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Effects of Rodent Isolation on Plant Community Structure and Greenhouse Gas Emission in the Alpine Grassland of the Qinghai–Tibet Plateau

Hongbao Wu [1,*], Ya Chen [1], Hasbagan Ganjurjav [2] and Jianrong Zhao [1]

[1] College of Resource and Environment, Anhui Science and Technology University, Chuzhou 233100, China
[2] Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences, Beijing 100081, China
* Correspondence: wuhb1120@163.com

Abstract: As one of the dominant species of the alpine grassland on the Qinghai–Tibet Plateau, the activities (e.g., gnawing, burrowing, and grass storage) of plateau pikas (*Ochotona curzoniae*) directly alter the plant community structure of the grassland ecosystem and affect livestock production and greenhouse gas emission. In order to investigate the effects of rodent isolation (RI) on plant community structure and greenhouse gas emission in the alpine grassland of the Qinghai–Tibet Plateau, we established plots of rodent isolation and rodent activity (i.e., the control sample (CK)) in the 14th village, Seni District, Nagqu City in May 2018. From July 2019 to September, the numbers, sizes, and total damaged area of effective holes; the height, coverage, and aboveground plant biomass; and the methane (CH_4) and nitrous oxide (N_2O) emissions of the alpine grassland were monitored by the quadrat survey method and static closed-chamber method. The results show that the invasion and tunneling of *Ochotona curzoniae* resulted in the destruction of alpine grassland measuring 0.064 m^2 per square meter, while the rodent isolation plots showed that 97.9% of the alpine grassland remained unaltered; such unaffected land implies that the economic income of herdsmen could increase by 140 CNY hm^{-2}. The rodent isolation plots also show that the height and proportion of grasses and sedges in the alpine grassland increased, while the proportion of poisonous weeds decreased. Moreover, the rodent isolation plots also showed a significantly increased coverage of aboveground biomass ($p < 0.05$), although species richness showed no significant effect based on the Shannon–Weiner, Simpson, and Pielou indices ($p > 0.05$). The soil uptake of CH_4 and N_2O was 204.99 ± 50.23 μg m^{-2} h^{-1} and 4.48 ± 1.02 μg m^{-2} h^{-1} in the rodent isolation plots, significantly higher by 465.75% and 3001.4% relative to the rodent activity plots, respectively ($p < 0.05$). Therefore, the establishment of rodent isolation areas can effectively alleviate the degree of damage to alpine grasslands in the short run and slow down the greenhouse gas emission rate to some extent. However, excessive rodent control may also have negative effects on grassland ecosystems, so more attention should be paid in future studies to determining the disturbance threshold of plateau pika in this area. These results provide theoretical guidance for rodent control, grassland protection, and ecological environment management on the Qinghai–Tibet Plateau.

Keywords: alpine grassland; rodent infestation; species diversity; greenhouse gas; economic income

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1. Introduction

As a natural resource, alpine grassland is an important ecosystem, the main animal husbandry production base, and an important ecological barrier area in China. As one of the wild herbivores in the grassland ecosystem, rodents cause serious damage to the grassland ecosystem when their population reaches a certain limit [1–3]. However, because they multiply quickly, have a short gestation period, and have a high fertility rate, rodent numbers (and plateau pikas, in particular) can increase sharply in a short period. By 2021, the destruction of grassland by rats accounted for about 13.55% of the total area of

grassland in China [4]. The gnawing, burrowing, and storing of grass by rodents cause inestimable losses to the grassland ecosystem. The increasing invasion of rodents has resulted in a dramatic decrease in grassland productivity and quality forage coverage. This in turn leads to the spread of weeds, poisonous grasses, and plants with low feeding value. Ultimately, the utilization value of alpine grassland on the Qinghai–Tibet Plateau may decrease significantly [5]. Meanwhile, continuous burrowing by rodents has changed the structure of the soil surface; for example, through expulsion of the subsurface soil layer with good fertility to the surface, resulting in a large loss of soil nutrients and water, and accelerating grassland desertification [6–8]. In addition, the infestation of rodents alters the surface soil nutrient components (e.g., carbon and nitrogen) [2,8], increases the soil ratio of C/N [1], reduces its bulk density, alters its permeability, stimulates microbial activity, accelerates gas diffusion in the soil, and interferes with soil greenhouse gas emission [9–11]. The accumulation of hazards caused by rodents has increased the difficulty of controlling the ecological environment of the grassland, resulting in a loss of grassland ecosystem biodiversity and contributing to climate change. Collectively, these seriously threaten the sustainable and healthy development of grassland animal husbandry. Therefore, it is particularly important to strengthen rodent control in grassland ecosystems. The continuous accumulation of hazards caused by rodents has led to further intensification of the difference between available grass and the livestock's food requirements. Moreover, severe climate change has increased the difficulty of controlling the ecological environment of the grassland, seriously threatening the sustainable and healthy development of grassland animal husbandry.

At present, however, the impact of rodents on alpine grasslands is still highly debated. On the contrary, previous studies have also demonstrated that rodents can alter the physical and chemical properties of soil and create niches, which further alter species composition and increase biodiversity [12]. As a key species of grassland ecosystem, the excessive removal of plateau pika may have some negative impacts on the grassland ecosystem in the long term, such as decreasing aboveground biomass, species diversity, and plant leaf nutrient content and altering plant species composition in the grassland ecosystem under drought conditions [12–15].

The Qinghai–Tibet Plateau is the largest plateau in Central and East Asia with a total area of 2.5×10^6 km^2 and is, on average, 4500 m a.s.l., approximately 40% of which is covered by alpine meadows [16–18]. However, due to climate change and overgrazing, the degraded area of grassland accounts for 41% of the total grassland area, among which severely degraded and extremely severely degraded grassland areas account for 19.0% and 6.5%, respectively [19,20]. In recent years, the invasion, burrowing, and storing of grass by rodents have further aggravated the degradation of the grassland, threatening the living environment of human beings and herbivorous livestock [21]. At present, among the alpine grassland affected by rodents on the Qinghai–Tibet Plateau, the lightly, moderately, severely, and extremely affected areas consist of 1.416, 2.388, 1.206, and 10.32 million hm^2, accounting for 1.18%, 1.98%, 1.01%, and 8.60% of the available grasslands, respectively [22]. Studies have shown that the rodent-infested area in Tibet accounts for 22% of the total grassland area. The loss of fresh grass due to rodent damage amounts to 30 billion kg a^{-1}, equivalent to reducing the carrying capacity of 20 million Tibetan sheep [23]. The Qinghai–Tibet Plateau is one of the five traditional pastoral areas in China, and animal husbandry has always been an important economic pillar. The output value of grassland animal husbandry has accounted for more than 60% of the total output value of agriculture for decades [24]. The local climate conditions are extremely harsh, with high altitudes and low temperatures, resulting in the forage supply usually failing to meet the growth needs of livestock in these pastoral areas. Therefore, the increasingly acute discrepancy between available grass and livestock demand is directly related to the sustainable and healthy development of grassland and social and economic stability in the alpine pastoral areas of the Qinghai–Tibet Plateau. Consequently, the Qinghai–Tibet Plateau has been listed as a key area for control and disaster reduction and ecological and environmental governance

by the state, and the spread of rodent infestation has been listed as the main natural disaster in the region and a key target for prevention and control.

Since 1960, the warming rate on the Qinghai–Tibet Plateau has been as high as 0.2 °C decade^{-1} and is expected to rise by 2.0–2.6 °C by 2030 [25,26], which is significantly higher than the national or even the global average. The emission of greenhouse gases, including CH_4 and N_2O, is an important cause of this warming phenomenon. However, grassland ecosystems act as an important carbon sink for atmospheric carbon, absorbing about 470 Tg of CH_4 from the atmosphere each year, accounting for about 10% of the global atmospheric CH_4 [27,28]. While previous studies have shown that rodent damage is one of the main reasons for aggravating the degradation of alpine grasslands, other studies have focused on the effects of rodent activities on plant community structure and biomass in alpine grasslands [29–31]. However, there have been very few studies on how rodent activities interfere with the soil carbon and nitrogen cycle in this alpine grassland ecosystem and none have studied their effect on the emission of greenhouse gases such as CH_4 and N_2O.

