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Effect of plateau pika presence on the ecosystem services of alpine meadows

Yingying Chen[1], Huan Yang[1], Gensheng Bao[2], Xiaopan Pang[1], Zhenggang Guo[1]

[1]Key Laboratory of Grassland Livestock Industry Innovation, Ministry of Agriculture and Rural Affairs; Engineering Research Center of Grassland Industry, Ministry of Education; College of Pastoral Agriculture Science and Technology, Lanzhou University, Lanzhou, 730020, P. R. China

[2]Academy of Animal and Veterinary Sciences, Qinghai University (Qinghai Academy of Animal and Veterinary Sciences), Xining, China

Correspondence: Zhenggang Guo (guozhg@lzu.edu.cn)

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Abstract

The activity of small mammalian herbivores influences grassland ecosystem services in arid and semi-arid regions. This study used plateau pika (*Ochotona curzoniae*) as an example to investigate the effect of small mammalian herbivores on meadow ecosystem services in alpine regions. In this study, a home-range scale was used to measure the forage availability, water conservation, carbon sequestration, and soil nutrient maintenance services (total nitrogen, phosphorus, and potassium) in the topsoil layer; and a quadrat scale was used to assess the biodiversity conservation service of alpine meadows. This study showed that plateau pika presence led to lower forage availability and water conservation services, and led to higher biodiversity conservation, carbon sequestration, soil nitrogen, and phosphorus maintenance services of meadow ecosystems, whereas it had no impact on soil potassium maintenance service of meadow ecosystems in alpine regions. This study further found that the forage availability, biodiversity conservation, and soil nutrient maintenance services of meadow ecosystems in alpine regions first increased and then decreased as the disturbance intensity of plateau pikas increased, whereas the water conservation service tended to decrease with the increasing disturbance intensity of plateau pikas. These results present a possible pattern of plateau pikas influencing the ecosystem services of meadow ecosystems in alpine regions and richen the small mammalian herbivores in relation to grassland ecosystem services.

1 Introduction

Grasslands provide multiple ecosystem services, including provisioning, regulating, supporting, and cultural services (Millennium Ecosystem Assessment, 2005), which sustain animal production, flora and fauna, and other human welfare (Costanza et al., 1997; Zhang et al., 2018; Dong et al., 2020). However, these ecosystem services are affected by multiple

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biotic factors, such as soil microbial communities (Van Eekeren et al., 2010), grazing by large herbivores (Lu et al., 2017), and the presence of small herbivores (Delibes-Mateos et al., 2011; Martínez-Estévez et al., 2013).

Small mammalian herbivores are common biotic factors that have widespread effects on grassland vegetation and soil (Davidson et al., 2012; Pang et al., 2020a, 2020b). Previous studies have shown that the presence of prairie dogs can increase the forage availability, water conservation, carbon sequestration, and biodiversity conservation services of grassland ecosystems in arid regions (Ceballos et al., 1999, Martínez-Estévez et al., 2013), whereas European rabbit presence can decrease the forage availability service (Delibes-Mateos et al., 2008; Eldridge and Myers, 2001), and increase biodiversity conservation (Delibes-Mateos et al., 2008) and nitrogen maintenance (Willott et al., 2000) services of grassland ecosystems in semi-arid regions. In addition to grasslands in arid and semi-arid regions, vast alpine meadows exist in high latitude and altitude regions throughout the world (Zhang et al., 2018; Dong et al., 2020). However, how small mammalian herbivores influence the ecosystem services in alpine meadows as much as they do in arid and semi-arid regions has not been well documented.

Plateau pika (*Ochotona curzoniae*) is a common, small mammalian herbivore that lives in alpine meadows of the Qinghai-Tibetan Plateau (Smith and Foggin, 1999). Plateau pika has been found to create extensive disturbances in alpine meadows, and often leads to discrete mosaics of vegetated surfaces and bare soil patches in the home range (Pang et al., 2020a, 2020b). Previous studies have demonstrated that the presence of plateau pika decreases (Liu et al., 2013) or has no significant effect on plant biomass (Pang and Guo, 2017), increases

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(Liu et al., 2017; Pang and Guo, 2017) or decreases (Sun et al., 2015) plant species richness, and increases (Yu et al., 2017a; Pang et al., 2020a, 2020b) or decreases (Sun et al., 2015) soil carbon and nutrients. In addition, previous studies have shown that the disturbance intensity of plateau pikas affects plant species richness, and soil nutrient stocks of alpine meadows (Yu et al., 2017a; Pang and Guo, 2018). These findings imply that plateau pika may have an impact on the ecosystem services of alpine meadows. Thus, further studies are needed to test whether plateau pika presence and its disturbance intensity influence the ecosystem services of alpine meadows, which can richen the presence of small mammalian herbivores in relation to grassland ecosystem services.

