

1 **Effect of the presence of plateau pikas on the ecosystem services of alpine meadows**

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12

13 **Abstract**

14 The activity of small mammalian herbivores influences grassland ecosystem services in arid
15 and semi-arid regions. Plateau pika (*Ochotona curzoniae*) was considered as a focal organism
16 to investigate the effect of small mammalian herbivores on meadow ecosystem services in
17 alpine regions. In this study, a home-range scale was used to measure the forage available to
18 livestock, water conservation, carbon sequestration, and soil nutrient maintenance (total
19 nitrogen, phosphorus, and potassium) in the topsoil layer; and a quadrat scale was used to
20 assess the biodiversity conservation of alpine meadows. This study showed that the forage
21 available to livestock and water conservation were 19 % and 16 % lower in the presence of
22 plateau pikas than in their absence, and biodiversity conservation, carbon sequestration, soil
23 nitrogen, and phosphorus maintenance were 15 %, 29 %, 10 % and 8.9 % higher in the
24 presence of plateau pikas than in their absence. In contrast, it had no impact on soil potassium
25 maintenance of meadow ecosystems in alpine regions. The forage available to livestock,
26 biodiversity conservation, and soil nutrient maintenance of meadow ecosystems in alpine
27 regions had maximum values as the disturbance intensity of plateau pikas increased; the water
28 conservation tended to decrease linearly with the increasing disturbance intensity of plateau
29 pikas. These results present a pattern of plateau pikas influencing the ecosystem services of
30 meadow ecosystems in alpine regions, enriching our understanding of the small mammalian
31 herbivores in relation to and grassland ecosystem service.

32 **1 Introduction**

33 Grasslands provide multiple ecosystem services, mainly including provisioning services
34 of food and water, regulating services of carbon sequestration and water conservation,
35 supporting services of soil nutrient maintenance and biodiversity conservation, and cultural

36 services of landscapes and recreation tourism (Millennium Ecosystem Assessment, 2005;
37 Bai and Cotrufo, 2022; Buisson et al., 2022; Strömberg and Staver, 2022). These ecosystem
38 services sustain animal production, flora and fauna, and other human welfare (Costanza et al.,
39 1997; Zhang et al., 2018; Dong et al., 2020); however, they are affected by multiple biotic
40 factors, such as soil microbial communities (Van Eekeren et al., 2010), grazing by large
41 herbivores (Lu et al., 2017), and the presence of small herbivores (Delibes-Mateos et al.,
42 2011; Martínez-Estévez et al., 2013).

43 Small mammalian herbivores are common biotic factors (Davidson et al., 2012). These
44 herbivores usually create extensive disturbances on grassland vegetation and soil (Pang et al.,
45 2020a, 2020b) by developing burrow systems (Delibes-Mateos et al., 2008; Sun et al., 2015),
46 excreting feces and urine (Zhang et al., 2016), consuming plants (Eldridge and Myers, 2001;
47 Liu et al., 2017), clipping tall plants (Zhang et al., 2020), and producing bare soil patches
48 (Guo et al., 2012a, 2012b; Yu et al., 2017a, 2017b) or mounds (Yang et al., 2021). Previous
49 studies have shown that the presence of prairie dogs (*Cynomys ludovicianus*) can increase the
50 forage available to livestock, water conservation, carbon sequestration, and biodiversity
51 conservation of grassland ecosystems in arid regions (Ceballos et al., 1999, Martínez-Estévez
52 et al., 2013), whereas the presence of European rabbit (*Oryctolagus cuniculus*) can decrease
53 the forage available to livestock (Delibes-Mateos et al., 2008; Eldridge and Myers, 2001), and
54 increase the biodiversity conservation (Delibes-Mateos et al., 2008) and nitrogen maintenance
55 (Willott et al., 2000) of grassland ecosystems in semi-arid regions. In addition to grasslands in
56 arid and semi-arid regions, vast alpine meadows exist in high latitude and altitude regions
57 throughout the world (Zhang et al., 2018; Dong et al., 2020). However, how small

58 mammalian herbivores influence the ecosystem services in alpine meadows as much as they
59 do in arid and semi-arid regions has not been well documented.

60 The plateau pika (*Ochotona curzoniae*) is a common, small mammalian herbivore that
61 mainly lives in alpine meadows of the Qinghai-Tibetan Plateau (Smith and Foggin, 1999).
62 This small mammalian herbivore with an average weight of 150 g are diurnally active and
63 non-hibernating (Smith and Wang, 1991; Fan et al., 1999), and preferentially consume
64 dicotyledons (Zhao et al., 2013; Pang and Guo, 2017). Plateau pikas, a sexual monomorphism
65 (Dobson et al., 1998) , often construct a family warren with numerous burrow entrances and
66 develop a complex burrow system with an average length and depth of 13 m and 30 cm (Fan
67 et al., 1999). This mammalian herbivore is social and philopatric (Dobson et al., 1998) and its
68 young offspring stay with its family during its birth year (Wang et al., 2020). Plateau pikas are
69 generally considered a pest in China (Harris, 2010; Pang and Guo, 2017) as they often
70 exacerbate the degradation of alpine meadows (Liu et al., 2013; Zhang et al., 2016). However,
71 some studies have argued that plateau pika is a key species in alpine meadow ecosystems
72 (Smith and Foggin, 1999; Delibes-Mateos et al., 2011). This disagreement has encouraged
73 professionals to re-evaluate the role of plateau pikas in alpine meadow ecosystems. Thus, the
74 effects of plateau pikas' presence on ecosystem services of alpine meadows allow insight into
75 the role of plateau pikas in alpine meadow ecosystems. Previous studies have demonstrated
76 that the presence of plateau pikas decreases (Liu et al., 2013) or has no significant effect on
77 plant biomass (Pang and Guo, 2017), increases (Liu et al., 2017; Pang and Guo, 2017) or
78 decreases (Sun et al., 2015) plant-species richness, and increases (Yu et al., 2017a; Pang et al.,
79 2020a, 2020b) or decreases (Sun et al., 2015) soil carbon and nutrients. In addition, previous

80 studies have shown that the disturbance intensity of plateau pikas affects plant-species
81 richness, and soil nutrient stocks of alpine meadows (Yu et al., 2017a; Pang and Guo, 2018).
82 These findings imply that plateau pikas may have an impact on the ecosystem services of
83 alpine meadows. Thus, further studies are needed to test whether the presence of plateau pikas
84 and its disturbance intensity influence the ecosystem services of alpine meadows, which can
85 enrich our understanding of the presence of small mammalian herbivores in relation to
86 grassland ecosystem services.

