

1 **Title:** Biocrust reduced soil water retention and soil infiltration in the alpine *Kobresia* meadow

2 **Running title:** Biocrust reduced soil water retention and soil infiltration

3 **Authors:** Licong Dai ¹, Ruiyu Fu¹, Xiaowei Guo^{2*}, Yangong Du², Guangmin Cao², Zhongmin Hu^{1*}

4 **Affiliations:**

5 ¹Key Laboratory of Agro-Forestry Environmental Processes and Ecological Regulation of Hainan
6 Province, Hainan University, Haikou, 570228, China

7 ²Qinghai Provincial Key Laboratory of Restoration Ecology for Cold Region, Northwest Institute
8 of Plateau Biology, Chinese Academy of Sciences, Xining 810001, China

9 * Corresponding author: Xiaowei Guo and Zhongmin Hu; **E-mail:** xwguo1206@163.com for
10 Xiaowei Guo and huzm@hainanu.edu.cn for Zhongmin Hu

11 **Postal address:** Renmin Road No 56, Haikou 570228, China

12

13 **Abstract**

14 Biocrust is a key component of ecosystems and plays a vital role in altering hydrological processes
15 in terrestrial ecosystems. The ~~role-effect~~impacts of biocrust on hydrological processes in arid and
16 semi-arid ecosystems has been widely documented; ~~however~~However, the effects and mechanisms
17 of biocrust on soil hydrological processes in alpine ecosystems are still poorly understood. In this
18 study, we selected two meadow types from the northern Qinghai-Tibet Plateau: normal *Kobresia*
19 meadow (NM) and biocrust meadow (BM). Both the soil hydrological and physicochemical
20 properties were examined. We found that in the 0–30 cm soil layer, soil water retention and soil
21 water content in NM were higher than those in BM, whereas the 30–40 cm layer's soil water
22 retention and soil water content in NM were lower than those in BM. The topsoil infiltration rate in

23 BM was lower than that in NM. Furthermore, the physicochemical properties were different
24 between NM and BM. The 0–10 cm soil layer’s clay content in BM was 9% higher than that in NM,
25 whereas the 0–30 cm layer’s soil capillary porosity in NM was higher than that in BM. In addition,
26 the 0–20 cm layer’s soil total nitrogen (TN) and soil organic matter (SOM) in NM were higher than
27 those in BM, implying that the presence of biocrust ~~did may~~ not favor the formation of soil nutrients
28 owing to its lower soil microbial biomass carbon and microbial biomass nitrogen. Overall, soil water
29 retention was determined by SOM by altering soil capillary porosity and bulk density. Our findings
30 ~~may suggested revealed~~ that the establishment of cyanobacteria crust biocrust ~~did may~~ not improve
31 soil water retention and infiltration, and the soil in cyanobacteria crust bioerust meadows ~~may could~~
32 be more vulnerable to runoff generation and consequent soil erosion. These results provide a
33 systematic and comprehensive understanding of the ~~role effects~~ of biocrust in the soil hydrology of
34 alpine ecosystems.

35 **Keywords:** Alpine meadow; biocrust; soil-soil water retention; soil water infiltration;
36 physicochemical properties

37 **1 Introduction**

38 Biocrusts are composed of living non-vascular plants (mosses, lichen and green algae) and
39 microorganisms (such as cyanobacteria, fungi and bacteria) associated with their bonding soil
40 particles that occur in the uppermost few millimeters ~~or even centimeters of surface soil~~ (Belnap et
41 al., 2016, Sun et al., 2022). As a crucial part of soil surface, biocrusts ~~are widely distributed in arid~~
42 ~~and semiarid regions throughout the world, and it~~ plays a vital role in regulating biogeochemical
43 processes, hydrology processes, and surface energy balance, ~~such as improving soil aggregation~~
44 ~~and stability, increasing the soil fertility and, reducing soil erosion and thus maintaining water~~

45 ~~availability~~ (Li et al., 2016), which can serve as “ecological engineers” in soil systems. However, to
46 our knowledge, the controlling mechanism of biocrust on soil hydrological processes is still unclear.
47 Most previous studies were conducted in arid and semi-arid ecosystems, such as the Tengger Desert,
48 Negev Deserts, and Loess Plateau hydrological processes where plant are limited by soil moisture.
49 Very few studies have focused on the role of biocrust on hydrological processes (i.e., soil water
50 content, soil water retention, and soil infiltration) in alpine ecosystems where plant are limited by
51 soil temperature, ~~and the mechanisms are poorly understood~~. Thus, examining the impact of biocrust
52 on hydrological processes ~~could provide insight could have substantial effects~~ on water balance in
53 alpine ecosystems and grassland management policies for maintaining the sustainability of meadow
54 ecosystems.