Since soil carbon and nutrients differ between vegetated and bare soil patches in the home range (Yu et al., 2017b), Pang et al. (2020a; 2020b) proposed that the home-range scale is a better proxy than the quadrat scale to estimate the complete effects of plateau pika presence on soil carbon and nutrient stocks. Although the provisioning, regulation, support, and cultural services of alpine meadows can be estimated by multiple indicators (Egoh et al., 2012; Brown et al., 2014), one or two can be used to verify whether the presence and intensity of plateau pika influence each ecosystem service. In previous studies, palatable plant biomass for livestock has been used to evaluate the provisioning services (Martínez-Estévez et al., 2013; Wen et al., 2013); soil water storage and soil organic carbon stock have been used to evaluate the regulating services (Li and Xie, 2015; Tang et al., 2019; Wen et al., 2013); and plant species richness and soil total nutrient stocks can be used to evaluate the supporting services (Wen et al, 2013). Notably, cultural services are particularly related to the spatial scale, as many are perceived visually over distant views (Norton et al., 2012). The plateau

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pika is territorial and its land-use is patchy within a given area (Pang et al. 2020a), which leads to mismatches between the scales and cultural services (de Groot et al., 2010). Therefore, the present study used forage availability, water conservation, carbon sequestration and soil nutrient maintenance, and biodiversity conservation services to test how plateau pika presence influences the ecosystem services of alpine meadows across five sites. In this study, we hypothesized that (1) the presence of plateau pika leads to lower forage availability service because of lower palatable plant biomass in the presence of small mammalian herbivores (Eldridge and Myers, 2001; Delibes-Mateos et al., 2008); (2) plateau pika presence leads to higher water conservation and carbon sequestration services because small mammalian herbivores can increase soil water storage and carbon stocks (Martínez-Estévez et al., 2013); and (3) plateau pika presence leads to higher biodiversity conservation and soil nutrient maintenance services because small mammalian herbivores can increase plant species richness (Ceballos et al., 1999; Delibes-Mateos et al., 2008) and soil nutrient stocks (Willott et al., 2000).

2 Materials and methods

2.1 Study site descriptions

Plateau pikas can live in various habitats with different soil types, topographies, and microclimates. To determine how the presence of plateau pika influences the ecosystem services of alpine meadows, five survey sites were selected in Luqu (102°22′12″E, 34°15′51″N), Gangcha (100°26′26″E, 37°36′12″N), Haiyan (100°54′33″E, 36°57′50″N), Qilian (100°34′48″E, 37°43′26″N), and Gonghe (99°47′11″E, 36°43′48″N) counties on the Qinghai-Tibetan Plateau. These five survey sites have a similar typical plateau continental

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climate, with elevations ranging from 3194 m at the Gonghe survey site to 3550 m at the Luqu survey site. Based on 5-year weather data, the mean annual temperatures are 3.1, 0.9, 1.9, 2.2, 3.3°C, and the mean annual precipitation is 439.5, 258.9, 257.4, 257.0, and 239.8 mm at Luqu, Gangcha, Haiyan, Qilian, and Gonghe, respectively. According to the Chinese soil classification system (Gong, 2001), the soil type at each site is alpine meadow soil, similar to Cambisol in the WRB soil classification system.

Animal husbandry is the dominant use of alpine meadows on the Qinghai-Tibetan Plateau, and herders traditionally graze their livestock seasonally on cold and warm grasslands. The survey sites in this study were all situated in cold grasslands, in which alpine meadows were fenced from mid-April to September, and fences were opened to grazing yaks from mid-October to early April (Zhang et al., 2020). All field data were collected in August when the annual population of plateau pikas was the highest and reproduction had largely ceased (Qu et al., 2013; Pang et al., 2020a, 2020b). The summer growing season is short, and many plant species are found until late summer. Therefore, sampling in August ensured an accurate census of the plant species. Because of grazing on survey site grasslands from mid-October to early April, the litter was consumed by livestock, which enabled the aboveground biomass estimation for the summer. Notably, within each site, the plateau pika was only a small burrowing herbivore in alpine meadows.