To connect plant community structure and greenhouse gas emissions in alpine meadows with rodent activity, we examined the effects of rodent control devices on species diversity and CH_4 and N_2O emissions on the Qinghai–Tibet Plateau. We hypothesized that the establishment of rodent isolation (RI) devices can effectively alleviate the degree of degradation of alpine grassland on the Qinghai–Tibet Plateau and reduce the rate of greenhouse gas emissions. We tested the above hypothesis by conducting a three-month experiment in RI areas and fenced breeding areas, aiming to provide a scientific basis and guidance for local rodent control, grassland protection, and the effective mitigation of greenhouse gas emissions.

2. Materials and Methods

2.1. Experiment Area

The experiment was located at the RI and Control Technology and Demonstration Test Base in 14th village, Seni District, Nagqu City, Qinghai–Tibet Plateau (31°17′ N, 92°07′ E, Figure 1). There were 0.162 effective rodent holes per meter squared, where each hole had an area of 0.009 m^2, and the total area damaged by rodents was 0.049 m^2. The region has an average height of 4500 m a.s.l. and is therefore referred to as the "third pole of the earth" and "roof of the world". The Tibet Autonomous Region is covered by approximately 8.92×10^7 ha of grassland, accounting for nearly 22.3% of the grassland in China, of which about 4.21×10^7 ha belong to Nagqu City. The experiment area has an alpine, semi-humid climate, with a mean annual temperature of −1.2 °C, a mean temperature during the growing season (May to September) of 8.1 °C, a mean annual precipitation of 431.7 mm, and the rainy season mainly occurs during the growing season (which receives 89% of the total annual precipitation) [32]. The dominant plant species present are *Carex moorcroftii*, *Kobresia pygmaea*, *Lancea tibetica*, *Poa pratensis*, and *Potentilla acaulis* in the experiment area. There are frequent rodent activities in the experiment area, and the main pest is *Ochotona curzoniae*.

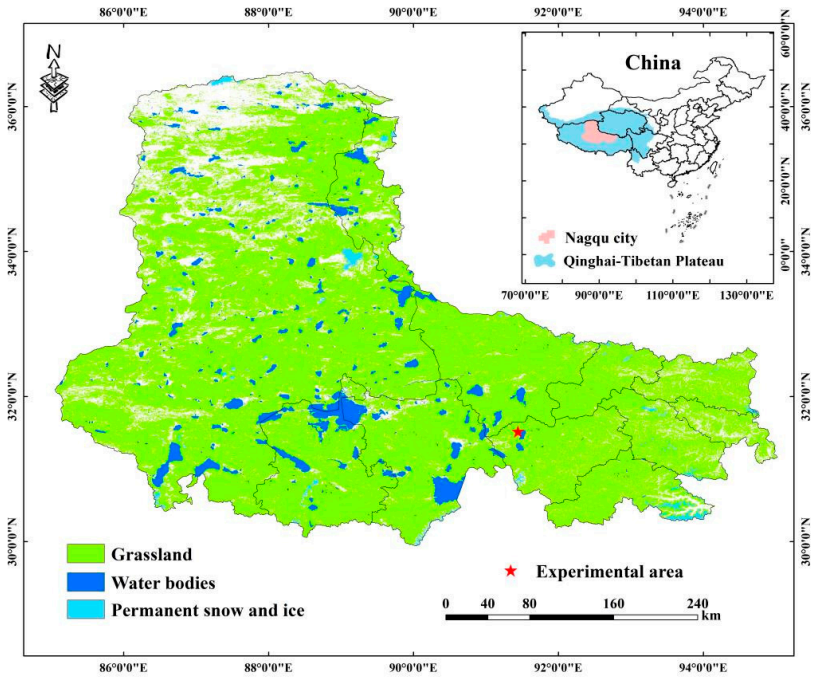


Figure 1. Location of the experiment site.

2.2. Sampling Plot Setting

In 2018, a degraded grassland with flat terrain and uniform degradation caused by rodents was selected in the study area for RI and fencing. Our experiment included two treatments: a fenced enclosure (i.e., the control, CK) and rodent isolation (RI). In May of the same year, the number and size of the rodent holes were monitored in the CK and RI plots, and rodent control was carried out on plateau pikas in the latter. An ultrasonic rodent-repellent device was installed around the RI plots to prevent the invasion of rodents, which has an effectiveness of more than 80%. Three subplots were set up in the CK and RI plots, each with an area of 30 m × 30 m. From July 2019 to September, the number, size, and total damaged area of the rodent holes were investigated and monitored in all plots. Meanwhile, we monitored CH_4 and N_2O emission fluxes above the sampled plots using static chambers. In addition, three sampling plots with an area of 1 m × 1 m were randomly set up in each of the 30 m × 30 m plots to investigate plant height, coverage, and aboveground biomass via the sampling method; the experiment was conducted once a month, and all measurements were repeated three times.

2.3. Sampling Method

2.3.1. Rodent Survey

The number of effective rodent burrows in the CK and RI plots was recorded by the hole-blocking method to characterize the relative density of pikas on the plateau. The effective rodent burrow area and the natural grassland area covered by soil dug by plateau pikas burrowing were measured with a tape measure and recorded as the area damaged by rodents. However, for irregular rodent holes and soil cover shapes, a 2 cm × 2 cm grid quadrat was used for calculation.

2.3.2. Investigating the Plant Community Structure

Three sampling plots of 1 m × 1 m were randomly selected from the plots of CK and RI to investigate the plant communities. Firstly, according to the plant species present in the area, the vegetation within the sampling plots was divided into grasses, sedges, and forbs, and basic information, such as the height and coverage of all vegetation species in the sampling plots, was recorded. Secondly, all plants that were classified in the sampling plots were cut with scissors just above the ground, and then marked and put into envelope

bags. The fresh plants were then dried in an oven at 105 °C for 0.5 h, and dried at 70 °C to a constant weight. Finally, the dried plant was weighed and the aboveground biomass was calculated.

2.3.3. Greenhouse Gas Sampling and Measurements

The concentrations of CH_4 and N_2O were measured every month at 9:00–11:00 a.m. from July–September during the growing seasons of 2019 using a stainless steel chamber (diameter of 40 cm, height of 31.8 cm) with an opaque top. The external surface of each chamber was covered with thermal insulation foam to minimize heating from solar radiation during sampling. In advance, twenty-four hours before greenhouse gas collection, we inserted the bottom seat of the chamber into the soil, below 3 cm of sampling plots, in order to minimize the disturbance of the soil environment when sampling. In addition, we filled the sink at the bottom of the chamber with water to prevent the outside air from entering the chamber during the sampling process, which would interfere with the accuracy of the experimental data. The gas inside the chamber was sampled at 0, 5, 15, and 30 min after the chamber was closed using a 60 mL plastic syringe. The collected gas samples were stored in vacuum-sealed glass bottles and then transported to the laboratory within 24 h and analyzed using gas chromatography (Agilent 7890, Agilent, Santa Clara, CA, USA) equipped with a Flame Ionization Detector (using 99.999% N_2 as the carrier gas) and a microelectron capture detector (using 99.999% N_2 and 10% CO_2 + 90% N_2 as the carrier gas and backup gas, respectively). The accuracy of the CH_4 and N_2O measurements were within ±3% and had detection limits of ~0.001 μg L^{-1} and ~0.0008 μg L^{-1}, respectively.

2.4. Data Calculation

2.4.1. Species Diversity Calculation

The species richness, the Shannon–Weiner, Simpson, and Pielou indices, and the importance value were calculated according to Wu et al. [11], respectively, as follows:

$$\text{Species richness} = N, \tag{1}$$

$$\text{Importance value } (IV) = (\text{relative coverage} + \text{relative height})/2, \tag{2}$$

$$\text{Shannon-Weiner index } H = -\sum Pi\lg(Pi), \tag{3}$$

$$\text{Simpson index } D = 1/\sum Pi^2, \tag{4}$$

$$\text{Pielou index } E = H/\ln S, \tag{5}$$

where S is the number of species in the quadrat (species richness), IV and Pi are the importance value and relative importance value, respectively, and H, D, and E are the Shannon–Weiner, Simpson, and Pielou indices, respectively.