55 The alpine meadow is an important ecosystem in the Qinghai-Tibet Plateau (QTP), which plays
56 an important role in water retention (Dai et al., 2019), ~~in~~ preventing soil erosion (Qian et al., 2021)
57 and ~~in~~ regulating energy exchange (Zhu et al., 2020) by altering soil surface features (i.e., such as
58 roughness, soil texture, porosity, and aggregation) (Li et al., 2016), ~~thereby modifying evaporation,~~
59 ~~soil water retention, and water infiltration processes~~. However, the formation of biocrust in alpine
60 meadows is different from that in arid areas, where the biocrust is formed from intensive land use
61 such as overgrazing. Overgrazing could reduce vegetation coverage, thereby increase soil light
62 condition, which favor the photosynthesis of cyanobacteria crust. Previous study have-d found a
63 well relationship between biocrust and vegetation coverage, i.e. the occurrence frequency of
64 cyanobacteria crust also increased with reducing vegetation coverage owing to overgrazing. ~~-(Li et~~
65 al., 2015). Moreover, ~~and~~ the biocrust types vary with the succession stage of alpine meadows (Li
66 et al., 2016b). For instance, as the degree of degradation increases, the moss-dominated crust is

67 transformed into cyanobacteria-dominated crust, followed by lichen-dominated crust from
68 *Graminoid*-dominated vegetation degradation to *Kobresia humilis* meadow (light degradation) and
69 then to *K. pygmaea* meadow (moderate degradation) (Li et al., 2016). Thus, we suggest that the
70 impact of biocrust on hydrologic processes in alpine meadows may differ from that in arid areas,
71 and vice versa.

72 To date, although numerous studies have pointed out that biocrust has substantial effects on
73 soil water retention and soil moisture infiltration processes by altering soil microenvironments, such
74 as soil roughness, soil porosity, and aggregation, no consensus has been reached. For instance, some
75 studies have found that biocrust could increase soil water infiltration and reduce runoff by increasing
76 soil porosity and aggregate stability compared with bare soil in cool desert ecosystems (Kidron and
77 Benenson, 2014; Wei et al., 2015). In contrast, other studies ~~found~~reported that soil water infiltration
78 was significantly reduced in crusted areas compared with non-crusted areas in arid ecosystems (Li
79 et al., 2010; Xiao and Hu, 2017). These discrepancies highlight the necessity to further explore the
80 effects of biocrust on hydrological processes, such as exploring the specific hydrological processes
81 by conducting soil infiltration experiments and soil water retention curve measurements.
82 Furthermore, most previous studies were mainly conducted in arid and semi-arid ecosystems, and
83 very few studies have focused on the effects of biocrust on the soil's hydrological processes in alpine
84 ecosystems. Therefore, it is crucial to assess the role of biocrust in soil water retention and
85 infiltration in alpine meadows.

86 To address these knowledge gaps, In this study, normal *Kobresia* meadow and biocrust
87 meadow in QTP were selected. ~~Both~~Both soil and hydrological features were measured, with the aim
88 of exploring the role of biocrust in hydrological processes in alpine ecosystems. Specifically, the

带格式的：字体：倾斜

89 objectives of this study were to explore the effect of biocrust on soil-hydrological features in alpine
90 ecosystems, to reveal how biocrust affects soil water retention by altering soil and vegetation
91 properties. ~~Our results, and could~~ provide insights into the management of biocrust in alpine
92 meadows.

93 **2 Materials and methods**

94 **2.1 Site description**

95 The field test sites were located in the northeastern Qinghai-Tibet Plateau (101° 19' E, 37° 37'
96 N), in Qinghai Province, China (Fig.1a). The area has a continental plateau climate with a mean air
97 temperature of -1.7°C and a mean annual precipitation of approximately 562 mm (Dai et al., 2020).
98 It should be noted that approximately 80% of the precipitation occurs during the growing season
99 (between May and September), and the other 20% occurs during the non-growing season. The main
100 vegetation type in this region is the *Kobresia* meadow, which is dominated by *Kobresia humilis*
101 (Fig.1b). The soil type in the study area is silt loam according to the in the USDA soil taxonomy
102 system of classification (Cusack and others 2018), with a soil thickness of approximately 60–80 cm.
103 The pH and EC is 7.5 m s⁻¹ and 6.7 in the study area, respectively. (Li et al., 2016).

104 **2.2 Experimental design and soil sampling**

105 In August 2020, we choose two study sites on the northeastern Qinghai-Tibet Plateau to avoid
106 pseudoreplication, and two types of soil surfaces were selected in each study site, i.e. normal
107 *Kobresia* meadow (NM, Fig. 1b) and biocrust meadow (BM, Fig. 1c). To reduce the differences
108 caused by spatial heterogeneity, the BM was selected adjacent to the NM. The vegetation cover in
109 BMs is usually less than 20% with a thick turf but no litter layer in topsoil, and the BM type is
110 dominated by cyanobacteria crust (ca. 80%) (Li et al., 2016). In contrast, NM has a dense vegetation

111 cover and is mainly dominated by *Kobresia pygmaea*, with average plant heights of 1–3 cm.
112 Furthermore, a clear typical turf horizon and litter layer was observed within the topsoil in NM, that
113 is, the Afe horizon. BM had a higher root biomass than that of NM, owing to its thick turf (Table 1).

114 We obtained the disturbed soil samples (i.e. non-ring knife soil sample) in NM and BM, ~~and~~
115 ~~Four~~ quadrats (1 × 1 m) were randomly selected for soil sampling with a depth of 10 cm in each
116 treatment using an earth boring auger, and then brought back to the laboratory to measure and
117 analyze soil organic matter (SOM), soil microbial biomass carbon (MBC), microbial biomass
118 nitrogen (MBN), total carbon (TC), total nitrogen (TN), and ~~soil particle size distributions~~soil texture
119 (PSD). Undisturbed cylindrical ring samples (i.e. ring knife soil sample) were also obtained in each
120 treatment to determine the soil bulk density (BD), soil porosity, and soil hydraulic properties (i.e.,
121 soil water retention and soil water supply capacity). The soil infiltration rates were measured using
122 a double-ring infiltrometer for each treatment.