2.2 Field survey design

Plateau pikas are social animals that usually live in low and open habitats, and their young offspring stay with their families during their birth year since they are philopatric (Smith and Wang, 1991; Dobson et al., 1998; Wang et al., 2020). Because the diffusion of

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plateau pikas is a gradual process (Pang et al., 2020a), it is easy to identify reference sites without plateau pika, even though these sites might be potential as suitable habitats. In this study, a home-range scale was used to calculate forage availability, water conservation, carbon sequestration, and soil nutrient maintenance services, and a quadrat scale was used to calculate the biodiversity conservation service.

A stratified random and paired design was used to select plots. The home range of the plateau pika was approximately 1262.5 m^2 (Fan et al., 1999), and the plot size was 35 × 35 m, which was similar to the average area of the plateau pika's home range. At each of the five sites, this study first selected 10 plots where plateau pikas were present, or where active burrow entrances were observed. The second plot was identified along the road when the first plot with plateau pikas was selected, the second plot was identified along the road. The distance between the two plots with plateau pikas was ensured to avoid overlaps among different plateau pika families. Second, a paired adjacent plot without plateau pikas and active burrow entrances was selected for each plot with plateau pikas. The distance between each plot with plateau pikas and its paired plot without plateau pikas ranged from 500 to 1000 m. If the distance between each paired plot was too close, the plateau pikas could move between plots with and without plateau pikas. To ensure that each plot with plateau pikas was paired with a plot without plateau pikas, each paired plot shared the same alpine meadow, with no obvious differences in soil type, topography, or microclimate. In total, there were 10 paired plots at each site and 100 plots across five sites, including 50 with and 50 without plateau pika.

2.3 Field sampling

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Field surveys and sampling were conducted in early August 2020. First, the active burrow entrance at each plot with plateau pikas was estimated by the "plugging tunnels method," in which the burrow entrances were plugged with hay for 3 days (Sun et al., 2015), and the number of plugs cleared by the plateau pikas to allow access to the meadow surface was recorded (Guo et al., 2012). The average number of burrow entrances with cleared plugs after 3 days was taken as the density of active burrow entrances. For plots with plateau pika, the density of active burrow entrances was used as a proxy for the intensity of the disturbance (Guo et al., 2012). Second, this study was restricted to plateau pikas in relation to the ecosystem services of alpine meadows. However, bare soil patches caused by other factors (no plateau pikas) is simultaneously existed on the vegetated surface in the presence/absence of plateau pikas. To actual quantify the effect of plateau pikas on ecosystem services of alpine meadows, this study only measured the area of bare soil patches caused by plateau pikas, although there exist multiple types of bare soil patches in alpine meadows. The area of each bare soil patch (created by plateau pikas) in the plot with plateau pikas was measured using the segmentation method (Han et al., 2011). Then, the sum of all bare soil patch areas in each plot with plateau pikas was calculated and defined as the bare soil area for that plot. Third, five vegetated quadrats (1 × 1 m) were placed on the vegetated surface approximately 8 m apart along a W pattern in all plots (with or without plateau pika), and were then moved slightly to avoid bare soil patches in plots with plateau pikas if needed. Fourth, a bare soil patch was selected as a paired bare soil quadrat for each vegetated quadrat in the plot with plateau pikas, and the distance between each paired bare soil quadrat and vegetated quadrat was as short as possible (less than 1 m). Thus, there were five paired quadrats, consisting of

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five vegetated and five bare soil quadrats in each plot with plateau pikas. Additionally, there were five vegetated quadrats in each plot without plateau pikas, since this study focused on bare soil patches induced by plateau pikas.

In each vegetated quadrat of the plot with or without plateau pikas, all vascular plant species were identified, and their numbers were recorded as plant species richness. Then, all plants rooted in a quadrat were harvested into palatable and unpalatable plants (Pang and Guo, 2017). Finally, all palatable plant samples were placed in envelopes and transported to the laboratory.