2.4.2. Greenhouse Gas Calculation

The fluxes of CH_4 and N_2O were calculated according to Wu et al. [11], as follows:

$$F = \rho \times \frac{V}{A} \times \frac{\Delta c}{\Delta t} \times \frac{273}{273 + T}, \tag{6}$$

where F_{CH_4} and F_{N_2O} are the CH_4 and N_2O fluxes (μg m^{-2} h^{-1}), respectively, ρ is the density of either CH_4 (0.714 kg m^{-3}) or N_2O (1.964 kg m^{-3}), V is the chamber volume (m^3), and A is the area (m^2). The quantity $\frac{\Delta c}{\Delta t}$ is the slope of the linear regression for the gas concentration gradient with time (m^3 m^{-3} h^{-1}) and T is the average temperature in the chamber during the sampling period.

2.5. Statistical Analysis

All statistical analyses were performed with IBM SPSS Statistics version 19.0 (IBM, Armonk, New York, NY, USA). A one-way analysis of variance was used to examine the significance of the measured data. Effects were deemed statistically significant if $p < 0.05$.

3. Results

3.1. Number and Size of Effective Rodent Holes and the Total Damaged Area

There were significant differences in the number, size, and total damaged area of the effective rodent burrows in the RI and CK plots ($p < 0.05$, Table 1). There were 0.188 and 0.013 effective rodent holes per square meter in the CK and RI plots, respectively. Compared with the CK plots, the number and size of effective rodent holes in the RI plots were significantly decreased by 93.9% and 55.5%, respectively. Therefore, the total area damaged by pika per square meter in the CK plots was 0.064 m^2, compared to 0.001 m^2 in the RI plots. Obviously, the installation of RI nets significantly decreased the rodent damage area by 97.9%.

Table 1. The number and size of effective rodent holes and the total area of rodent damage.

	Effective Hole (Hole m^{-2})	Hole Size (m^2)	Damaged Area (m^2 m^{-2})
CK	0.188 ± 0.020 a	0.012 ± 0.001 a	0.064 ± 0.005 a
RI	0.013 ± 0.002 b	0.005 ± 0.001 b	0.001 ± 0.000 b

Note: Lowercase letters represent significant differences at $p < 0.05$ level between the plots of CK and RI.

3.2. Plant Height

Apart from forbs, there was a significant difference in plant height between the RI and CK plots ($p < 0.05$; Figure 2). The average height of the grasses and sedges in the CK plots were 3.97 ± 0.38 cm and 2.24 ± 1.16 cm, and those in the RI plots were 7.75 ± 0.63 cm and 6.38 ± 0.74 cm, respectively, which were significantly higher than those in the CK plots by 95.4% and 184.2%, respectively. The average height of poisonous weeds in the CK plots was 8.92 ± 2.13 cm. It is worth noting that with the setting of the RI device, the poisonous weeds in the RI plots disappeared.

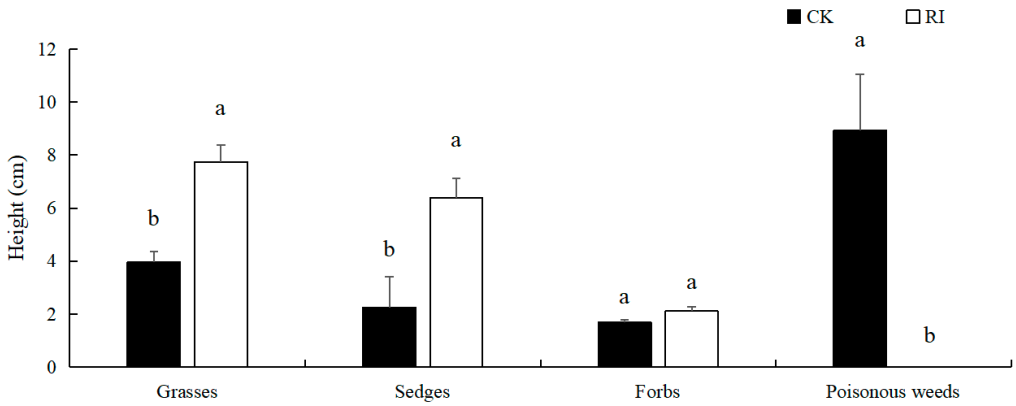


Figure 2. The difference in plant height between the RI plots and CK plots. Note: Lowercase letters represent significant differences at $p < 0.05$ level between the plots of CK and RI.

3.3. Plant Species Composition and Importance Value

The RI device had an important effect on the composition and importance value of species in the alpine grassland plots (Table 2 and Figure 3). Compared with the CK plots, there were obvious differences in plant species composition in the RI plots. In the CK plots, the invasion, gnawing, and burrowing behavior of the plateau pikas were conducive to the breeding and complex species composition of poisonous weeds such as *Euphorbia fischeriana*, *Morina kokonorica*, *Saussurea japonica*, and *Ajuga lupulina*. However, after installation of the

RI devices, *Leontopodium leontopodioides*, *Saussurea japonica*, *Ajuga lupulina*, *Stracheya tibetica*, *Euphorbia fischeriana*, and *Morina kokonorica* were unable to thrive in the RI plots, but we did observe an increase in the proportion of *Poa pratensis* and *Koeleria litvinowii* species in the grasses. The dominant species in the CK plots were *Elymus nutans*, *Stipa purpurea*, *Carex rigescens*, *Saussurea japonica*, *Euphorbia fischeriana*, and *Morina kokonorica*, while in the RI plots, *Poa pratensis*, *Koeleria litvinowii*, *Carex moorcroftii*, and *Potentilla bifurca* were prevalent. Compared with the CK plots, the proportion of grasses and sedge plant species in the RI plots increased by 22.8% and 15.9%, respectively, while the proportion of forbs decreased by 14.5% and poisonous grasses disappeared (Figure 3).

Table 2. Species composition and importance value of the alpine grassland communities in the RI plots and CK plots.

Plant Group	Species	Importance Value	
		CK	RI
Grasses	*Poa pratensis*	—	0.162
	Elymus nutans	0.064	0.034
	Koeleria litvinowii	—	0.156
	Stipa purpurea	0.094	0.055
	Festuca ovina	0.022	—
Sedges	*Carex moorcroftii*	0.020	0.249
	Carex rigescens	0.071	—
Forbs	*Leontopodium leontopodioides*	0.028	—
	Saussurea japonica	0.159	—
	Oxytropis subfalcata	0.016	—
	Potentilla bifurca	0.019	0.214
	Microula sikkimensis	—	0.014
	Heteropappus hispidus	—	0.077
	Salsola collina	—	0.007
	Artemisia frigida	0.011	0.032
	Ajuga lupulina	0.116	—
	Stracheya tibetica	0.049	—
	Chenopodium album	0.029	—
	Other weed	0.062	—
Poisonous weeds	*Euphorbia fischeriana*	0.156	—
	Morina kokonorica	0.086	—

"—" represents that this species did not appear in the experiment plots.

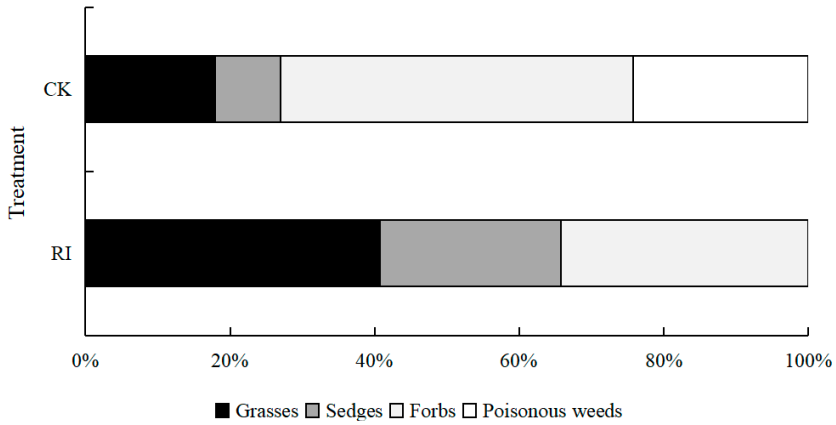


Figure 3. The difference in importance values for the species in the RI plots and CK plots.