87 Since soil carbon and nutrients differ between vegetated and bare soil patches in the
88 home range (Yu et al., 2017b), Pang et al. (2020a; 2020b) proposed that the home-range scale
89 is a better proxy than the quadrat scale to estimate the complete effects of the presence of
90 plateau pikas on soil carbon and nutrient stocks. Although the provisioning, regulation,
91 support, and cultural services of alpine meadows can be estimated by multiple indicators
92 (Egoh et al., 2012; Brown et al., 2014), one or two can be used to verify whether the presence
93 and intensity of plateau pikas influence each ecosystem service. In previous studies, palatable
94 plant biomass for livestock has been used to evaluate the provisioning services
95 (Martínez-Estévez et al., 2013; Wen et al., 2013); soil-water storage and soil organic carbon
96 stock have been used to evaluate the regulating services (Wen et al., 2013; Li and Xie, 2015;
97 Tang et al., 2019;); and plant-species richness and soil total nutrient stocks can be used to
98 evaluate the supporting services (Wen et al., 2013). Notably, cultural services are particularly
99 related to the spatial scale, as many are perceived visually over distant views (Norton et al.,
100 2012). The plateau pika is territorial and its habitat use is patchy within a given area (Pang et
101 al., 2020a), which leads to mismatches between the spatial scale and cultural services (De

102 Groot et al., 2010). Therefore, the present study used ecological services of forage available to
103 livestock, water conservation, carbon sequestration and soil nutrient maintenance, and
104 biodiversity conservation to test how the presence of plateau pikas influences the ecosystem
105 services of alpine meadows across five sites. In this study, we hypothesized that (1) the
106 presence of plateau pikas leads to lower forage available to livestock because of lower
107 palatable plant biomass in the presence of small mammalian herbivores; (2) the presence of
108 plateau pikas leads to higher water conservation and carbon sequestration because small
109 mammalian herbivores can increase soil-water storage and carbon stocks; and (3) the
110 presence of plateau pikas leads to higher biodiversity conservation and soil nutrient
111 maintenance because small mammalian herbivores can increase plant-species richness and
112 soil nutrient stocks.

113 **2 Materials and methods**

114 **2.1 Study site descriptions**

115 Plateau pikas can live in various habitats with different soil types, topographies, and
116 microclimates on the Qinghai-Tibetan Plateau. To determine how the presence of plateau
117 pikas generally influences the ecosystem services of alpine meadows, five survey sites were
118 selected in Luqu (102°22'12"E, 34°15'51"N), Gangcha (100°26'26"E, 37°36'12"N), Haiyan
119 (100°54'33"E, 36°57'50"N), Qilian (100°34'48"E, 37°43'26"N), and Gonghe (99°47'11"E,
120 36°43'48"N) counties on the Qinghai-Tibetan Plateau. These five survey sites have a similar
121 typical plateau continental climate, with elevations ranging from 3194 m at the Gonghe
122 survey site to 3550 m at the Luqu survey site. Based on 5-year weather data, the mean annual
123 temperatures are 3.1, 0.9, 1.9, 2.2, 3.3 °C at Luqu, Gangcha, Haiyan, Qilian, and Gonghe,

124 respectively, of which the average temperature in warm season are 9.3, 8.3, 9.6, 10.3, 9.9 °C
125 and in cold season are -3.1, -6.5, -5.8, -5.9, -3.4 °C. The mean annual precipitation is 439.5,
126 258.9, 257.4, 257.0, and 239.8 mm, of which the warm season accounts for 83.4 %, 92.8 %, 89.3 %, 91.5 %, 91.4 % at Luqu, Gangcha, Haiyan, Qilian, and Gonghe, respectively.
127
128 According to the Chinese soil classification system (Gong, 2001), the soil type at each site is
129 alpine meadow soil, similar to Cambisol in the WRB soil classification system.

130 Animal husbandry is the dominant use of alpine meadows on the Qinghai-Tibetan
131 Plateau, and herders traditionally graze their livestock seasonally on cold and warm
132 grasslands. The survey sites in this study were all situated in cold grasslands, in which alpine
133 meadows were fenced from mid-April to September, and fences were opened to grazing yaks
134 from mid-October to early April (Zhang et al., 2020). All field data were collected in August
135 when the annual population of plateau pikas was the highest and reproduction had largely
136 ceased (Qu et al., 2013; Pang et al., 2020a, 2020b). In addition, the growing season for plants
137 is short on the Qinghai-Tibetan Plateau, and some plants don't turn green until July. Therefore,
138 sampling in August is optimal because August is good time to identify all plants and ensure
139 an accurate survey of the plant species. Notably, the small burrowing herbivore at each survey
140 site was only plateau pikas.

141 **2.2 Field survey design**

142 The adult dispersal of plateau pikas is a gradual process (Pang et al., 2020a), it is easy to
143 identify reference sites without plateau pikas, even though these sites might be potential as
144 suitable habitats. In this study, a home-range scale was used to calculate the forage available
145 to livestock, water conservation, carbon sequestration, and soil nutrient maintenance, and a

146 quadrat scale was used to calculate the biodiversity conservation.

