leaves, more photosynthetic area, and more resources can be invested in reproductive organs, so the large individual *P. viviparum* has a higher reproductive investment. This also shows that the size of each part of the plant has a certain proportion, and the plants with larger biomass have larger biomass reproductive components.

4.2. Effects of Rest Grazing at Different Stages on Reproductive Characteristics of *P. viviparum*

During plant growth, the reproductive stage is most sensitive to the external environment [3]. Many plants reproduce in both sexual and asexual ways. Sexual reproduction can maintain the genetic diversity of species and improve the ability of plants to adapt to the external environment. Asexual propagation can save resources [5], improve the utilization rate of species in the environment, and reduce the risk of interference. There is a tradeoff between these two reproductive modes in plants, which may be closely related to plant longevity, genetic factors, environmental conditions, and competition [25].

In each treatment, the number of bulbils was greater than the number of flowers, the biomass of bulbils was greater than that of flowers, the biomass proportion of asexual reproduction organs was greater than the sexual reproduction, and the bulbil spike length was longer than the flower spike length, indicating that *P. viviparum* generally tended toward vegetative reproduction, but sexual reproduction gradually increased with the advance of rest grazing. This is similar to the experimental results of Bai et al. [16] and

Peng et al. [17] on the reproductive characteristics of *K. humilis* and *C. capillifolia*. Early rest grazing can incline plants more toward sexual reproduction. The survival rate of asexual reproduction plants is higher, and fewer resources are consumed, which can maintain a certain number of populations [26]. After the bulbils of *P. viviparum* mature, they fall around the mother plant, germinate, and root into new plants, rapidly increasing the density, coverage, and biomass of *P. viviparum* in the grassland community. The seeds used for sexual reproduction are light in weight and scattered far away from the plant, which is also conducive to the spread of the *P. viviparum* population. In continuous adaptation to the external environment, plant generations produce higher-quality seeds and improve the genetic diversity of the offspring to ensure the maintenance of the population under complex external conditions. Both propagation methods were conducive to the spread of the *P. viviparum* population. Grass is soft, its protein content is high, and it has a high feeding value. Rapid increases in quantity and quality can improve the total economic benefits of grasslands.

P. viviparum gives priority to asexual reproduction, with rest grazing advancing gradually, enhancing sexual reproduction to a certain extent, and increasing the diversity of reproduction. P1 was rested before the grass regreening, *P. viviparum* was the least affected by grazing, and more resources were used for vegetative and sexual reproduction. The longest grazing time in the traditional rest grazing treatment and the growth of the aboveground parts of *P. viviparum* were hindered by the feeding and trampling of livestock. The input of leaves, stalks, and sexual reproduction was minimized, and the input of the underground biomass was increased to achieve the purpose of sharing the interference. Through this resource allocation, *P. viviparum* ensures normal reproduction and renewal of the population under the condition of resisting the interference of external environmental changes.

4.3. The Effects of Different Periods of Rest Grazing on *P. viviparum* Seeds

During grazing, the ingestion and trampling of livestock can cause irreversible effects on forage [27], as the soil surface is moist and susceptible to erosion, and trampling alters the soil structure on the surface of the grassland, which ultimately affects plant reproduction and growth [28]. Reproductive allocation greatly affects a plant's ability to access resources and is an important factor in determining seed yield and size [29].

The findings of this study showed that the seed yield and its components of P5 were lower than those of other treatments. There was no significant difference in seed yield between the early stage of grass regreening, the late stage of grass regreening, and the traditional rest grazing plot. From the early stage of soil thawing to the traditional rest grazing period, delays in rest grazing time had a greater impact on seed yield. During the critical period of soil thawing, the seed yield of the three forage grasses was the highest. Compared with the sample plot in P5, the seed yield of *P. viviparum* increased by 1268.89%. In the studies by Bai et al. [16] and Peng et al. [17], the seed yield of *K. humilis* and *C. capillifolia* increased by 142.48% and 340.35%, respectively. The seed yield of *P. viviparum* increased the most during the critical period of soil thawing, which was also consistent with the response of the sexual reproduction effort of the three plants to the advance of the rest of the grazing period. Among the components of seed yield, single-grain weight had the greatest impact, which is inconsistent with the research results of Bai et al. [16] and Peng et al. [17] on the effects of different periods of rest grazing on the reproduction of *K. humilis* and *C. capillifolia*, respectively. The density of reproductive branches had the greatest impact on seed yield, which may be due to the different sexual reproduction strategies of several forages. The seed production of *P. viviparum* is mainly based on the number of seeds, but the seed-setting rate is far lower than that of the other two forages. The seed production of *K. humilis* and *C. capillifolia* is mainly based on seed quality. The responses of seed quality-related indicators to different rest grazing periods are inconsistent. The seed volume, seed setting rate, number ratio, and weight ratio of plump grains in P1 were larger than those in the other treatments. With the advancement of rest grazing, *P.*

viviparum promoted sexual reproduction by increasing seed yield and seed quality. Rest grazing started during the critical period of soil thawing to avoid the negative impact of livestock trampling and feeding on *P. viviparum* seedlings, to protect plant survival and late growth and development, to use more energy for reproduction, and to ensure the reproductive regeneration of *P. viviparum* populations.

Overall, with the delay in rest grazing time, the yield and quality of *P. viviparum* seeds were reduced. To protect the seeds of *P. viviparum* for sexual reproduction, rest grazing during the critical period of soil thawing is recommended. This experiment may be suitable for similar grassland types, but further verification is needed.

Our rest grazing experiment is still continuing, and there have been reports on grassland vegetation and soil biodiversity research. We intend to study the long-term effects of rest grazing in different periods of spring on various aspects of grassland, such as vegetation, soil, and so on. In the long-term study, there will be a more comprehensive understanding of its benefits and potential shortcomings. Through medium and long-term research, it can provide certain technical support to local herdsmen and promote, on the basis of this experimental field, grassland protection. From the perspective of herdsmen, the challenge is to find supplementary forage sources.

5. Conclusions

In the sample plots where grazing ceased at the critical stage of soil thawing, the biomass proportion of sexual reproduction organs, biomass proportion of asexual reproduction organs, flower spike length, bulbil spike length, etc. were higher than those in other treatments. *P. viviparum* reproduces mainly by asexual reproduction. With the advancement of rest grazing, sexual reproduction will be enhanced, and reproductive diversity will increase. During the critical period of soil thawing, rest-grazing *P. viviparum* reduced the underground part input, maintained asexual reproduction, and maximized sexual reproduction. Traditional rest grazing of *P. viviparum* increases the input of underground parts, reduces sexual reproduction, and maximizes asexual reproduction to maintain the continuation of the population.

The TOPSIS comprehensive analysis method was used to analyze the indexes of *P. viviparum*, and the score order of comprehensive traits of *P. viviparum* under different periods of rest grazing treatment was obtained as follows: P1 > P2 > P3 > P4 > P5. It is recommended to start spring rest grazing during the critical period of soil thawing to protect the reproduction and vegetation restoration of *P. viviparum*.

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