123 2.3 Laboratory measurements and analyses

124 First, the disturbed soil samples were sieved through 0.25 mm and 2-mm soil sieves to remove
125 debris and roots for the analysis of soil properties. SOM was measured based on the Walkley &
126 Black procedure (Nelson and Sommers, 1982), MBC and MBN were measured by the chloroform
127 fumigation-direct extraction method (Vance et al., 1987), and TC and TN were measured using an
128 element analyzer (Elementar Vario EL III, Hanau, Germany). PSD was determined using a
129 Mastersizer 2000 (Malvern Instruments, UK). BD was measured as the ratio of the oven-dry soil
130 mass to the core volume (100 cm³). The soil total porosity, soil capillary porosity, and soil non-
131 capillary were measured using the following equation (Dai et al., 2020):

$$132 \quad TP = \left(1 - \frac{BD}{d_s}\right) \times 100\% \quad (1),$$

133
$$CP = CWC \times BD \quad (2),$$

134
$$NCP = TP - CP \quad (3),$$

135 where TP, CP, and NCP represent soil total porosity (%), soil capillary porosity (%), and soil non-
136 capillary porosity (%), respectively; CWC represents soil capillary water capacity; d_s is the soil
137 particle density, which was assumed to be $2.65 \text{ (g cm}^{-3}\text{)}$.

138 The soil water retention curves (SWRCs) were measured using a pressure plate apparatus (1500
139 F1, Soil Moisture Equipment Corp., SEC, USA), and the relationship between soil water content
140 and matric potential was fitted by the Gardner model. The formula of the Gardner model is as
141 follows (Gardner et al., 1970):

142
$$h = A\theta^B,$$

143 where h is the soil water content (%), θ is the matric potential (kPa), and A and B are the fitting
144 parameters. Higher values of $A \cdot B$ and A indicate a higher soil water supply capacity and soil water
145 retention capacity, respectively.

146

147 **2.4 Statistical analysis**

148 In this study, to compare the differences between BM and NM on soil water retention and soil
149 properties, we conducted one-way analysis of variance (ANOVA) statistical tests to determine
150 differences in plant and soil properties for the same soil layers between the BM and NM, and a least-
151 significant-difference test ($P < 0.05$) was conducted when significant differences were detected by
152 ANOVA. To explore the relationship between soil properties and soil-soil water retention, and
153 quantitative evaluation of the effects of soil properties on soil-soil water retention, Pearson's
154 correlation and variance partition in the analysis were used by R software version 3.4.3 (R

155 Development Core Team, 2006) with the “hier.part” and “corrplot” packages. Furthermore,
156 structural equation modeling was used to examine the soil properties' direct and indirect effects on
157 soil water retention.

158

159 3 Results

160 3.1 Soil texture~~Soil particle size distribution~~Soil texture among two surface soil types

161 Silt content dominated the ~~soil particle size distribution~~soil texture in the 0–40 cm soil layer
162 across the two surface soil types (mean 61.69%), followed by sand (mean 30.13%), and clay (mean
163 8.18%) (Fig. 2). Specifically, the 0–10 cm ~~soil layer's~~ clay content in BM was 9% higher than that
164 in NM, whereas the 10–40 cm ~~soil layer's~~ clay content in BM was 16% lower than that in NM,
165 especially for the 10–20 cm soil layer ($P<0.001$). In contrast, the 0–40 cm ~~soil layer's~~ silt content
166 in BM was higher than that in NM, especially for the 20–30 cm soil layer ($P<0.05$). However, no
167 clear pattern was observed for the sand content between BM and NM. Overall, ~~in the 0-40 cm soil~~
168 ~~layer,~~ clay content (8.62%) in NM was 11% higher than that in BM (7.69%), whereas in the 0–40
169 cm ~~soil layer,~~ silt content (61.24%) in NM was nearly equal to that in BM (62.13%).

170 3.2 Soil physicochemical properties among two surface soil types

171 There were no significant differences for 0–40 cm BD, 0–40 cm TP, 0–40 cm CP and 0–40 cm
172 NCP ($P>0.05$) (Fig.3), but the 0–20 cm BD in NM was 13% lower than that of BM, and the TP and
173 CP in NM were 7% and 5% higher than that of BM. No clear pattern was observed for NCP in NM
174 and BM (Fig.3). Furthermore, the 0–20 cm TN and SOM in NM were much higher than those in
175 BM and reached a significant level at 0–10 cm ($P<0.05$), whereas the 30–40 cm TN and SOM in
176 NM were lower than those in BM (Fig.3). Similarly, the 0–10 cm ~~soil layer's~~ TC and C: N ratio in

177 NM were significantly higher than those in BM, whereas the 30–40 cm soil layer's TC and C: N
178 ratio in NM were lower than those in BM (Fig.3). Additionally, the 0–40 cm soil layer's MBC and
179 MBN in NM were higher than those in BM and reached a significant level at 0–10 cm ($P<0.05$)
180 (Fig. 4).