147 A stratified random and paired design was used to select plots. The home range of the
148 plateau pika was approximately 1262.5 m² (Fan et al., 1999), and the plot size was 35 × 35 m,
149 which was similar to the average area of the plateau pika's home range. At each of the five
150 sites, this study first selected 10 plots where plateau pikas were present, or where active
151 burrow entrances were observed. The second plot was identified along the road when the first
152 plot with plateau pikas was selected. The distance between the two plots with plateau pikas
153 was more than 3 km, which ensured that plateau pikas of the same family would not appear in
154 two plots at the same time. Second, a paired adjacent plot without plateau pikas and active
155 burrow entrances was selected for each plot with plateau pikas. The plots without plateau
156 pikas were in any direction of plots with plateau pikas. The distance between each plot with
157 plateau pikas and its paired plot without plateau pikas ranged from 500 to 1000 m. If the
158 distance between each paired plot was too close, the plateau pikas could move between plots
159 with and without plateau pikas. To ensure that each plot with plateau pikas was paired with a
160 plot without plateau pikas, each paired plot shared the alpine meadow with same dominant
161 plant, with no obvious differences in soil type, topography, or microclimate. In total, there
162 were 10 paired plots at each site and 100 plots across five sites, including 50 with and 50
163 without plateau pikas. Each paired plot shared the same grazing intensity during the cold
164 season; however, 50 paired plots consisted of different yak grazing intensity, and this can
165 permit the general pattern relating to the effect of plateau pika disturbance on alpine meadow
166 ecosystem services.

167 **2.3 Field sampling**

168 Field surveys and sampling were conducted in early August 2020. First, the active
169 burrow entrance at each plot with plateau pikas was estimated by the “plugging tunnels
170 method,” in which the burrow entrances were plugged with hay for 3 days (Sun et al., 2015),
171 and the number of plugs cleared by the plateau pikas to allow access to the meadow surface
172 was recorded (Guo et al., 2012a). The average number of burrow entrances with cleared plugs
173 after 3 days was taken as the density of active burrow entrances. For plots with plateau pikas,
174 the density of active burrow entrances was used as a proxy for the intensity of the disturbance
175 (Guo et al., 2012a; Sun et al., 2015). Second, this study was restricted to plateau pikas in
176 relation to the ecosystem services of alpine meadows. However, bare soil patches caused by
177 other factors (no plateau pikas) is simultaneously existed on the vegetated surface in the
178 presence/absence of plateau pikas. To actual quantify the effect of plateau pikas on ecosystem
179 services of alpine meadows, this study only measured the area of bare soil patches caused by
180 plateau pikas, although there exist multiple types of bare soil patches in alpine meadows. The
181 soil bare patches caused by plateau pikas is easily to identify because one soil bare patch
182 caused by plateau pikas is paired with a visible burrow entrance (Pang et al., 2021a). Other
183 soil bare patches are not paired with visible burrow entrance. The area of each bare soil patch
184 (created by plateau pikas) in the plot with plateau pikas was measured. Each bare soil patch
185 was identified as regular shape or irregular shape. If one bare soil patch was identified as
186 regular shape, such as rectangle, circle, trapezoid, etc; a ruler was used to measure its length,
187 width, height, diameter, upper and lower bottom, and these data was used to calculate the area
188 of that bare soil patch. If one bare soil patch was identified as irregular shape, this bare soil
189 patch was divided into several regular shapes; the areas of these regular shapes were

190 calculated, respectively; the area sum of these regular shapes form irregular bare soil patch
191 was considered as the area of that irregular bare soil patch (Han et al., 2011). Then, the sum of
192 all bare soil patch areas in each plot with plateau pikas was calculated and defined as the bare
193 soil area for that plot. Third, five vegetated quadrats (1 × 1 m) were placed on the vegetated
194 surface approximately 8 m apart along the shape of a W pattern in all plots (with or without
195 plateau pikas). In plot with plateau pikas, if quadrat was justly covered with the bare patches
196 caused by plateau pikas, the quadrat was slightly moved to avoid it; if quadrat was justly
197 covered with the bare patches caused by other factors, the quadrat was not moved. Fourth,
198 alpine meadows in plot with plateau pikas consisted of bare and vegetated surface, and a bare
199 soil patch was selected as a paired bare soil quadrat for each vegetated quadrat in the plot with
200 plateau pikas, and the distance between each paired bare soil quadrat and vegetated quadrat
201 was as short as possible (less than 1 m). Bare soil patch quadrat and each vegetated quadrat
202 were beneficial to accurately measure the soil nutrient, carbon concentrations and plant
203 biomass, which reflected the effect of plateau pikas' presence on ecosystem services in alpine
204 meadows by comparing the parameters between plots with and without plateau pikas at home
205 range scale. Thus, there were 5 paired quadrats, consisting of 5 vegetated and 5 bare soil
206 quadrats in each plot with plateau pikas. Additionally, there were 5 vegetated quadrats in each
207 plot without plateau pikas, since this study focused on bare soil patches induced by plateau
208 pikas.

209 In each vegetated quadrat of the plot with or without plateau pikas, all vascular plant
210 species were identified, and the number of plant species were recorded as plant-species
211 richness. Then, all plants rooted in a quadrat were harvested into palatable and unpalatable

212 plants, in which palatable plants or unpalatable plants were for yak and Tibetan sheep (Pang
213 and Guo, 2017). Finally, all palatable plant samples were placed in envelopes and transported
214 to the laboratory.