3.4. Species Diversity

The species richness was 8.67 ± 0.88 and 7.33 ± 0.33 in the CK and RI plots, respectively, and the species richness significantly decreased in the RI plots by 15.4% ($p < 0.05$) (Figure 4a). The values of the Shannon–Weiner, Simpson, and Pielou indices for CK plots were 1.79 ± 0.08, 0.83 ± 0.004, and 0.84 ± 0.03, and the values for RI plots were 1.70 ± 0.08, 0.79 ± 0.004, and 0.86 ± 0.03, respectively. Compared with the CK plots, the Shannon–Weiner and Simpson index values of the RI plots were slightly lower by 4.7% and 4.8%, respectively, while the Pielou index increased slightly by 2.5%. However, there was no significant difference between the RI and CK plots for the Shannon–Weiner, Simpson, and Pielou indexes (Figure 4b).

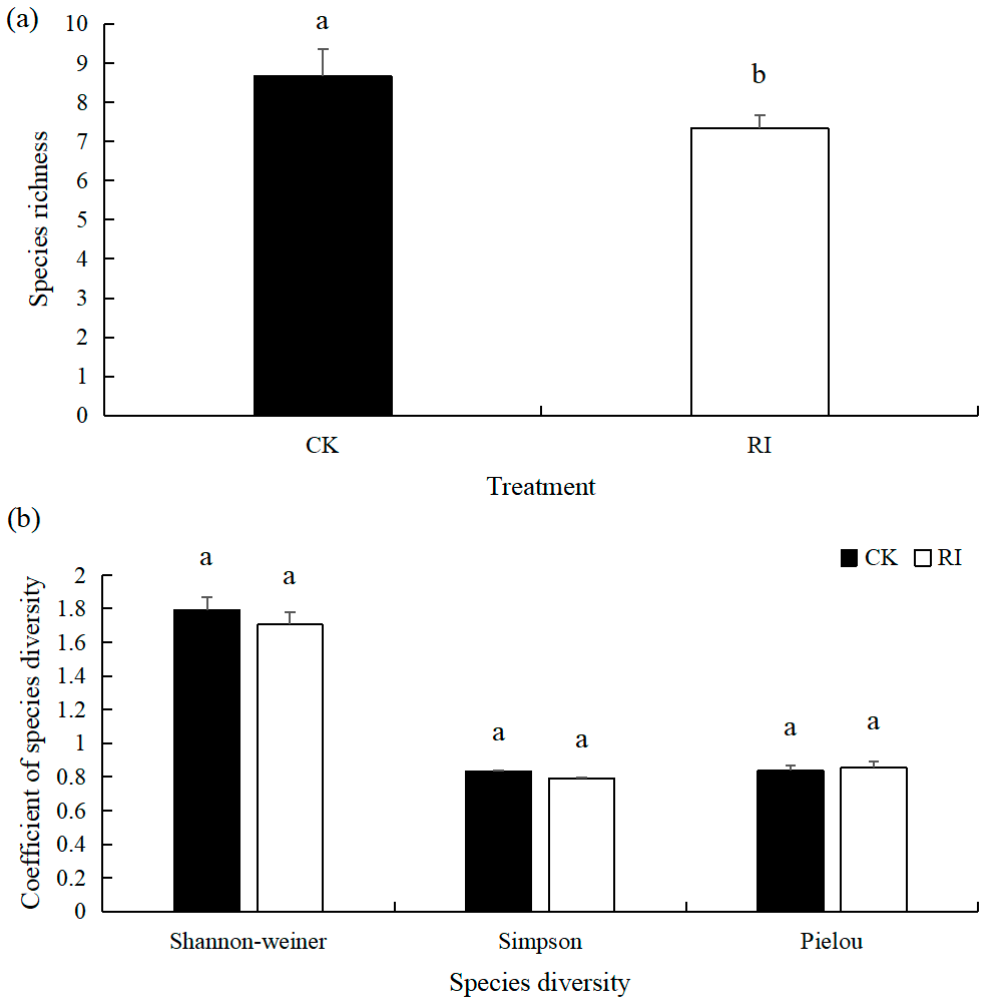


Figure 4. Difference in species diversity between the RI plots and CK plots. Note: Lowercase letters represent significant differences at $p < 0.05$ level between the plots of CK and RI.

3.5. Aboveground Biomass

The coverage of high-quality forage (grasses and sedges), forbs, and poisonous grass in the CK plots was 8.93 ± 1.60%, 39.43 ± 11.59%, and 10.30 ± 2.76%, respectively. It can be seen that the coverage of forbs and poisonous grass was significantly higher than that of quality forage ($p < 0.05$). Compared with the CK plots, the coverage of high-quality forage in the RI plots was significantly higher by 50.47% ($p < 0.05$); on the contrary, there was no significant difference in the coverage of forbs ($p > 0.05$, Figure 5a) in the two types of plots.

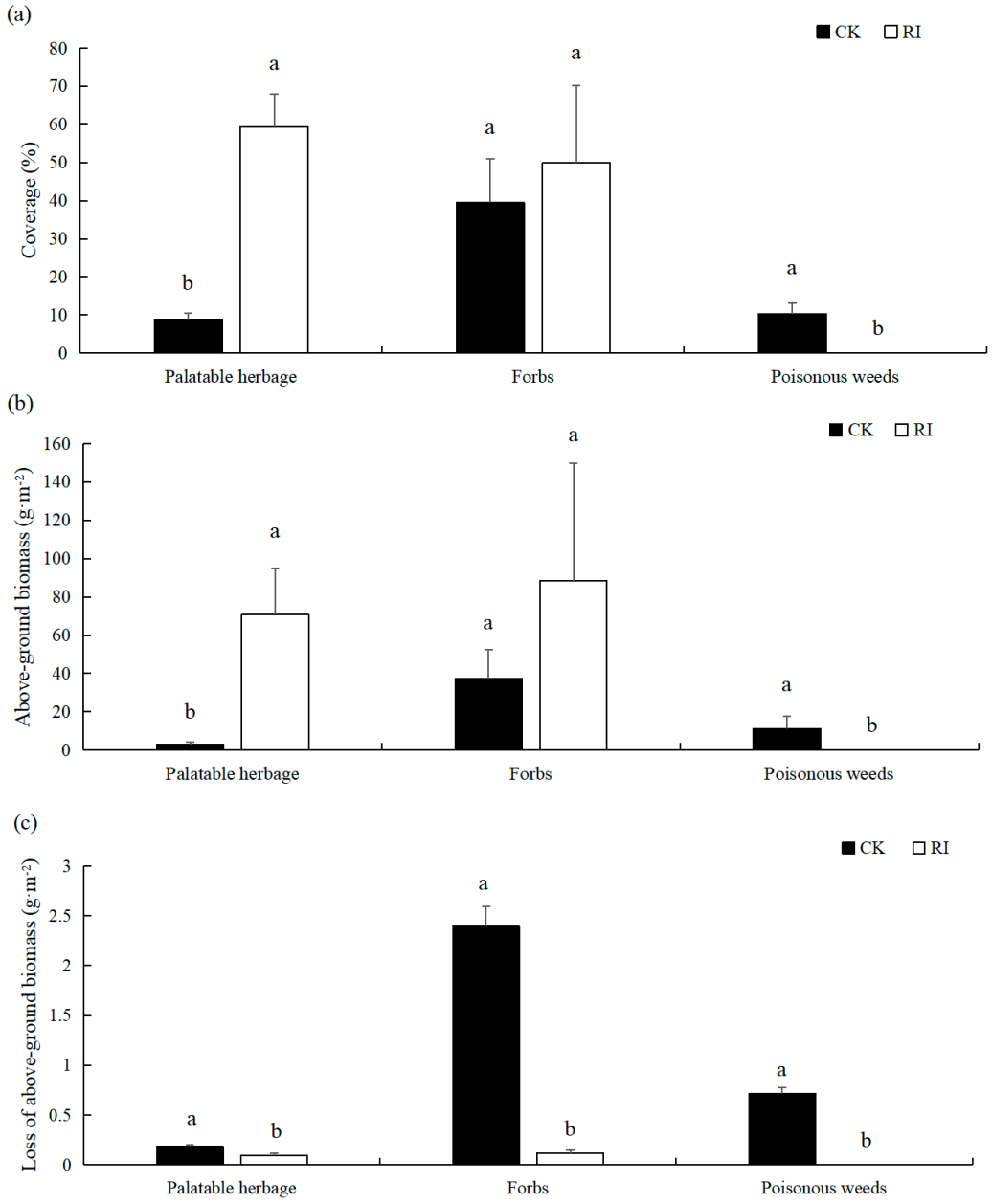


Figure 5. The difference in aboveground biomass between the RI plots and CK plots. Note: Lowercase letters represent significant differences at $p < 0.05$ level between the plots of CK and RI.