181 3.3 Soil hydrological processes among two surface soil types

182 The soil hydrological processes varied between crust BM and NM (Fig.5 and Table 1). Given
183 that parameter A fitted by the Gardner model represents the soil water retention (a higher A value
184 indicates higher soil water retention), the soil water content was reduced with decreasing matric
185 potential and reduced sharply at high matric potential, but remained stable at low matric potential
186 (Fig. 5). The 0–30 cm layer's soil water content and soil water retention in NM were higher
187 than those in BM, whereas the 30–40 cm layer's soil water content and soil water retention in NM
188 were lower than those in BM (Table 1 and Fig. 6b). Similarly, the 0–10 and 20–30 cm layers' soil
189 water supply capacity (i.e., $A*B$ fitted by the Gardner model) in NM was higher than that in BM,
190 while the 10–20 and 30–40 cm layers' soil water supply capacity in NM was lower than that in BM
191 (Fig. 6a). Furthermore, the surface infiltration rate in the BM was significantly lower than that in
192 the NM (Table 1).

193 3.4 Dominated factors affecting soil-soil water retention

194 Pearson correlation analysis showed that soil water retention was significantly negatively
195 related to BD, but significantly positively related to TP, CP, and SOM (Fig.7a), whereas soil particle
196 size distribution soil texture exerted weak soil water retention (Fig.7a). Furthermore, the variance
197 partition showed that SOM explained the greatest variability in soil-soil water retention (24.40%),
198 followed by CP (21.24%), BD (18.22%), and TP (18.22%) (Fig. 8b), and structural equation modeling

199 showed that the effect of SOM on soil water retention was achieved by altering CP and BD (Fig. 8).

200 **4 Discussion**

201 **4.1 Effect of biocrust on soil properties**

202 The effects of biocrust on soil properties have been widely explored in previous studies (Guo
203 et al., 2008; Liu et al., 2019). Compared with non-biocrust and most studies conducted in arid
204 regions, ~~we have found that~~ the presence of biocrust could improve soil aggregation and stability (Wu
205 et al., 2020), increase soil fertility (Zhou et al., 2020), and reduce soil erosion (Chamizo et al., 2017).

206 In this study, however, we found that the presence of cyanobacteria crust could improve topsoil
207 texture compared with normal meadow, but not that of deep soil. The 0–10 cm ~~soil layer's~~ clay
208 content in cyanobacteria crust meadow was higher than that for normal meadow, whereas the 10–
209 40 cm ~~soil layer's~~ clay content in cyanobacteria crust meadow was lower than that for normal
210 meadow, which is in line with previous studies conducted in arid and semi-arid regions (Liu et al.,
211 2016; Wu et al., 2020). The higher clay content in cyanobacteria crust meadow was attributed to the
212 exudation and cohesiveness of the biocrust, which promoted clay and silt formation and reduced
213 sand content (Wang et al., 2021). Furthermore, we found that the 0–20 cm ~~soil layer's~~ soil bulk
214 density in normal meadow was lower than that in cyanobacteria crust meadow, thereby leading to
215 higher soil porosity and total capillary porosity in normal meadow. Such higher soil capillary
216 porosity in normal meadow was attributed to its higher soil organic matter content, which was also
217 confirmed by the significant positive relationship between soil organic matter and soil capillary
218 porosity (Fig. 7). ~~Because it~~ has been well documented that a higher soil organic matter could
219 improve soil aggregation and stability and subsequently increase soil capillary porosity (Cui et al.,
220 2021).

221 Moreover, ~~more-most~~ previous ~~found-indicated~~ that the presence of cyanobacteria crust can
222 also improve soil nutrient conditions in the process of mobile sand fixation (Belnap et al., 2004;
223 Guo et al., 2008; Li et al., 2005a). However, we found that the presence of cyanobacteria crust
224 reduces the 0–10 cm ~~layer's~~ soil total carbon, total nitrogen, and C: N ratio compared with normal
225 meadow, which is in contrast to most previous studies conducted in arid and semi-arid regions
226 (Chamizo et al., 2012b; Zhao et al., 2010). A ~~probable-possible~~ reason for these differences may
227 ascribe to the environmental differences. It is well ~~documented~~~~documented~~ that the formation of
228 biocrust is a changing process from simple to complex in its morphology, the early cyanobacteria
229 crust was formed only under favorable hydrothermal conditions such as temperature, soil water,
230 solar radiation, and nutrient content (Belnap et al., 2004; Li et al., 2005b). For instance, biocrust is
231 metabolically active when the external environment is wet, and its metabolically active environment
232 is sensitive to temperature (Belnap et al., 2004; Li et al., 2005b), otherwise the biocrust may choose
233 to enter the dormant stage when the external environment is under unfavorable conditions. Therefore,
234 compared to the higher soil temperatures in arid and semi-arid lands, the biocrust in alpine
235 ecosystems may be in a dormant stage owing to its lower temperature and less available nutrients.
236 Moreover, the biocrust in our study was mostly dominated by cyanobacteria crust, which was
237 vulnerable to external disturbances such as grazing activity; ~~thus~~Thus, the biocrust may choose
238 dormancy when it is subjected to grazing pressure, ~~which-this evidence~~ was also confirmed by the
239 significantly lower microbial soil carbon and microbial soil nitrogen content in cyanobacteria crust
240 meadow compared with normal meadow (Fig. 4).