215 Generally, most burrows derived from the activities of plateau pikas are less than 20 cm
216 in depth (Yu et al., 2017b), although a few burrows extend to depths of 60 cm (Fan et al.,
217 1999). In addition, the majority of plant roots in alpine meadows of the Qinghai-Tibetan
218 Plateau are in the top 20 cm of the soil. The soil samples were collected at a depth of 20 cm.
219 Soil samples were collected from vegetated and bare soil quadrats for each plot with plateau
220 pikas and vegetated quadrats for each plot without plateau pikas. Before collecting the soil
221 samples, plants and litter were removed from the soil surface. First, a 5 cm diameter soil
222 auger was used to collect soil samples, which were used to measure soil organic carbon and
223 soil nutrient concentrations (total nitrogen, phosphorus, and potassium). Second, soil profiles
224 in each quadrat were obtained using a spade, and a stainless-steel cutting ring (with a volume
225 of 100 cm³) was used to collect soil cores to determine soil bulk density and soil water
226 content. Soil samples used to determine soil bulk density were packed into aluminum boxes
227 with recorded weights, and each aluminum box was numbered. The aluminum boxes
228 containing fresh soil were immediately weighed, recorded, stored at 4 °C, and then
229 transported to the laboratory. Thus, in this study, 10 soil samples were collected to analyze the
230 soil carbon, nitrogen, phosphorus, and potassium concentrations, and 10 soil samples were
231 obtained to determine the soil bulk density in each plot with plateau pikas. Because this study
232 is constricted with bare soil patch caused by plateau pikas, bare soil quadrats was not
233 considered in plot without plateau pikas; therefore, 5 soil samples were used to determine the

234 soil carbon, nitrogen, phosphorus, and potassium concentrations, and 5 samples were obtained
235 for the analysis of soil bulk density in each plot without plateau pikas. 5 soil samples in each
236 plot were individually measured. The average value of five soil samples in one plot was
237 considered as the representative data of that plot.

238 **2.4 Analysis of samples**

239 In the laboratory, palatable plant samples were dried in an oven at 80 °C for 48 h and
240 weighed. The soil samples used to measure soil bulk density and soil-water content were
241 dried to a constant weight at 105±2 °C, and the aluminum boxes with dry soil were weighed
242 and the values were recorded. The soil samples used to measure soil organic carbon, total
243 nitrogen, phosphorus, and potassium concentrations were air-dried, gravel and roots were
244 manually picked out, and the proportion of gravel larger than 2.0 mm in the soil sample was
245 determined by passing through a 2.0 mm sieve. Finally, soil samples were sieved at 0.15 mm
246 to analyze soil organic carbon, nitrogen, phosphorus, and potassium concentrations in the
247 laboratory. Soil organic carbon was measured using the dichromate heating-oxidation
248 (Naelson and Sommers, 1982). Soil total nitrogen concentration was measured using the
249 Kjeldahl procedure. Soil total phosphorus concentration was measured using the
250 Molybdenum blue colorimetric method. Soil total potassium concentration was measured
251 using flame photometry.

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

256 2.5 Calculations

257 The bare soil area consisted of all bare soil patches, and the vegetated surface area was
258 estimated from the plot areas minus the bare soil areas. This study only measured the area of
259 bare soil patches caused by plateau pikas, although there were other kinds of bare soil patches
260 in alpine meadows. Therefore, bare soil areas caused by plateau pikas were considered to be
261 zero in each plot without plateau pikas, and the vegetated surface area was considered to be
262 100%.

263 The palatable plant biomass was calculated using the following equation:

$$264 \quad GB = B_q \times \delta_{va} \quad (1)$$

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

267 The plant-species richness in a quadrat ($1 \times 1 \text{ m}$) was measured using the species number
268 of each quadrat.

269 Soil-water storage was determined using the method recommended by Jia et al. (2020),
270 and it was calculated by the following equation:

$$271 \quad SWS_{pika} = (SWC_{BA} \times BD_{BA} \times T \times (1 - \theta_{BA}) \times 0.01 \times BA) + (SWC_{VA} \times BD_{VA} \times T \times (1 - \theta_{VA}) \times 0.01 \times VA) \quad (2)$$

272 Where SWS_{pika} , SWC_{BA} , BD_{BA} , and θ_{BA} were soil-water storage in a plot with plateau
273 pikas, water content (g kg^{-1}), soil bulk density (g cm^{-3}) and soil fraction of gravel larger than 2
274 mm in bare soil areas of plots with plateau pikas, respectively; BA was the percentage of
275 bare soil areas in plots with plateau pikas; SWC_{VA} , BD_{VA} , and θ_{VA} were water content (g kg^{-1}),
276 soil bulk density (g cm^{-3}) and soil fraction of gravel larger than 2 mm in vegetated areas of a
277 plot with plateau pikas, respectively; and T was soil thickness (20 cm); VA was the percentage

278 of vegetated surface area in plots with plateau pikas; SWC_{BA} and SWC_{VA} was measured by
279 oven drying method.

$$280 \quad SWS_{no\ pika} = SWC_{no\ pika} \times BD_{no\ pika} \times T \times (1 - \theta_{no\ pika}) \times 0.01 \times 100\% \quad (3)$$

281 Where $SWS_{no\ pika}$, $SWC_{no\ pika}$, $BD_{no\ pika}$ and $\theta_{no\ pika}$ were soil-water storage in a plot without
282 plateau pikas, soil water content ($g\ kg^{-1}$), soil bulk density ($g\ cm^{-3}$) and soil fraction of gravel
283 larger than 2 mm in plots without plateau pikas, respectively; and T is soil thickness (20 cm).