Generally, most burrows derived from plateau pika activities are less than 20 cm in depth (Yu et al., 2017b), although a few burrows extend to depths of 60 cm (Fan et al., 1999). In addition, the majority of plant roots in alpine meadows of the Qinghai-Tibetan Plateau are in the top 20 cm of the soil. The soil samples were collected at a depth of 20 cm. Soil samples were collected from vegetated and bare soil quadrats for each plot with plateau pikas and vegetated quadrats for each plot without plateau pikas. Before collecting the soil samples, plants and litter were removed from the soil surface. First, a 5 cm diameter soil auger was used to collect soil samples, which were used to measure soil organic carbon and soil nutrient concentrations (total nitrogen, phosphorus, and potassium). Second, soil profiles in each quadrat were obtained using a spade, and a stainless-steel cutting ring (with a volume of 100 cm^3) was used to collect soil cores to determine soil bulk density and soil water content. Soil samples used to determine soil bulk density were packed into aluminum boxes with recorded weights, and each aluminum box was numbered. The aluminum boxes containing fresh soil were immediately weighed, recorded, stored at 4°C, and then transported to the laboratory.

Thus, in this study, 10 soil samples were collected to analyze the soil carbon, nitrogen, phosphorus, and potassium concentrations, and 10 soil samples were obtained to determine the soil bulk density in each plot with plateau pika. Five soil samples were used to determine the soil carbon, nitrogen, phosphorus, and potassium concentrations, and five samples were obtained for the analysis of soil bulk density in each plot without plateau pikas.

2.4 Analysis of samples

In the laboratory, palatable plant samples were dried in an oven at 80°C for 48 h and weighed. The soil samples used to measure soil bulk density and soil water content were dried to a constant weight at 105±2°C, and the aluminum boxes with dry soil were weighed and the values were recorded. The soil samples used to measure soil organic carbon, total nitrogen, phosphorus, and potassium concentrations were air-dried, gravel and roots were artificially removed, and the proportion of gravel larger than 2.0 mm in the soil sample was determined by passing through a 2.0 mm sieve. Finally, the soil organic carbon, nitrogen, phosphorus, and potassium concentrations were determined by passing through a 0.15 mm sieve. Soil organic carbon and total nitrogen concentrations were measured using the $K_2Cr_2O_7$-H_2SO_4 oxidation method described by Walkey and Black (Naelson and Sommers, 1982) and the Kjeldahl procedure (Foss Kieltec 8400, FOSS, DK). The soil total phosphorus and potassium concentrations were measured using Mo-Sb colorimetry (UV-2102C, UNICO, Shanghai, China) and flame photometry (Model 2655-00 Digital Flame Analyzer, Cole-Parmer Instrument Company, Chicago, IL, USA) following the digestion of soil with perchloric acid and nitric acid (Nelson and Sommers, 1982).

Soil bulk density, soil organic carbon, and nutrient concentrations (total nitrogen,

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phosphorus, and potassium) were used to calculate the soil organic carbon, total nitrogen, phosphorus, and potassium stocks. Soil bulk density and soil water content were used to calculate the soil water storage (Jia et al., 2020).

2.5 Calculations

The bare soil area consisted of all bare soil patches, and the vegetated surface area was estimated from the plot areas minus the bare soil areas. The bare soil area in the plot with plateau pikas was estimated by adding all areas of bare soil patches. In each plot without plateau pikas, bare soil areas were considered to be zero, and the vegetated surface area was considered to be 100%.

The palatable plant biomass was calculated using the following equation:

$$GB=B_q\times\delta_{va} \quad (1)$$

where GB, B_q, and δ_{va} are the palatable plant biomass of the plot, palatable plant biomass on the quadrat scale (g m^{-2}), and vegetated surface area, respectively.

The plant species richness in a quadrat (1 × 1 m) was measured using the species number of each quadrat. Soil water storage was determined using the method recommended by Jia et al. (2020). The soil organic carbon stock per plot was estimated using the method described by Pang et al. (2020b). The soil total nitrogen, phosphorus, and potassium stocks per plot were quantified using the method described by Pang et al. (2020a).

2.6 Data analysis

All data variables (palatable plant biomass, plant species richness, soil water storage, soil organic carbon stock, soil total nitrogen stock, soil total phosphorus stock, and soil total potassium stock) were assessed for the normality and homogeneity by using the Shapiro-Wilk

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test. If necessary, the data were base-10 log-transformed to fit the assumption of normality and homogeneity for further variance analysis.