241 4.2 Effect of biocrust on soil hydrology and their underlying mechanisms

242 We found that soil water infiltration was greatly reduced in cyanobacteria crust meadow

243 compared with that in normal meadow, which was consistent with the results of a previous study
244 conducted in alpine meadows (Li et al., 2016b). However, it is in contrast to other studies conducted
245 in cool desert ecosystems where biocrust increased soil water infiltration and reduced runoff by
246 increasing soil porosity and aggregate stability compared with physical crusts and non-crusts bare
247 soils (Kidron and Benenson, 2014; Wei et al., 2015). These discrepancies were associated with soil
248 texture and biocrust developmental stage. In general, soil water infiltration in coarse-textured soils
249 is higher than that in fine-textured soils owing to its large pores compared with the narrow pores in
250 fine-textured soils, which reduces the movement of water into the soil (Belnap, 2006). However, we
251 found that the establishment of cyanobacteria crust increased clay content and subsequently reduced
252 soil macropores, which hindered soil water infiltration. Therefore, we conclude that the soil in the
253 cyanobacteria crust meadow may be more vulnerable to runoff generation and consequent soil
254 erosion, owing to its lower soil water infiltration and soil water retention capacity. On the other hand,
255 biocrust can reduce available pore spaces for water to infiltrate by clogging the soil surface
256 conductive pores owing to its higher water absorption and swelling of biocrust (Fischer et al., 2010),
257 and consequently reduce soil infiltration. In addition, soil water infiltration was ~~also affected~~
258 by the developmental stage of the biocrust in homogeneous soil. A previous study ~~indicated~~
259 that soil hydraulic parameters differed significantly between cyanobacterial biocrust and moss
260 biocrust (Wang et al., 2017). For instance, Chamizo et al. (2012a) reported that the incipient-
261 cyanobacterial crust had a lower soil infiltration rate than that of the cyanobacterial crust, whereas
262 the dark-colored mosses' crust had higher surface soil infiltration capacity by increasing
263 macroporosity and unsaturated hydraulic conductivity in the grasslands ~~dominated by *A. splendens*~~
264 (Jiang et al., 2018). In our study, the biocrust was dominated by incipient-cyanobacterial crust,

265 which had low biological activity and low porosity owing to the predominance of vesicle pores,
266 thereby leading to a lower soil infiltration rate.

267 Furthermore, the soil water retention and soil water supply capacity varied significantly
268 between the biocrust and normal meadows. We found that in the 0–10 cm soil water retention and
269 soil water supply capacity in normal meadow were higher than that in cyanobacteria crust meadow,
270 which was not in line with previous studies conducting in drylands in which biocrusts enhanced
271 surface soil water retention capacity and water availability (Sun et al., 2022). We speculate that the
272 lower soil water retention in the cyanobacteria crust meadow was related to its lower soil organic
273 matter; this evidence was also confirmed the lower microbial biomass carbon (Fig. 4a). Furthermore,
274 the structural equation model indicated that the effect of soil organic matter on water retention was
275 mainly achieved by altering soil bulk density and soil porosity (Fig. 8) because higher soil organic
276 matter could reduce soil bulk density and thereby increase soil porosity (Liu et al., 2019), leading
277 to higher soil water retention. This result was also confirmed by the significant positive relationship
278 between soil organic matter and soil water retention (Fig. 7). Considering soil organic matter was
279 derived from vegetation litter and root biomass, whereas the vegetation litter in cyanobacteria crust
280 meadow was lower than that in normal meadow owing to its lower aboveground biomass and
281 vegetation coverage, ultimately resulting in lower soil organic matter in cyanobacteria crust meadow.

282 4.3 Implications for the effect role of biocrust in alpine meadows

283 Grassland ecosystems cover more than 60% of the QTP and provide important ecosystem
284 services, such as biodiversity conservation, carbon storage, and water conservation (Dong et al.
285 2020). However, in recent decades, grasslands in the QTP have suffered from serious degradation
286 due to increasing human activity (Cao et al. 2019). Biocrust is an important surface feature of the

带格式的：字体颜色：红色

287 degraded alpine meadows. It is acknowledged that biocrust has a positive effect on soil nutrient and
288 soil water content retention in arid regions. In contrast, we found that the presence of cyanobacteria
289 crust decreased soil water retention and soil infiltration rate, which did not improve water
290 conservation in alpine meadows. Therefore, the soil in the ~~cyanobacteria crust~~ region may
291 be more vulnerable to runoff generation and consequent soil erosion. Moreover, soil nutrients, such
292 as SOM, TC, and TN, were reduced significantly in the cyanobacteria crust meadow, suggesting
293 that the growth of vegetation in the cyanobacteria crust meadow may be limited by soil nutrients.
294 Considering the negative effects of biocrust on alpine meadows, some steps should be taken to
295 reduce the formation of ~~cyanobacteria crust~~ in degraded alpine meadows, such as reducing
296 grazing intensity ~~and~~. ~~Nevertheless, our study results were only obtained only by conducting ed-in~~
297 ~~site scale, which may not sufficiently to extrapolate the whole QTP owing to its high spatial~~
298 ~~heterogeneity. Thus, a~~
299 ~~it is necessary larger scale or more study sites is necessary to have a generalizability conclusion~~
300 ~~regarding the effects of biocrust on hydrological processes in alpine meadow of QTP-owing to~~
301 ~~its considering the high spatial heterogeneity in QTP. –~~