284 The soil organic carbon stock per plot was estimated using the method described by Pang
285 et al. (2020b), and it was calculated by following equation:

$$286 \quad SOCS_{pika} = (SOC_{BA} \times BD_{BA} \times T \times (1 - \theta_{BA}) \times 0.01 \times BA) + (SOC_{VA} \times BD_{VA} \times T \times (1 - \theta_{VA}) \times 0.01 \times VA) \quad (4)$$

287 Where $SOCS_{pika}$ was soil organic carbon stock in a plot with plateau pikas ($kg\ m^{-2}$);
288 SOC_{BA} , BD_{BA} , and θ_{BA} were soil organic carbon concentration ($g\ kg^{-1}$), soil bulk density (g
289 cm^{-3}) and soil fraction of gravel larger than 2 mm in bare soil areas of plots with plateau pikas,
290 respectively; BA was the percentage of bare soil areas in plots with plateau pikas; SOC_{VA} ,
291 BD_{VA} , and θ_{VA} were organic carbon concentration ($g\ kg^{-1}$), soil bulk density ($g\ cm^{-3}$) and soil
292 fraction of gravel larger than 2 mm in vegetated areas of a plot with plateau pikas,
293 respectively; and T was soil thickness (20 cm); VA was the percentage of vegetated surface
294 area in plots with plateau pikas.

$$295 \quad SOCS_{no\ pika} = SOC_{no\ pika} \times BD_{no\ pika} \times T \times (1 - \theta_{no\ pika}) \times 0.01 \times 100\% \quad (5)$$

296 Where $SOCS_{no\ pika}$ was soil organic carbon stock in the plot without plateau pikas (kg
297 m^{-2}); and $SOC_{no\ pika}$, $BD_{no\ pika}$ and $\theta_{no\ pika}$ were soil organic carbon concentration ($g\ kg^{-1}$), soil
298 bulk density ($g\ cm^{-3}$) and soil fraction of gravel larger than 2 mm in plots without plateau
299 pikas, respectively; and T was soil thickness (20 cm).

300 The soil total nitrogen, phosphorus, and potassium stocks per plot were quantified using

301 the method described by Pang et al. (2020a), and it was calculated by the following
302 equation:

$$303 \quad SNSi_{pika} = (SNi_{BA} \times BD_{BA} \times T \times (1 - \theta_{BA}) \times 0.01 \times BA) + (SNi_{VA} \times BD_{VA} \times T \times (1 - \theta_{VA}) \times 0.01 \times VA) \quad (6)$$

304 Where $SNSi_{pika}$ was soil total nitrogen, phosphorus, potassium stock in plot with plateau
305 pikas (kg m^{-2}), and SNi_{BA} , BD_{BA} , and θ_{BA} were soil nutrient concentration (g kg^{-1}), soil bulk
306 density (g cm^{-3}) and soil fraction of gravel larger than 2 mm in bare soil area of plots with
307 plateau pikas, respectively; BA was the percentage of bare soil areas in plots with plateau
308 pikas; SNi_{VA} , BD_{VA} , and θ_{VA} were soil nutrient concentration (g kg^{-1}), soil bulk density (g cm^{-3})
309 and soil fraction of gravel larger than 2 mm in vegetated areas of a plot with plateau pikas,
310 respectively; and T was soil thickness (20 cm); VA was the percentage of vegetated surface
311 area in plots with plateau pikas.

$$312 \quad SNSi_{no\ pika} = SNi_{no\ pika} \times BD_{no\ pika} \times T \times (1 - \theta_{no\ pika}) \times 0.01 \times 100\% \quad (7)$$

313 Where $SNSi_{no\ pika}$ was soil total nitrogen, phosphorus, potassium stock in the plot without
314 plateau pikas (kg m^{-2}), $SNi_{no\ pika}$, $BD_{no\ pika}$ and $\theta_{no\ pika}$ were soil nutrient concentration (g kg^{-1}),
315 soil bulk density (g cm^{-3}) and soil fraction of gravel larger than 2 mm in plots without plateau
316 pikas, respectively; and T was soil thickness (20 cm).

317 2.6 Data analysis

318 Data from 50 disturbed plots and 50 undisturbed plots were used to examine the
319 difference in ecosystem services of alpine meadows between the presence of plateau pikas
320 and the absence of plateau pikas; and then data from 50 disturbed plots were used to examine
321 the responses of each ecosystem service of alpine meadows to the disturbance intensity of
322 plateau pikas.

323 All data variables (palatable plant biomass, plant-species richness, soil-water storage,

324 soil organic carbon stock, soil total nitrogen stock, soil total phosphorus stock, and soil total
325 potassium stock) were assessed for the normality and homogeneity by using the Shapiro-Wilk
326 test. If necessary, the data were base-10 log-transformed to fit the assumption of normality
327 and homogeneity for further variance analysis.

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

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

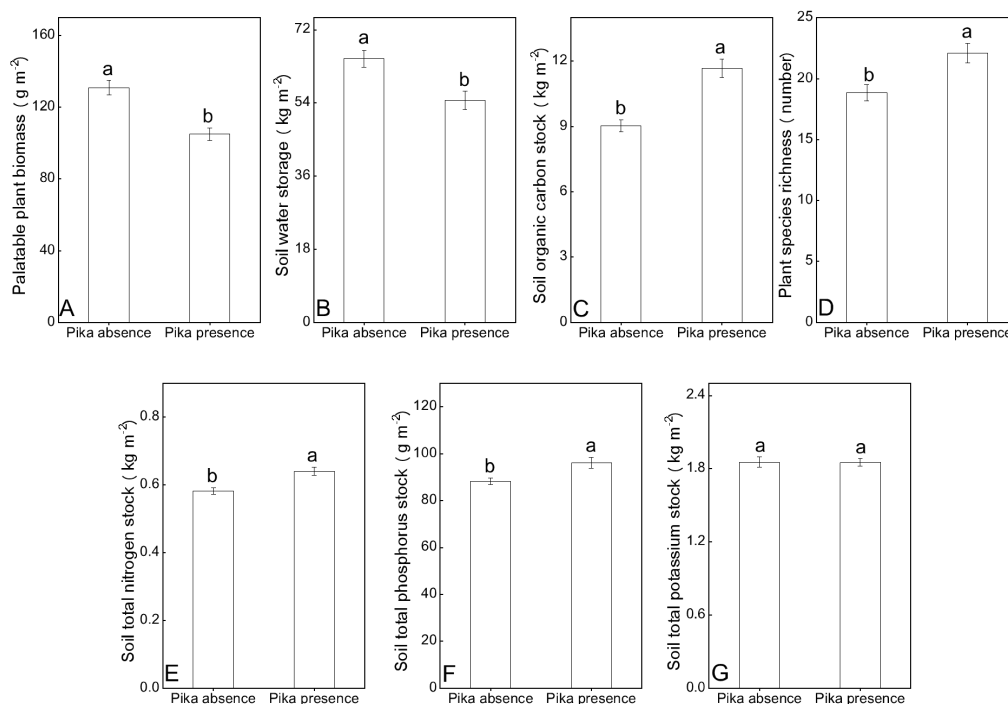
346 as the final regression models.