The aboveground biomass in the CK plots was 51.56 g·m^{-2}, among which high-quality forage, forbs, and poisonous grass amassed to 2.91, 37.45, and 11.20 g·m^{-2}, respectively. These numbers suggest that the biomass of forbs and poisonous grass was significantly higher than for forage ($p < 0.05$). The total aboveground biomass in the RI plots was 159.12 g·m^{-2}, including high-quality forage with 70.76 g·m^{-2} and forbs with 88.36 g·m^{-2}, and there was no statistically significant difference between them ($p < 0.05$). Compared with the CK plots, the amount of high-quality forage in the RI plots was significantly larger by 2334.40% ($p < 0.05$); however, there was no significant difference in the total amount of forbs ($p < 0.05$) relative to the CK plots, and no poisonous grass was present (Figure 5b). Due to the burrowing behavior of the pikas, the loss of aboveground biomass in the CK and RI plots was 3.29 g·m^{-2} and 0.22 g·m^{-2}, respectively, whereas the biomass of high-quality forage and forbs decreased significantly by 48.1% and 95.0%, respectively, and the amount of loss in the RI plots was significantly lower than in the CK plots (Figure 5c).

Based on the total area of damage caused by rodents in the CK plots and the amount of aboveground biomass in the RI plots, we calculate that the amount of aboveground biomass in the alpine grassland of the Qinghai–Tibet Plateau could increase by 10.16 $g \cdot m^{-2}$ due to the establishment of RI devices, in which high-quality forage and forbs could increase by 4.52 $g \cdot m^{-2}$ and 5.64 $g \cdot m^{-2}$, respectively. According to the average purchase price of high-quality forage in 2020–2022 of 3.1 $CNY \cdot kg^{-1}$, the increase in high-quality forage production arising from the use of RI devices could increase the economic income of the herdsmen by 140 $CNY \cdot hm^{-2}$ (Table 3).

Table 3. Aboveground biomass and economic losses.

	Palatable Herbage Plants	Forbs
Increased aboveground biomass ($g \cdot m^{-2}$)	4.52	5.64
Economic losses ($CNY \cdot hm^{-2}$)	140	—

Note: "—"indicates that the economic loss of Forbs has not been calculated.

3.6. Emission Fluxes of CH_4 and N_2O

CH_4 and N_2O emission fluxes were -204.99 ± 50.23 $\mu g \cdot m^{-2} \cdot h^{-1}$ and -4.48 ± 1.02 $\mu g \cdot m^{-2} \cdot h^{-1}$ in the RI plots, and -36.23 ± 15.34 $\mu g \cdot m^{-2} \cdot h^{-1}$ and -0.14 ± 0.31 $\mu g \cdot m^{-2} \cdot h^{-1}$ in the CK plots, respectively. These results indicate that both the CK and RI plots are important sinks of atmospheric CH_4 and N_2O (Figure 6). Compared with the CK plots, the uptake of CH_4 and N_2O in the RI plots was significantly larger by 465.8% and 3100.0%, respectively ($p < 0.05$).

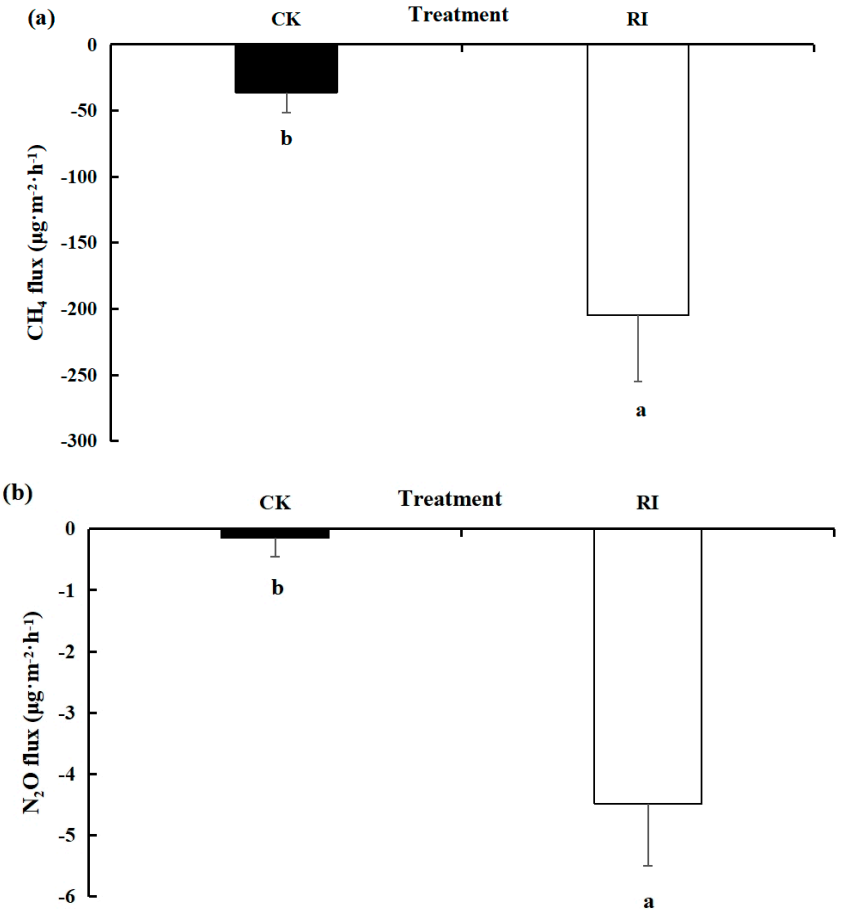


Figure 6. The CH_4 and N_2O fluxes in the RI plots and CK plots (**a**,**b**). Note: Lowercase letters represent significant differences at $p < 0.05$ level between the plots of CK and RI.

4. Discussion

4.1. Effects of Rodent Control on Plant Community Characteristics and Biomass in Alpine Grassland

In the grassland ecosystem, the species composition, structure, biomass, and species diversity of grassland plants are altered by the disturbance of herbivores [31,33]. In this study, the establishment of an RI area effectively prevented disturbances caused by plateau pikas on alpine grassland. We observed that the plant species composition of the alpine grassland significantly changed compared with the control area, where the proportion of grass and sedge plant species in the grassland increased, the proportion of mixed grass species decreased, and poisonous grasses such as *Euphorbia fischeriana* and *Morina kokonorica* disappeared. In addition, the establishment of RI devices significantly increased the height, quality forage coverage, and aboveground biomass of grasses and sedges, while it had no significant effect on the height, coverage, and aboveground biomass of forbs. These results indicate that the establishment of RI areas can have a positive effect on the community structure of the dominant functional groups (grasses and sedges) of alpine grassland and that RI technology is conducive to vegetation restoration in degraded alpine grassland. The changes in the plant coverage, height, importance value, and biomass of different functional groups are mainly affected by continuous burrowing and selective feeding by herbivores [29,34]. During the re-greening period of grass in the alpine grassland of the Qinghai–Tibet Plateau, the frequent burrowing behavior of rodents pushes a large amount of subsoil to the surface, forming mounds of various shapes, while the holes cause the grass to die due to soil burial, thus significantly reducing the plant coverage of the alpine grassland [35]. In addition, when rodents forage for grassland plants, they preferentially target high-quality forage with greater height and coverage (grasses and sedges), resulting in the lower height and coverage of these dominant functional groups of plants, inhibiting the growth of excellent forage and reducing their survival competitiveness with other species [31,36,37].