302 5 Conclusions

303 Soil hydrological processes were significantly affected by the establishment of ~~cyanobacteria~~
304 ~~crust~~, and we found that the ~~cyanobacteria crust~~ could reduce topsoil water and
305 infiltrate topsoil, which suggested that the establishment of ~~cyanobacteria crust~~ ~~did may~~ not
306 favor soil hydrological processes in alpine meadows. Furthermore, the presence of ~~cyanobacteria~~
307 ~~crust~~ increased topsoil clay content, while the 0–30 cm layer's soil capillary porosity in NM
308 was higher than that in BM, indicating that the presence of ~~cyanobacteria crust~~ reduced soil

309 porosity and thereby reduced topsoil water infiltration. This suggested that the discrepancies in soil
310 water retention and topsoil infiltration were close to physicochemical properties, and that SOM
311 plays a role in soil water retention by affecting CP and BD. Our study ~~are may helpful provides~~
312 ~~insight into the role of for making reasonable management policies to maintaining the sustainability~~
313 ~~of meadow ecosystems in the long run, especially under intensifies dramatic human activity and~~
314 ~~climate change in QTP. climate changes during the anthropocene bioerust in soil hydrological~~
315 ~~processes in alpine ecosystems.~~

316 **Acknowledgments**

317 This work was supported by the National Natural Science Foundation of China (41730752),
318 the Natural Science Foundation of Qinghai (2021-HZ-811).

319 **Author contribution**

320 Licong Dai: Investigation, Data curation, Writing – original draft, Formal analysis. Ruiyu Fu :
321 Investigation, Data curation, Writing – original draft, Formal analysis, Visualization. Xiaowei Guo
322 and Zhongmin Hu: Investigation, Data curation, Project administration, Supervision. Yangong Du:
323 Writing – original draft, review & editing. Guangmin Cao: Conceptualization, Methodology,
324 Funding acquisition, Supervision.

325 **Declaration of competing interest**

326 The authors declare that they have no known competing financial interests or personal
327 relationships that could have appeared to influence the work reported in this paper

328 **Data availability statement**

329 The data that support the findings of this study are available from the corresponding author
330 upon reasonable request.

331 **References**

- 332 Assouline, S. et al., 2015. The dual role of biocrusts in desertification. *Journal of Geophysical*
333 *Research: Biogeosciences*, 120, 2108-2119. <https://doi.org/10.1002/2015JG003185>.
- 334 Belnap, J., 2006. The potential roles of biological biocrusts in dryland hydrologic cycles.
335 *Hydrological Processes: An International Journal*, 20, 3159-3178.
- 336 Belnap, J., Phillips, S.L., Miller, M.E., 2004. Response of desert biological biocrusts to alterations
337 in precipitation frequency. *Oecologia*, 141, 306-316.
- 338 Belnap, J., Weber, B., Büdel, B., 2016. Biological biocrusts as an organizing principle in drylands,
339 *Biological biocrusts: an organizing principle in drylands*. Springer, pp. 3-13.
- 340 Chamizo, S., Canton, Y., Lázaro, R., Solé-Benet, A., Domingo, F., 2012a. Crust composition and
341 disturbance drive infiltration through biological biocrusts in semiarid ecosystems.
342 *Ecosystems*, 15, 148-161.
- 343 Chamizo, S., Cantón, Y., Miralles, I., Domingo, F., 2012b. Biological biocrust development affects
344 physicochemical characteristics of soil surface in semiarid ecosystems. *Soil Biology and*
345 *Biochemistry*, 49, 96-105. <https://doi.org/10.1016/j.soilbio.2012.02.017>.
- 346 Chamizo, S., Rodríguez-Caballero, E., Cantón, Y., Asensio, C., Domingo, F., 2015. Penetration
347 resistance of biological biocrusts and its dynamics after crust removal: relationships with
348 runoff and soil detachment. *Catena*, 126, 164-172.
- 349 Chamizo, S., Rodríguez-Caballero, E., Román, J.R., Cantón, Y., 2017. Effects of biocrust on soil
350 erosion and organic carbon losses under natural rainfall. *Catena*, 148, 117-
351 125. <https://doi.org/10.1016/j.catena.2016.06.017>
- 352 Chen, X., Duan, Z., 2015. Impacts of biocrusts on soil physicochemical characteristics in different

353 rainfall zones of the arid and semi-arid desert regions of northern China. *Environmental*
354 *Earth Sciences*, 73, 3335-3347. <https://doi.org/10.1007/s12665-014-3622-x>

355 Cui, Z. et al., 2021. Litter cover breaks soil water repellency of biocrust, enhancing initial soil water
356 infiltration and content in a semi-arid sandy land. *Agricultural Water Management*, 255,
357 107009.10.1016. <https://doi.org/j.agwat.2021.107009>

358 Dai, L. et al., 2019. Seasonal dynamics and controls of deep soil water infiltration in the seasonally-
359 frozen region of the Qinghai-Tibet plateau. *Journal of Hydrology*, 571, 740-748.
360 <https://doi.org/10.1016/j.jhydrol.2019.02.021>.