347 The Bonferroni's test used to adjust P values and made to correct for experiment-wise
348 error rates. All statistical analyses were performed with R 4.0.2 (R Foundation for Statistical
349 Computing, Vienna, Austria).

350 3 Results

351 3.1 Effects of the presence of plateau pikas on the ecosystem services of alpine meadows

352 The palatable plant biomass (Fig. 1A) and soil-water storage (Fig. 1B) were 19 % and
353 16 % lower in the plots with plateau pikas than in the plots without plateau pikas, whereas
354 soil organic carbon stock (Fig. 1C), plant-species richness (Fig. 1D), soil total nitrogen (Fig.
355 1E) and total phosphorus stocks (Fig. 1F) in the plots with plateau pikas were 29 %, 15 %,
356 10 % and 8.9 % higher than those in the plots without plateau pikas. In addition, there was no
357 difference in the soil total potassium stock between the plots with and without plateau pikas
358 (Fig. 1G).

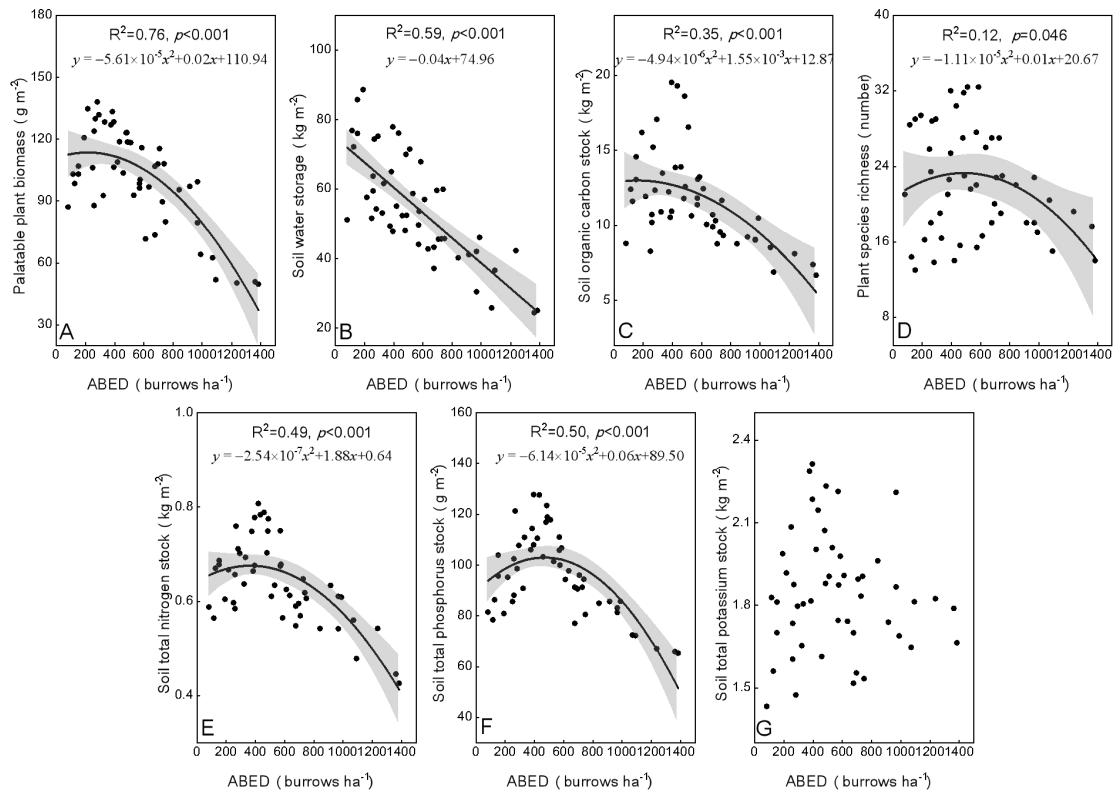


359

360 **Figure 1.** Palatable plant biomass (A, $F = 46$, $p < 0.001$), soil-water storage (B, $F = 35$, $p <$
361 0.001), soil organic carbon stock (C, $F = 88$, $p < 0.001$), plant-species richness (D, $F = 64$, $p =$
362 0.003), soil total nitrogen stock (E, $F = 22$, $p < 0.001$), soil total phosphorus stock (F, $F = 12$,
363 $p = 0.004$), and soil total potassium stock (G, $F = 0.03$, $p = 0.88$) of plots with and without
364 plateau pikas (mean \pm standard error). Lower case represents a significant difference between
365 the absence and presence of pika based on an LMM.

366 **3.2 Effects of plateau pikas' disturbance intensity on the ecosystem services of alpine** 367 **meadows**

368 The palatable plant biomass (Fig. 2A), soil organic carbon stock (Fig. 2C), plant-species
369 richness (Fig. 2D), soil total nitrogen (Fig. 2E), and phosphorus (Fig. 2F) stocks had the
370 maximum values as the plateau pikas' disturbance intensity increased. While the soil-water
371 storage of the topsoil layer (Fig. 2B) decreased linearly with increasing disturbance intensity
372 of plateau pikas. In addition, the disturbance intensity of plateau pikas had no obvious
373 relationship with soil total potassium (Fig. 2G).