A Linear Mixed Model (LMM) with the function "lmer" from the lme4 package was used to examine differences in palatable plant biomass, plant species richness, soil water storage, soil organic carbon stock, soil total nitrogen stock, soil total phosphorus stock, and soil total potassium stock between the presence and absence of plateau pika across the five sites. In linear mixed models, the abovementioned parameters acted as response variables, the absence/presence were introduced as predictors, and the paired plots nested within each site as a random factor.

To clarify the responses of palatable plant biomass, plant species richness, soil water storage, soil organic carbon stock, soil total nitrogen stock, soil total phosphorus stock, and soil total potassium stock to the disturbance caused by plateau pikas, a linear model (LM) was used to examine the relationships between these variables and active burrow entrance densities in all plots with plateau pikas, the densities of active burrow entrances were considered a fixed factor, and were used to construct regression analysis between palatable plant biomass, plant species richness, soil water storage, soil organic carbon stock, soil total nitrogen stock, soil total phosphorus stock, soil total potassium stock, and active burrow entrance densities. To select the final regression models, likelihood ratio tests were used to compare simple linear regression and polynomial regression models. After likelihood ratio tests, the models with $p < 0.05$ and the smaller Akaike Information Criterion (AIC) were used as the final regression models.

Differences were considered significant at $p < 0.05$. All statistical analyses were

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performed with R 4.0.2 (R Foundation for Statistical Computing, Vienna, Austria).

3 Results

3.1 Effects of plateau pika presence on the ecosystem services of alpine meadows

The palatable plant biomass (Fig. 1A) and soil water storage (Fig. 1B) were lower in the plots with plateau pikas than in the plots without plateau pikas, indicating that the presence of plateau pika led to lower provisioning services of forage availability and regulating services of water conservation in alpine meadows. Whereas soil organic carbon stock (Fig. 1C), plant species richness (Fig. 1D), soil total nitrogen (Fig. 1E) and total phosphorus stocks (Fig. 1F) in the plots with plateau pikas was higher than those in the plots without plateau pikas, demonstrating that the presence of plateau pika increased the regulating services of carbon sequestration, the supporting services of biodiversity conservation, and soil nitrogen and phosphorus maintenance. In addition, there was no difference in the soil total potassium stock between the plots with and without plateau pika (Fig. 1G), indicating that the presence of plateau pika had no significant effect on the supporting service of soil potassium maintenance.

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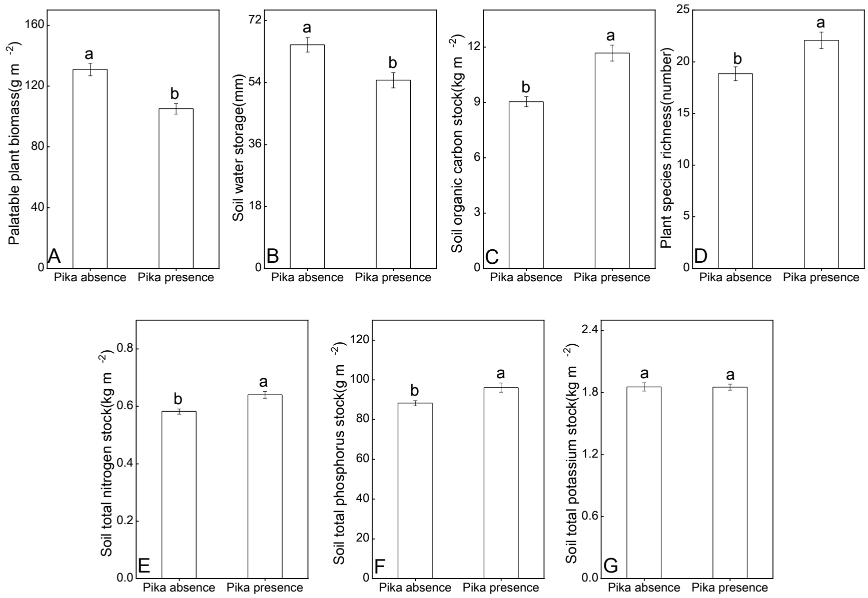

Figure 1. Palatable plant biomass (A, F = 46.254, p < 0.001), soil water storage (B, F = 35.189, p < 0.001), soil organic carbon stock (C, F = 87.628, p < 0.001), plant species richness (D, F = 63.569, p < 0.001), soil total nitrogen stock (E, F = 22.477, p < 0.001), soil total phosphorus stock (F, F = 11.724, p = 0.001), and soil total potassium stock (G, F = 0.026, p = 0.873) of plots with and without plateau pika (mean ± standard error). Lower case represents a significant difference between the absence and presence of pika based on an LMM.