361 Dai L, Yuan Y, Guo X, et al. Soil water retention in alpine meadows under different degradation
362 stages on the northeastern Qinghai-Tibet Plateau. *Journal of Hydrology*, 2020, 590:
363 125397. <https://doi.org/10.1016/j.jhydrol.2020.125397>

364 Faist, A.M., Herrick, J.E., Belnap, J., Van Zee, J.W., Barger, N.N., 2017. Biological biocrust and
365 disturbance controls on surface hydrology in a semi-arid ecosystem. *Ecosphere*, 8,
366 e01691. <https://doi.org/10.1002/ecs2.1691>.

367 Ferrenberg, S., Reed, S.C., Belnap, J., 2015. Climate change and physical disturbance cause similar
368 community shifts in biological biocrusts. *Proceedings of the National Academy of Sciences*,
369 112, 12116-12121.

370 Fischer, T., Veste, M., Wiehe, W., Lange, P., 2010. Water repellency and pore clogging at early
371 successional stages of microbiotic crusts on inland dunes, Brandenburg, NE Germany.
372 *Catena*, 80, 47-52. <https://doi.org/10.1016/j.catena.2009.08.009>.

373 Guo, Y., Zhao, H., Zuo, X., Drake, S., Zhao, X., 2008. Biological biocrust development and its
374 topsoil properties in the process of dune stabilization, Inner Mongolia, China.

375 Environmental Geology, 54, 653-662. <https://doi.org/10.1007/s00254-007-1130-y>.

376 Havrilla, C.A. et al., 2019. Towards a predictive framework for biocrust mediation of plant
377 performance: A meta-analysis. Journal of Ecology, 107, 2789-2807.
378 <https://doi.org/10.1111/1365-2745.13269>.

379 Jiang, Z.-Y. et al., 2018. Contrasting surface soil hydrology regulated by biological and physical
380 biocrusts for patchy grass in the high-altitude alpine steppe ecosystem. Geoderma, 326,
381 201-209. <https://doi.org/10.1016/j.geoderma.2018.04.009>.

382 Kidron, G.J., Benenson, I., 2014. biocrust serve as biomarkers for the upper 30 cm soil water content.
383 Journal of Hydrology, 509, 398-405. <https://doi.org/10.1016/j.jhydrol.2013.11.041>.

384 Li, H. et al., 2016. Differentiation of microbial activity and functional diversity between various
385 biocrust elements in a heterogeneous crustal community. Catena, 147, 138-
386 145. <https://doi.org/10.1016/j.catena.2016.07.008>.

387 Li, W., Ren, T., Zhou, Z., Liu, J., 2005a. Study on the soil physicochemical characteristics of
388 biological crust on sand dune surface in Gurbantünggüt Desert, Xinjiang Region. J. Glaciol.
389 Geocryol, 27, 619-627.

390 Li, X.-R., Jia, X.-H., Long, L.-Q., Zerbe, S., 2005b. Effects of biological biocrusts on seed bank,
391 germination and establishment of two annual plant species in the Tengger Desert (N China).
392 Plant and soil, 277, 375-385. <https://doi.org/10.1007/s11104-005-8162-4>.

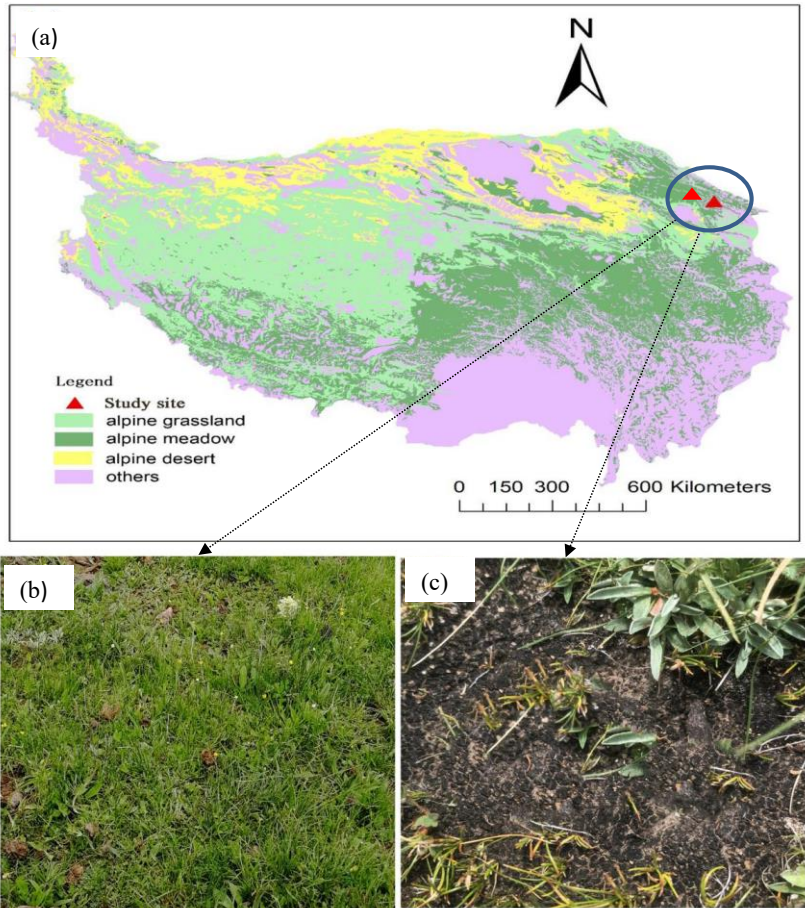
393 Li, X., Tian, F., Jia, R., Zhang, Z., Liu, L., 2010. Do biological biocrusts determine vegetation
394 changes in sandy deserts? Implications for managing artificial vegetation. Hydrological
395 Processes, 24, 3621-3630. <https://doi.org/10.1002/hyp.7791>.