374

375 **Figure 2.** The palatable plant biomass (A, F = 69), soil-water storage (B, F = 69), soil organic
 376 carbon stock (C, F = 13), plant-species richness (D, F = 3.3), soil total nitrogen stock (E, F =
 377 23), soil total phosphorus stock (F, F = 24), soil total potassium stock (G) for different
 378 disturbance intensity of plateau pikas based on linear models (LMs). An adjusted local
 379 smoothed regression line (black) with its 95 % confident interval (gray) was used to
 380 determine the relationship between the disturbance intensity of plateau pikas and the above
 381 indicators. ABED: active burrow entrance densities

382 4 Discussion

383 Prairie dogs and European rabbits have been shown to affect grassland ecosystem
 384 services in arid and semi-arid regions (Delibes-Mateos et al., 2011; Martínez-Estévez et al.,
 385 2013). This study combined the home-range scale and a quadrat scales to test how the
 386 presence of plateau pikas and its disturbance intensity influence the ecosystem services of

387 alpine meadows, and found that the presence of plateau pikas and its disturbance intensity
388 indeed impacts the ecosystem services of alpine meadows, similar to prairie dogs and
389 European rabbits in grassland ecosystem services in arid and semi-arid regions.

390 Lower palatable plant biomass in the presence of plateau pikas indicates that the
391 presence of plateau pikas reduces the forage available to livestock, which is consistent with
392 the results of European rabbits in semi-arid regions (Eldridge and Myers, 2001;
393 Delibes-Mateos et al., 2008), and is not consistent with results from prairie dogs in arid
394 regions (Martínez-Estévez et al., 2013). Prairie dogs benefit perennial plants in arid
395 grasslands, in which blue gramma (*Bouteloua gracilis*) and vine mesquite (*Panicum obtusum*)
396 are palatable perennials for livestock (Sierra-Corona et al., 2015), whereas European rabbits
397 increase unpalatable plants (*Marrubium vulgare* and *Colchicum melitensis*) because they
398 prefer grasses (Leigh et al., 1989; Eldridge and Myers, 2001). Plateau pikas enable more
399 unpalatable broad-leaved plants to grow in alpine meadows (Pang and Guo, 2018) and can
400 bury many plants (Pang and Guo, 2017). However, their consumption patterns can benefit the
401 growth of palatable plants (Pang and Guo, 2017), because plateau pikas preferentially
402 consume unpalatable dicotyledons (Zhao et al., 2013; Pang and Guo, 2017). The tradeoff
403 between the decrease and increase in palatable plant biomass contributes to a negative effect
404 on palatable plant biomass on a home-range scale, resulting in a decrease in the forage
405 available to livestock. These results demonstrate that the presence of small mammalian
406 herbivores affects the forage available to livestock of grassland ecosystems may be related to
407 environmental conditions. Specific performance is that the presence of small mammalian
408 herbivores is disadvantageous to the forage available to livestock in semi-arid and alpine

409 regions, but it is beneficial to forage available to livestock in arid regions.

410 The presence of plateau pikas has different impacts on regulating services of alpine
411 meadows, when assessed by different indicators. The presence of plateau pikas leads to lower
412 soil-water storage, resulting in a decrease in the water conservation, whereas the presence of
413 plateau pikas can lead to higher soil organic carbon stock, implying that the presence of
414 plateau pikas can increase the carbon sequestration. Lower water conservation of alpine
415 meadows in relation to the presence of plateau pikas is consistent with the effect of European
416 rabbits' presence on the water conservation of grasslands in semi-arid regions (Eldridge et al.,
417 2010), whereas it is inconsistent with the presence of prairie dogs in relation to the water
418 conservation in arid regions (Martínez-Estévez et al., 2013). This difference is ascribed to
419 evaluation indicators for the water conservation. The water infiltration rate is considered as an
420 index to evaluate the effect of prairie dogs on the water conservation of grasslands in arid
421 regions (Martínez-Estévez et al., 2013). In contrast, the water storage of topsoil is used to
422 evaluate the effects of European rabbits and plateau pikas on the water conservation of
423 grasslands in semi-arid grassland and alpine meadow (Eldridge et al., 2010). The activities of
424 European rabbits and plateau pikas can reduce the crust cover of grasslands and increase
425 water infiltration from top soil to deep soil in semi-arid regions (Eldridge et al., 2010; Li et al.,
426 2015), contributing to a negative effect on the water conservation in the topsoil layer. This
427 study shows that the presence of plateau pikas leads to higher the carbon sequestration in
428 alpine meadows, similar to the effect of the presence of prairie dogs in arid regions
429 (Martínez-Estévez et al., 2013) and European rabbits in semi-arid regions (Delibes-Mateos et
430 al., 2011). Plateau pikas can input extra organic matter through the deposition of uneaten food

431 (Liu et al., 2009; Zhang et al., 2016; Yu et al., 2017a) and the excretion of urine and feces
432 (James et al., 2009; Yu et al., 2017b), which increases the soil organic carbon stock and
433 contributes to an increase in the carbon sequestration of alpine meadows. These results
434 indicate that the presence of small mammalian herbivores can increase the carbon
435 sequestration of grasslands.