3.2 Effects of plateau pika disturbance intensity on the ecosystem services of alpine meadows

The palatable plant biomass (Fig. 2A), soil organic carbon stock (Fig. 2C), plant species richness (Fig. 2D), soil total nitrogen (Fig. 2E), and phosphorus (Fig. 2F) stocks significantly increased at first and then decreased gradually as the disturbance intensity of plateau pikas increased, indicating that disturbance intensity of plateau pikas had a clear threshold for the

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provisioning services of forage availability, regulating services of carbon sequestration, supporting services of biodiversity conservation, and soil nitrogen and phosphorus maintenance. While the soil water storage of the topsoil layer (Fig. 2B) decreased linearly with increasing disturbance intensity of plateau pikas, which implied that the regulating services of water conservation of alpine meadows in the topsoil layer showed a linearly decreasing trend as the disturbance intensity of plateau pikas increased. In addition, the disturbance intensity of plateau pikas had no obvious relationship with soil total potassium (Fig. 2G).

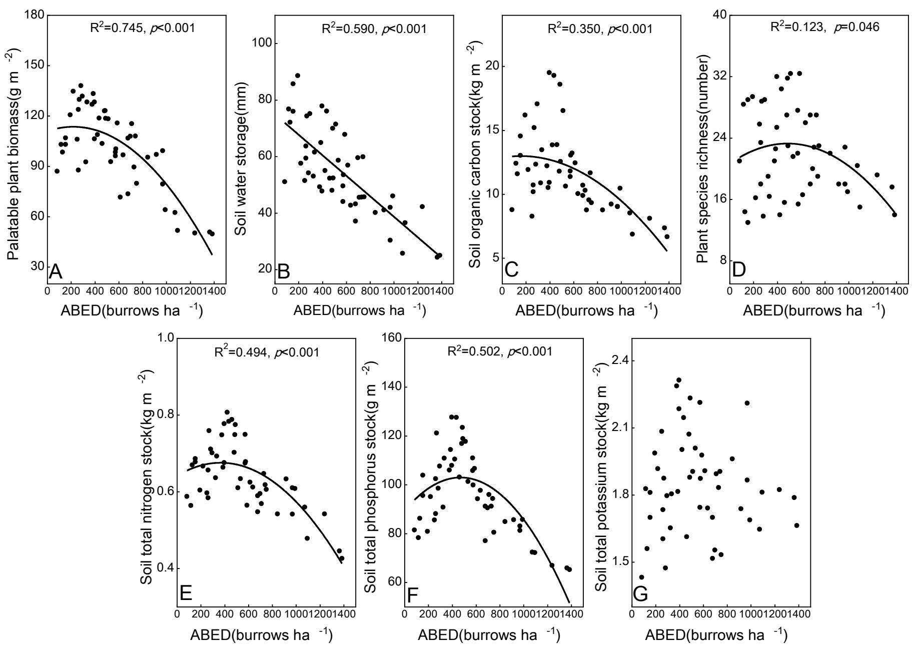

Figure 2. The palatable plant biomass (A, F = 68.534), soil water storage (B, F = 69.102), soil organic carbon stock (C, F = 12.642), plant species richness (D, F = 3.292), soil total nitrogen stock (E, F = 22.901), soil total phosphorus stock (F, F = 23.652), soil total potassium stock (G) for different disturbance intensity of plateau pika based on linear models (LMs). An

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adjusted local smoothed regression line was used to determine the relationship between the disturbance intensity and the above indicators. ABED: active burrow entrance densities

4 Discussion

Prairie dogs and European rabbits have been shown to affect grassland ecosystem services in arid and semi-arid regions (Delibes-Mateos et al., 2011; Martínez-Estévez et al., 2013). This study combined the home-range scale and a quadrat scales to test how plateau pika presence and its disturbance intensity influence the ecosystem services of alpine meadows, and found that the presence of plateau pika and its disturbance intensity indeed impacts the ecosystem services of alpine meadows, similar to prairie dogs and European rabbits in grassland ecosystem services in arid and semi-arid regions.