Disturbances caused by plateau pikas lead to heterogeneity in their grassland ecosystem habitat, including loose soil and reduced soil water content [7,31], which provide a better living environment for poisonous weeds (e.g., *Euphorbia fischeriana* and *Ajuga lupulina*). When the grasses and sedges in the upper layers of the community are eaten by plateau pikas, the competition for light resources among the poisonous weeds in the middle and lower layers is reduced, which promotes the tilling, reproduction, and development of poisonous weeds, leading to an increase in their height, coverage, and productivity [34]. Although plateau pikas have a compensatory increase in the intake of high-quality grasses, the rate of this compensatory increase is much lower than the nibbling rate of herbivores [31]. Plateau pikas do not feed on poisonous weeds, so the amount of quality forage in alpine grassland is significantly reduced. However, the establishment of RI areas can effectively reduce or block the disturbances caused by plateau pikas on alpine grassland, reducing the amount of damaged grassland area, increasing the height and coverage of high-quality forage, and promoting its growth. When grasses and sedges become the upper layer of the community, a shaded local environment is formed for the whole community, which inhibits the absorption of nutrients by noxious weeds in the middle and lower layers of the community [38].

However, a factor that cannot be ignored is that in the initial period of the rodent isolation device, the plants of grasses and sedges recover faster. However, the forbs recovered gradually with the prolongation of the rodent isolation device time [39]. With the banning of grazing, the species composition of the grassland community will gradually change to sub-stable scrub vegetation and relatively stable steppe vegetation, resulting in an increase in the proportion of forbs [40]. In this study, we only considered the short-term effects of rodent isolation; we will focus on the effects of long-term rodent isolation on the species composition of grassland ecosystems in the future.

Previous research has shown that disturbances caused by plateau pikas on grassland ecosystems can increase plant species richness [1]. Because plateau pikas push a large amount of deep soil to the surface in excavation activities, this forms a secondary bare land.

This can cause a secondary succession of plant communities, resulting in the flourishing of poisonous weeds and other plants in the secondary bare land, which increases species richness. Similarly, in this study, we also found that the species richness in the RI plots was slightly higher than that in the CK plots, which is consistent with previous research results. Wu et al. (2019) pointed out that the variation trend of the Shannon–Weiner index was a suitable proxy for species richness in the alpine grassland of the Qinghai–Tibet Plateau [32], which showed a decreasing trend in their RI area.

Although the installation of rodent isolation devices can effectively reduce the damage of plateau pika to the alpine grassland in the present study, the continuous reduction of plateau pika activities may also bring negative effects on the alpine grassland ecosystem in the long term, as shown in previous studies [12,13]. At present, the climate of the Qinghai-Tibet Plateau is developing towards a warmer and drier trend [25,26]. The aboveground biomass and leaf nitrogen content of plants on the mounds produced by pika digging were higher than those in the grassland areas with less pika interference under drought conditions [12,13]. In addition, the compensatory growth of grassland induced by the moderate nibbling behavior of pika will increase the aboveground biomass and promote the stability of the grassland ecological community [31,41]. Therefore, excessive removal of pika will lead to serious ecological problems such as a decrease in aboveground biomass and the loss of plant leaf nutrient content in the grassland ecosystem of the Qinghai–Tibet Plateau in the future under drought conditions. Moreover, with a decrease in animal activity in the grassland, the species composition of the grassland community will gradually change from ephemeral to sub-stable scrub vegetation and relatively stable steppe vegetation, resulting in a decrease in species richness and primary productivity and an increase in the proportion of forbs [40,42]. Therefore, determining the disturbance threshold of plateau pika in the Qinghai–Tibet Plateau grassland ecosystem is the focus of our future research.

4.2. Effect of Rodent Control on Soil CH_4 and N_2O Emissions

Plateau pikas are an important participant in soil material cycling in grassland ecosystems, which can directly and indirectly affect the uptake and emission of soil CH_4 and N_2O. Most previous results showed that there are significant differences in the response of soil moisture and nutrient content to the degree of disturbance caused by pikas in grassland ecosystems [7,43]. When the disturbance degree is slight, soil moisture and nutrient content may increase, but when the disturbance degree is excessive, soil moisture and nutrient content will significantly reduce, which promotes habitat drought [2,44]. The contents of ammonium nitrogen, nitrate nitrogen, inorganic nitrogen, and carbon in the soil of rodent hummocks are higher than those in the soil of grassland undisturbed by rodents [1,29]. Burrowing behavior not only increases the accumulation of surface soil organic matter by rodents but also reduces the soil's bulk density, changes the soil's permeability, stimulates soil microbial activity, and accelerates gas diffusion in the soil [5,10,11]. Further, the alteration of soil carbon and nitrogen content will directly or indirectly cause the uptake and emission of soil CH_4 and N_2O [11,45]. Previous studies have shown that CH_4 emission is positively correlated with soil carbon and nitrogen content in grassland ecosystems; that is, higher soil carbon and nitrogen contents stimulate more CH_4 and N_2O emissions [46,47]. In addition, it has been reported that CH_4 and N_2O emissions from animal feces amount to about 867×10^3 t and 44×10^3 t, respectively, accounting for 2.53% and 5.18% of the total CH_4 and N_2O emissions in China [48]. The feces produced by the plateau pikas will also produce a large amount of greenhouse gases during the process of disposal and storage. Fecal patch coverage has a stimulating effect on CH_4 and N_2O emissions in alpine grassland ecosystems [49] because the diversity of soil microorganisms in fecal matter is significantly higher than that in other regions [50], which greatly enhances the heterogeneity of the soil environment and further promotes the production of soil CH_4 emissions in the alpine grassland ecosystem [51]. Moreover, animal gnawing and burrowing not only regulate the processes of soil nitrogen mineralization, nitrification, and denitrification, but the plant residues after gnawing are mixed into the soil, which increases the content of soil

organic matter; collectively, these cause the N_2O emissions to increase by 64.7% [52,53]. Similarly, in the present study, we also find that the soil CH_4 and N_2O emissions in the RI area were significantly lower than in the CK area, which agrees with the findings of many previous studies.

4.3. Effect of Rodent Control on the Development of Animal Husbandry in Alpine Grasslands

The Qinghai–Tibet Plateau has about 14×10^8 hm^2 of natural grassland [54], approximately 41% of which has been degraded because of climate change and overgrazing, among which the severely and extremely degraded grassland areas account for proportions of 19.0% and 6.5%, respectively [19,20]. Moreover, disturbances caused by rodents further aggravate grassland degradation, resulting in a sharp decrease in forage biomass and a more prominent gulf between available grass and livestock demand. In this study, we find that the total area of alpine grassland lost due to plateau pikas is 0.064 $m^2 \cdot m^{-2}$, which results in a total decrease of 4.52 $g \cdot m^{-2}$ of high-quality forage and a direct economic loss of 140 $CNY \cdot hm^{-2}$. Previous studies confirmed that when the density of plateau pikas reaches 7380$\cdot km^{-2}$, they are able to consume 7.011×10^5 kg of pasture in the growing season, which is equivalent to the annual food intake of 480 Tibetan sheep [21]. Obviously, plateau pikas have a significant impact on the alpine grassland ecosystem and social and economic development. According to previous reports, the per capita disposable income of Tibetan herders is still lagging behind that of neighboring provinces. The burrowing and nibbling of plateau pikas cause a lack of natural forage, forcing herdsmen to purchase more feed to alleviate the more prominent difference between available grass and the livestock's food requirements, which seriously hinders the economic and social development of pastoral areas. To alleviate this problem, installing RI nets can effectively control the number of plateau pikas in the alpine grassland, reduce the damaged area of grassland, enhance the stability of the alpine grassland ecosystem, and promote the growth of high-quality forage. Together, these can provide a favorable outcome for grassland protection, rodent control, and sustainable economic, ecological, and social development in pastoral areas.