436 Higher plant-species richness in the presence of plateau pikas shows that the presence of
437 plateau pikas can lead to higher biodiversity conservation, similar to the effect of European
438 rabbits in semi-arid regions (Delibes-Mateos et al., 2008) and prairie dogs in arid regions
439 (Davidson et al., 2012). The mechanisms by which small mammalian herbivores lead to
440 higher plant-species richness have been discussed in many previous studies (Zhang et al.,
441 2020; Pang et al., 2021b). The presence of plateau pikas can lead to higher soil total nitrogen
442 and total phosphorus stocks, demonstrating that plateau pikas can increase the soil nitrogen
443 and phosphorus maintenance. In addition, there was no difference in the soil total potassium
444 stock between the areas with and without plateau pikas, indicating that the presence of plateau
445 pikas had no effect on the soil potassium maintenance. This effect was also observed with
446 prairie dogs and European rabbits in arid (Delibes-Mateos et al., 2011) and semi-arid regions
447 (Delibes-Mateos et al., 2008; Willott, 2001). Some of the following factors explain the higher
448 soil nitrogen and phosphorus stocks caused by plateau pikas. The presence of plateau pikas
449 can increase the input of soil organic material (Liu et al., 2013; Zhang et al., 2016; Pang et al.,
450 2020a). Secondly, the presence of plateau pikas can result in higher organic nitrogen and
451 phosphorus stocks (Yu et al., 2017b), which contributes to higher soil nitrogen and
452 phosphorus maintenance. These results suggest that a general pattern can be identified

453 regarding the effect of the presence of small mammalian herbivores on the supporting
454 services of biodiversity conservation, soil nitrogen, and phosphorus maintenance.

455 This study also shows that the disturbance intensity of plateau pikas also affects the
456 forage available to livestock, biodiversity conservation, water conservation, carbon
457 sequestration, and soil total nitrogen and phosphorus maintenance, and these effects is related
458 to disturbance intensity of plateau pikas. In this case, the active burrow entrances caused by
459 plateau pkas was used to indicate the all disturbance intensity of plateau. However, active
460 burrow entrances in disturbed plots was greatly changeable. This study just uses the field
461 survey data in this experiment to simulate the effect of disturbance intensity of plateau pikas
462 on the palatable plant biomass, soil organic carbon stock, plant-species richness, soil total
463 nitrogen, phosphorus and potassium stocks. As found in plant-species richness and
464 aboveground plant productivity (Dial and Roughgarden, 1998; Gao and Carmel, 2020), the
465 response of plant-species richness and palatable plant biomass to the disturbance intensity of
466 plateau pikas follow the pattern for the intermediate disturbance hypothesis in this study. In
467 addition, the soil organic carbon stock, soil total nitrogen and phosphorus stocks at
468 home-range scale also support the intermediate disturbance hypothesis. However, the top soil
469 water storage does not conform the intermediate disturbance hypothesis.

470 At lower disturbance intensity, stronger competition of dominant sedges often restrains
471 the grass to grow well (Pang and Guo, 2018) and the rare plants to coexist (Wang et al., 2012),
472 which leads the forage available to livestock and biodiversity conservation of alpine meadows
473 to be maintained at a low level. Although the presence of plateau pikas can increase the input
474 of soil organic matter, this increase is low (Pang and Guo, 2017; Pang et al., 2020b), which

475 enables the soil organic carbon sequestration and soil nitrogen and phosphorus maintenance
476 of alpine meadows to maintain a relatively low level.

477 At intermediate disturbance intensity, the activities of plateau pikas improve the growth
478 potential of grass plants (Wang et al., 2012), and increase the input of organic matter, soil total
479 nitrogen (Li et al., 2014), organic carbon accumulation (Yu et al., 2017b), which contributes
480 to higher the biodiversity conservation, forage available to livestock, carbon sequestration,
481 soil total nitrogen and phosphorus maintenance services.

482 At higher disturbance intensity of plateau pikas, frequent bioturbation can enable all
483 species to be at risk of going extinct (Dial and Roughgarden, 1998). Low soil water content in
484 alpine meadows (Liu et al., 2013) only sustains the xerophytes and mesophytes, most of
485 which are unpalatable (Pang and Guo, 2018). This contributes to relatively lower forage
486 available to livestock and biodiversity conservation. Low vegetation biomass decreases the
487 input resources of soil organic matter (Sun et al., 2015; Pang and Guo, 2017), contributing to
488 a decrease in the soil organic carbon sequestration and soil nitrogen and phosphorus
489 maintenance of alpine meadows.

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

494 Together with previous studies (Delibes-Mateos et al., 2011; Martínez-Estévez et al.,
495 2013), this study demonstrates that the presence of small mammalian herbivores has similar
496 impacts on the biodiversity conservation, soil nutrient maintenance, and carbon sequestration

497 of grasslands throughout the arid, semi-arid, and alpine regions, whereas the effects of the
498 presence of small mammalian herbivores on the forage available to livestock and water
499 conservation are dependent on environmental conditions. This study further verifies that the
500 disturbance intensity of plateau pikas also has a significant impact on the ecosystem services
501 of alpine ecosystems. These results concur with the findings in research fields of small
502 mammalian herbivores in relation to grassland ecosystem services.

503 **5 Conclusions**

504 This study focused on plateau pikas to investigate the responses of forage available to
505 livestock, water conservation, carbon sequestration, soil nutrient maintenance, and
506 biodiversity conservation of meadow ecosystems to the presence of a small mammalian
507 herbivore and its disturbance intensity across five sites. This will provide insight into the
508 relationship between small mammalian herbivores and ecosystem services of grasslands. The
509 results of this study showed that the presence of plateau pikas led to higher biodiversity
510 conservation, soil nitrogen and phosphorus maintenance, and carbon sequestration of alpine
511 meadows, whereas it led to lower forage available to livestock and water conservation of
512 alpine meadows. Furthermore, this study found that the effect of plateau pikas disturbance
513 intensity on the forage available to livestock, biodiversity conservation, soil maintenance of
514 nitrogen and phosphorus, and carbon sequestration also conformed to the moderate
515 disturbance hypothesis. These results verified that plateau pikas could affect the ecosystem
516 services of meadow ecosystems in alpine regions and present a relatively complete pattern of
517 small mammalian herbivores influencing grassland ecosystem services.

518

519 *Author contributions.* YC and ZG conceived the ideas and designed the methodology; YC, XP,
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522

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