Plateau pika presence reduces the availability of forage services, which is consistent with the results of European rabbits in semi-arid regions (Eldridge and Myers, 2001; Delibes-Mateos et al., 2008), and is not consistent with results from prairie dogs in arid regions (Martínez-Estévez et al., 2013). Prairie dogs benefit perennial plants in arid grasslands, in which blue gramma (*Bouteluoa gracilis*) and vine mesquite (*Panicum obtusum*) are palatable perennials for livestock (Sierra-Corona et al., 2015), whereas European rabbits increase unpalatable plants (*Marrubium vulgare* and *Colchicum melitensis*) because they prefer grasses (Leigh et al., 1989; Eldridge & Myers, 2001). Plateau pikas enable more unpalatable broad-leaved plants to grow in alpine meadows (Pang and Guo, 2018) and can bury many plants (Pang and Guo, 2017). However, their consumption patterns can benefit the growth of palatable plants (Pang and Guo, 2017), because plateau pikas preferentially consume unpalatable dicotyledons (Zhao et al., 2013; Pang and Guo, 2017). The tradeoff

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between the decrease and increase in palatable plant biomass contributes to a negative effect on palatable plant biomass on a home range scale, resulting in a decrease in forage availability. These results demonstrate that the presence of small mammalian herbivores in relation to the forage availability service of grassland ecosystems may be related to environmental conditions, indicating that the presence of small mammalian herbivores is disadvantageous to the forage availability service in semi-arid and alpine regions, but it is beneficial to the forage availability service in arid regions.

Plateau pika presence leads to lower water conservation service, but higher carbon sequestration service of alpine meadows, which demonstrates that plateau pika presence has different impacts on regulating services of alpine meadows, when assessed by different indicators. Lower water conservation services of alpine meadows in relation to plateau pika presence is consistent with the effect of European rabbit presence on water conservation services of grasslands in semi-arid regions (Eldridge et al., 2010), whereas it is inconsistent with the presence of prairie dogs in relation to water conservation services in arid regions (Martínez-Estévez et al., 2013). Prairie dogs have been found to increase soil water storage in arid regions (Martínez-Estévez et al., 2013), resulting in an increase in water conservation services. In contrast, the activities of European rabbits and plateau pikas can reduce the crust cover of grasslands and increase water infiltration from top soil to deep soil in semi-arid regions (Eldridge et al., 2010; Li et al., 2015), contributing to a negative effect on water conservation services in the topsoil layer. This study shows that plateau pika presence leads to higher carbon sequestration service in alpine meadows, similar to the effect of the presence of prairie dogs in arid regions (Martínez-Estévez et al., 2013) and European rabbits in semi-arid

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regions (Delibes-Mateos et al., 2011). Plateau pikas can input extra organic matter through the deposition of uneaten food (Liu et al., 2009; Zhang et al., 2016; Yu et al., 2017a) and the excretion of urine and feces (James et al., 2009; Yu et al., 2017b), which increases the soil organic carbon stock and contributes to an increase in carbon sequestration service of alpine meadows. These results indicate that the presence of small mammalian herbivores can increase the carbon sequestration service of grasslands.

Plateau pika presence leads to higher biodiversity conservation, similar to the effect of European rabbits in semi-arid regions (Delibes-Mateos et al., 2008) and prairie dogs in arid regions (Davidson et al., 2012). The effect ascribed to higher plant species richness in the presence of small mammalian herbivores. The mechanisms by which small mammalian herbivores lead to higher plant species richness have been discussed in many previous studies (Zhang et al., 2020; Pang et al., 2021). Plateau pika presence leads to higher soil nitrogen and phosphorus maintenance services, but has no effect on soil potassium maintenance service and this effect was also observed with prairie dogs and European rabbits in arid (Delibes-Mateos et al., 2011) and semi-arid regions (Delibes-Mateos et al., 2008; Willott, 2001). Some of the following factors explain the higher soil nitrogen and phosphorus stocks caused by plateau pikas. The presence of plateau pika can increase the input of soil organic material (Liu et al., 2013; Zhang et al., 2016; Pang et al., 2020a). Secondly, plateau pika presence can result in higher organic nitrogen and phosphorus stocks (Yu et al., 2017b), which contributes to higher soil nitrogen and phosphorus maintenance services. These results suggest that a general pattern can be identified regarding the effect of the presence of small mammalian herbivores on the supporting services of biodiversity conservation, soil nitrogen,

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and phosphorus maintenance.