5. Conclusions

The specific objective of this study was to investigate the effects of RI on plant community structure and greenhouse gas emission in the alpine grassland of the Qinghai–Tibet Plateau. Our results indicate that the establishment of RI areas can effectively prevent the invasion of plateau pikas, resulting in the height and proportion of grasses and sedges in the alpine grassland increasing and the proportion of poisonous weeds decreasing. Moreover, on the basis of the above results from our research, RI also increases high-quality forage yield and reduces the economic burden of herdsmen. In the field of species diversity, RI significantly increases species richness, but its effect was not statistically significant from the results of the Shannon–Weiner, Simpson, and Pielou indices. However, of special interest is the fact that RI stimulated uptakes of CH_4 and N_2O in soil, implying that the grasslands of the Qinghai–Tibet Plateau may have the potential to remove more CH_4 and N_2O from the atmosphere under future global warming conditions.

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References

1. Liu, C.F.; Duan, Y.Y.; Wang, L.L.; Wang, Y.M.; Guo, Z.G. Effects of plateau pika (*Ochotona curzoniae*) disturbance on the relationship between plant species diversity and soil ecological stoichiometry in alpine meadows. *Acta Prataculturae Sin.* **2023**, *32*, 157–166.
2. Liu, Y.S.; Fan, J.W.; Harris, W.; Shao, Q.Q.; Zhou, Y.C.; Wang, N.; Li, Y.Z. Effects of plateau pika (*Ochotona curzoniae*) on net ecosystem carbon exchange of grassland in the Three Rivers Headwaters region, Qinghai-Tibet, China. *Plant Soil* **2013**, *366*, 491–504. [CrossRef]
3. Wang, Y.; Pang, X.P.; Xiao, Y.; Jia, T.T.; Wang, Q.; Yu, C.; Guo, Z.G. The effect of plateau pika (*Ochotona curzoniae*) disturbance on the relationship between plant diversity and soil nutrients of alpine meadow. *Acta Ecol. Sin.* **2016**, *36*, 5485–5496.
4. Jin, L.; Sun, L.; Cui, H.J.; Zhao, J.J.; Liu, X.C.; Tang, P.J.; Wang, X.J. Correlation between the distribution characteristics of poisonous plants and *Ochotona curzoniae*, *Myospalax baileyi* in the East of Tibetan Plateau Alpine meadow ecosystem. *Acta Ecol. Sin.* **2014**, *34*, 2208–2215.
5. Li, W.J.; Zhang, Y.M. Impacts of plateau pikas on soil organic matter and moisture content in alpine meadow. *Acta Theriol. Sin.* **2006**, *26*, 331–337.
6. Shi, H.X.; Yu, J.L. Influence of burrowing rodent density plots on the alpine *Kobresia* meadows structure and soil water content. *Chin. J. Grassl.* **2010**, *32*, 109–112.
7. Yu, C.; Jia, T.T.; Pan, X.P.; Guo, Z.G. Effects of plateau pika (*Ochotona curzoniae*) disturbing soil carbon and nitrogen distribution in alpine meadow. *Acta Pedol. Sin.* **2016**, *53*, 768–778.
8. Zhang, W.N.; Jin, S.H.; Yu, C.; Pang, X.P.; Wang, J.; Guo, Z.G. Influence of the density of burrow entrances of plateau pika on the concentration of soil nutrients in a *Kobresia pygmaea* meadow. *Pratacultural Sci.* **2018**, *35*, 1593–1601.
9. Canals, R.M.; Herman, D.J.; Firestone, M.K. How disturbance by fossorial mammals alters N cycling in a California annual grassland. *Ecology* **2003**, *84*, 875–881. [CrossRef]
10. Liu, W.; Xu, Q.M.; Wang, X.; Zhao, J.Z.; Zhou, L. Influence of burrowing activity of plateau pikas (*Ochotona curzoniae*) on nitrogen in soils. *Acta Theriol. Sin.* **2010**, *30*, 35–44.
11. Wu, H.B.; Wang, X.X.; Ganjurjav, H.; Hu, G.Z.; Qin, X.B.; Gao, Q.Z. Effects of increased precipitation combined with nitrogen addition and increased temperature on methane fluxes in alpine meadows of the Tibetan Plateau. *Sci. Total Environ.* **2020**, *705*, 135818. [CrossRef] [PubMed]
12. Zhao, G.Q.; Li, G.Y.; Ma, W.H.; Zhao, D.Z.; Li, X.Y. Impacts of *Ochotona pallasi* disturbance on alpine grassland community characteristics. *Chin. J. Appl. Ecol.* **2013**, *24*, 2122–2128.
13. Wesche, K.; Nadrowski, K.; Retzer, V. Habitat engineering under dry conditions: The impact of pikas (*Ochotona pallasi*) on vegetation and site conditions in southern Mongolian steppes. *J. Veg. Sci.* **2007**, *18*, 665–674. [CrossRef]
14. Miao, F.H.; Guo, Y.J.; Miao, P.F.; Guo, Z.G.; Shen, Y.Y. Influence of enclosure community characteristics of alpine in the northeastern edge region of the Qinghai-Tibetan Plateau. *Acta Prataculturae Sin.* **2012**, *21*, 11–16.
15. Heske, E.J.; Brown, J.H.; Guo, Q.F. Effects of kangaroo rat exclusion on vegetation structure and plant species diversity in the Chihuahuan Desert. *Oecologia* **1993**, *95*, 520–524. [CrossRef]
16. Hu, Y.G.; Chang, X.F.; Lin, X.W.; Wang, Y.F.; Wang, S.P.; Duan, J.C.; Zhang, Z.H.; Yang, X.X.; Luo, C.Y.; Xu, G.P.; et al. Effects of warming and grazing on N_2O fluxes in an alpine meadow ecosystem on the Tibetan plateau. *Soil Biol. Biochem.* **2010**, *42*, 944–952. [CrossRef]
17. Wei, D.; Xu-Ri; Tenzin-Tarchen; Wang, Y.S.; Wang, Y.H. Considerable methane uptake by alpine grasslands despite the cold climate: In situ measurements on the central Tibetan Plateau, 2008–2013. *Glob. Chang. Biol.* **2015**, *21*, 777–788. [CrossRef] [PubMed]
18. Qu, B. Water Chemistry and Greenhouse Gases Emission the Rivers of the "Third Pole"/"Water Tower of Asia". Ph.D. Thesis, Mikkeli University Consortium, Mikkeli, Finland, 2017.
19. Cao, X.J. Grassland Degradation and Its Response to Climate Change in the Qinghai-Tibet Plateau. Master's Thesis, Chinese Academy of Agricultural Sciences, Beijing, China, 2017.
20. Cao, X.J.; Ganjurjav, H.; Liang, Y.; Gao, Q.Z.; Zhang, Y.; Li, Y.E.; Wan, Y.F.; Danjiu, L.B. Temporal and spatial distribution of grassland degradation in northern Tibet based on NDVI. *Acta Prataculturae Sin.* **2016**, *25*, 1–8.
21. Yang, Z.Y.; Jiang, X.L. The harm of plateau pika on grassland vegetation and its control threshold value. *Pratacultural Sci.* **2002**, *19*, 63–65.
22. Luo Sang, L.Z.D.J. *Prataculture Development and Ecological Environment in Qinghai-Tibet Plateau*; China Tibetology Publishing House: Beijing, China, 2000; pp. 50–151.
23. Shu, Y. The Research and Application of Ecological Control Technology of Grassland Rodent. Master's Thesis, Sichuan Agricultural University, Chengdu, China, 2014.
24. Zheng, H.M. Study on Seed Germination Characteristics and Molecular Phylogeny on Kobresia in Tibetan Plateau. Ph.D. Thesis, Northwest A&F University, Yangling, China, 2008.