In addition to the presence of plateau pika, this study found that the disturbance intensity of plateau pikas also affects the meadow ecosystem in alpine regions. With the increasing disturbance intensity of plateau pikas, the forage availability, biodiversity conservation, carbon sequestration, and soil nitrogen and phosphorus maintenance services first increase and then decrease, demonstrating that there are thresholds for disturbance intensity of plateau pikas to maximize forage availability, biodiversity conservation, carbon sequestration, and soil nitrogen and phosphorus maintenance services. When the disturbance intensity is below the threshold, stronger competition of dominant sedges often restrains the grass to grow well (Pang and Guo, 2018) and the rare plants to coexist (Wang et al., 2012), which leads forage availability service and biodiversity conservation service of alpine meadows to be maintained at a low level. The increase in soil organic matter input caused by plateau pikas at low disturbance intensity is less than the threshold (Pang and Guo, 2017; Pang et al., 2020b), which enables soil organic carbon sequestration and soil nitrogen and phosphorus maintenance services of alpine meadows at low disturbance intensity to maintain a relatively low level. Once the disturbance intensity surpasses its threshold, low soil water content in alpine meadows (Liu et al., 2013) only sustains the xerophytes and mesophytes, most of which are unpalatable (Pang and Guo, 2018). This contributes to relatively low forage availability and biodiversity conservation services. Low vegetation biomass at high disturbance intensity decreases the input resources of soil organic matter (Sun et al., 2015; Pang and Guo, 2017), contributing to a decrease in soil organic carbon sequestration and soil nitrogen and phosphorus maintenance services of alpine meadows. Additionally, the linearly

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negative relationship between water conservation service of alpine meadow and disturbance intensity is ascribed to evaporation and more water infiltration on bare soil patches, as the amount of water evaporation and infiltration tends to increase as the area of bare soil increases (Liu et al., 2013).

Together with previous studies (Delibes-Mateos et al., 2011; Martínez-Estévez et al., 2013; Willott, 2001), this study demonstrates that the presence of small mammalian herbivores has similar impacts on biodiversity conservation, soil nutrient maintenance, and carbon sequestration service of grasslands throughout the arid, semi-arid, and alpine regions, whereas the effects of the presence of small mammalian herbivores on forage availability and water conservation services are dependent on environmental conditions. This study further verifies that the disturbance intensity of plateau pikas also has a significant impact on the ecosystem services of alpine ecosystems. These results concur with the findings in research fields of small mammalian herbivores in relation to grassland ecosystem services.

5 Conclusions

This study focused on plateau pikas to investigate the responses of forage availability, water conservation, carbon sequestration, soil nutrient maintenance, and biodiversity conservation services of meadow ecosystems to the presence of a small mammalian herbivore and its disturbance intensity across five sites. This will provide insight into the relationship between small mammalian herbivores and ecosystem services of grasslands. The results of this study showed that the presence of plateau pika led to higher biodiversity conservation, soil nitrogen and phosphorus maintenance, and carbon sequestration service of alpine meadows, whereas it led to lower forage availability and water conservation services of alpine

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meadows. Furthermore, this study found that the disturbance intensity of plateau pikas had thresholds for maximizing forage availability, biodiversity conservation, soil maintenance of nitrogen and phosphorus, and carbon sequestration services. These results verified that plateau pikas could affect the ecosystem services of meadow ecosystems in alpine regions and present a relatively complete pattern of small mammalian herbivores influencing grassland ecosystem services.

Author contributions. YC and ZG conceived the ideas and designed the methodology; YC, XP, GB and HY collected the data; YC analysed the data; YC and ZG wrote the manuscript. All of the authors contributed critically to the drafts and gave their final approval for publication.

Competing interests. The authors declare that they have no known competing financial interests or personal relationships that could have influenced to influence the work reported in this paper.

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