25. Chen, H.; Zhu, Q.A.; Peng, C.H.; Wu, N.; Wang, Y.F.; Fang, X.Q.; Gao, Y.H.; Zhu, D.; Yang, G.; Tian, J.Q.; et al. The impacts of climate change and human activities on biogeochemical cycles on the Qinghai: Tibetan Plateau. *Glob. Chang. Biol.* **2013**, *19*, 2940–2955. [CrossRef]
26. National Development and Reform Commission. *China's National Climate Change Programme*; Environmental Policy Collection; National Development and Reform Commission: Beijing, China, 2007; pp. 1–62.
27. Mer, J.L.; Roger, P. Production, oxidation, emission and consumption of methane by soils: A review. *Eur. J. Soil Biol.* **2001**, *37*, 25–50. [CrossRef]
28. Lowe, D.C. Global change: A green source of surprise. *Nature* **2006**, *439*, 148–149. [CrossRef]
29. Liu, W.; Yan, H.Y.; Wang, X.; Wang, C.T. Effects of plateau pikas on restoring succession of degraded grassland and plant community structure. *Acta Theriol. Sin.* **2014**, *34*, 54–61.
30. Zhang, W.H.; Miao, Y.J.; Zhao, Y.H.; Wang, X.T.; Xu, Y.M.; Wei, X.H.; Sun, L. Effects of plateau pika (*Ochotona curzoniae*) on alpine meadow in Tibet. *Acta Prataculturae Sin.* **2018**, *27*, 115–122.
31. Xu, H.L.; Wang, X.; Liu, W. Effects of disturbance of plateau pika (*Ochotona curzoniae*) on plant community in alpine meadow under grazing condition. *Acta Theriol. Sin.* **2019**, *39*, 537–545.
32. Wu, H.B.; Shui, H.W.; Hu, G.Z.; Wang, X.X.; Ganjurjav, H.; Yan, J.; He, S.C.; Xie, W.D.; Gao, Q.Z. Species diversity and biomass distribution patterns of alpine grassland along an elevation gradient in the Northern Tibetan Plateau. *Ecol. Environ. Sci.* **2019**, *28*, 1071–1079.
33. Davidson, A.D.; Ponce, E.; Lightfoot, D.C.; Fredrickson, E.L.; Brown, J.H.; Cruzado, J.; Brantley, S.L.; Sierra-Corona, R.; List, R.; Toledo, D.; et al. Rapid response of a grassland ecosystem to an experimental manipulation of a keystone rodent and domestic livestock. *Ecology* **2010**, *91*, 3189–3200. [CrossRef] [PubMed]
34. Duan, M.J.; Gao, Q.Z.; Wan, Y.F.; Li, Y.E.; Guo, Y.Q.; Danjiu, L.B.; Luosang, J.C. Effect of grazing on community characteristics and species diversity of Stipa purpurea alpine grassland in Northern Tibet. *Acta Ecol. Sin.* **2010**, *30*, 3892–3900.
35. Zhang, X.L.; Li, G. Effects of rodents activities on grazing land and ecosystem in alpine meadow. *Pratacultural Sci.* **2015**, *32*, 816–822.
36. Ren, Q.J.; Cui, X.L.; Zhao, B.B. Effects of grazing impact on community structure and productivity in an alpine meadow. *Acta Prataculturae Sin.* **2008**, *17*, 134–140.
37. Niu, K.C.; Zhang, S.T.; Zhao, B.B.; Du, G.Z. Linking grazing response of species abundance to functional traits in the Tibetan alpine meadow. *Plant Soil* **2010**, *330*, 215–223. [CrossRef]
38. Zhou, H.K.; Zhou, X.M.; Zhao, X.Q.; Julia, K. A preliminary study on the influence of simulated greenhouse effect on a *Kobresia Humilis* meadow. *Acta Phytoecol. Sin.* **2000**, *24*, 547–553.
39. Zhang, W.N. The plant and soil characteristics of the alpine meadow under different periods of grazing ban in Northern Tibet. Master's Thesis, Chinese Academy of Agricultural Sciences, Beijing, China, 2016.
40. Wu, J.B.; Bao, X.Y.; Li, J.; Zhao, N.X.; Gao, Y.B. Influence of fencing duration on community and population of *Stipa grandis* in a typical steppe. *Acta Agrestia Sin.* **2010**, *18*, 490–495.
41. Smith, A.T.; Foggin, J.M. The plateau pika (*Ochotona curzoniae*) is a keystone species for biodiversity on the Tibetan Plateau. *Anim. Conserv.* **1999**, *2*, 235–240. [CrossRef]
42. Zhou, X.R.; Guo, Z.G.; Guo, X.H. The role of plateau pika and plateall zokor in alpine meadow. *Pratacult. Sci.* **2010**, *27*, 38–44.
43. Liu, W.; Li, L.; Yan, H.Y.; Sun, H.Q.; Zhang, L. Effects of burrowing activity of plateau pika (*Ochotona curzoniae*) on plant species richness and aboveground biomass. *Acta Theriol. Sin.* **2012**, *32*, 216–220.
44. Guo, Z.G.; Zhou, X.R.; Hou, Y. Effect of available burrow densities of plateau pika (*Ochotona curzoniae*) on soil physicochemical property of the bare land and vegetation land in the Qinghai-Tibetan Plateau. *Acta Ecol. Sin.* **2012**, *32*, 104–110. [CrossRef]
45. Li, M.J.; Ge, Y.Q.; Ganjurjav, H.; Hu, G.Z.; Wu, H.B.; Yan, J.; He, S.C.; Gao, Q.Z. Warming intensified the effects of nitrogen addition on N_2O emissions from alpine meadow in the northern Qinghai–Tibet Plateau. *Adv. Clim. Chang. Res.* **2024**, *15*, 101–112. [CrossRef]
46. Fang, H.J.; Cheng, S.L.; Yu, G.R.; Cooch, J.; Wang, Y.S.; Xu, M.J.; Li, L.S.; Dang, X.S.; Li, Y.N. Low-level nitrogen deposition significantly inhibits methane uptake from an alpine meadow soil on the Qinghai-Tibetan Plateau. *Geoderma* **2014**, *213*, 444–452. [CrossRef]
47. Yan, Y.L.; Ganjurjav, H.; Hu, G.Z.; Liang, Y.; Li, Y.; He, S.C.; Danjiu, L.B.; Yang, J.; Gao, Q.Z. Nitrogen deposition induced significant increase of N_2O emissions in an dry alpine meadow on the central Qinghai-Tibetan Plateau. *Agric. Ecosyst. Environ.* **2018**, *265*, 45–53. [CrossRef]
48. Dong, H.M.; Li, Y.; Tao, X.P.; Peng, X.P.; Li, N.; Zhu, Z.P. China greenhouse gas emissions from agricultural activities and its mitigation strategy. *Trans. Chin. Soc. Agric. Eng.* **2008**, *24*, 269–273.
49. Ge, S.D.; Xu, T.W.; Li, B.; Cao, H.; Zhao, L.; Xu, S.X. Effects of yak dung on greenhouse gas emission during growing season in the alpine meadow. *Pratacultural Sci.* **2014**, *31*, 40–48.
50. Amador, J.A.; Görres, J.H. Microbiological characterization of the structures built by earthworms and ants in an agricultural field. *Soil Biol. Biochem.* **2007**, *39*, 2070–2077. [CrossRef]
51. Aira, M.; McNamara, N.P.; Piearce, T.G.; Domínguez, J. Microbial communities of Lumbricus terrestris L. middens: Structure, activity, and changes through time in relation to earthworm presence. *J. Soils Sediments* **2009**, *9*, 54–61. [CrossRef]

52. Lu, M.Z.; Lv, X.G.; Guan, Q.; Wu, H.T. Advancement in study on effect of earthworm on greenhouse gas emission in soil and its mechanism. *Acta Pedologica Sin.* **2015**, *52*, 1209–1225.
53. Giannopoulos, G.; Pulleman, M.M.; Van Groenigen, J.W. Interactions between residue placement and earthworm ecological strategy affect aggregate turnover and N_2O dynamics in agricultural soil. *Soil Biol. Biochem.* **2010**, *42*, 618–625. [CrossRef]
54. Buren, B.Y.; Xu, G.P.; Duan, J.C.; Chang, X.F.; Zhang, Z.H.; Wang, S.P. Primary productivity and its main affecting factors of alpine meadows on the Tibetan plateau. *Guihaia* **2010**, *30*, 760–769.

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