396 [Y.-k. et al., et al., 2015. Evolution characteristics of biological soil crusts \(BSCs\) during alpine](#)

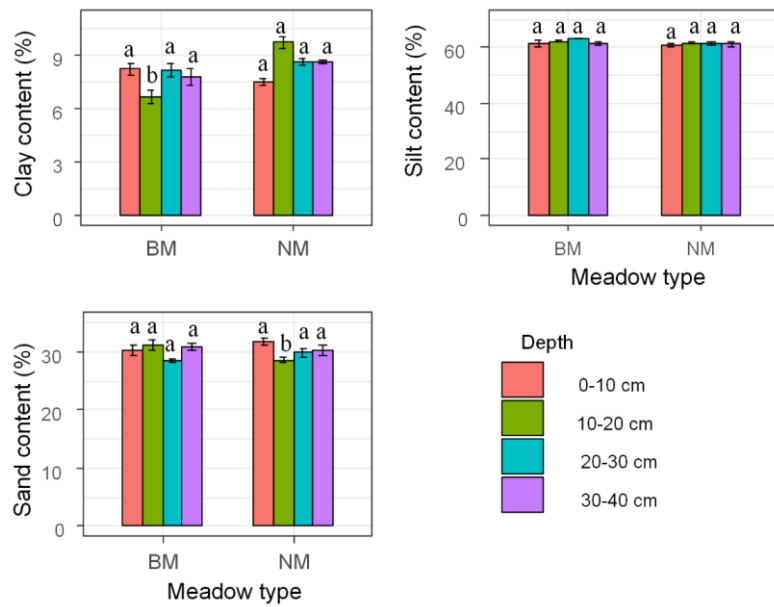
- 397 [meadow degradation. Chinese Journal of Ecology, 34\(8\): 2238.](#)
- 398 Li, Y.-k. et al., 2016b. Alterations to biological biocrusts with alpine meadow retrogressive
399 succession affect seeds germination of three plant species. *Journal of Mountain Science*,
400 13, 1995-2005. <https://doi.org/10.1007/s11629-016-3917-3>.
- 401 Letendre A C, Coxson D S, Stewart K J. Restoration of ecosystem function by soil surface
402 inoculation with biocrust in mesic and xeric alpine ecosystems[J]. *Ecological Restoration*,
403 2019, 37(2): 101-112. <https://doi.org/10.3368/er.37.2.101>.
- 404 Liu, F., Zhang, G.h., Sun, L., Wang, H., 2016. Effects of biological biocrusts on soil detachment
405 process by overland flow in the Loess Plateau of China. *Earth Surface Processes and*
406 *Landforms*, 41, 875-883. <https://doi.org/10.1002/esp.3870>.
- 407 Liu, Y., Cui, Z., Huang, Z., Miao, H.-T., Wu, G.-L., 2019. The influence of litter crusts on soil
408 properties and hydrological processes in a sandy ecosystem. *Hydrology and Earth System*
409 *Sciences*, 23, 2481-2490. <https://10.5194/hess-23-2481-2019>.
- 410 Qian, D., Du, Y., Li, Q., Guo, X., Cao, G., 2021. Alpine grassland management based on ecosystem
411 service relationships on the southern slopes of the Qilian Mountains, China. *Journal of*
412 *Environmental Management*, 288, 112447. <https://doi.org/10.1016/j.jenvman.2021.112447>.
- 413 Ries, J.B., Hirt, U., 2008. Permanence of soil surface crusts on abandoned farmland in the Central
414 Ebro Basin/Spain. *Catena*, 72, 282-296. <https://doi.org/10.1016/j.catena.2007.06.001>.
- 415 Rodríguez-Caballero, E., Cantón, Y., Chamizo, S., Afana, A., Solé-Benet, A., 2012. Effects of
416 biological biocrusts on surface roughness and implications for runoff and erosion.
417 *Geomorphology*, 145, 81-89. doi.org/10.1016/j.geoderma.2022.116136.
- 418 Sun F, Xiao B, Kidron G J. Towards the influences of three types of biocrusts on soil water in

- 419 drylands: Insights from horizontal infiltration and soil water retention[J]. *Geoderma*, 2022,
420 428: 116136.
- 421 Wang, H., Zhang, G., Liu, F., Geng, R., Wang, L., 2017. Effects of biological crust coverage on soil
422 hydraulic properties for the Loess Plateau of China. *Hydrological Processes*, 31, 3396-3406.
423 <https://doi.org/10.1002/hyp.11263>.
- 424 Wang, J., Zhao, W.W., Wang, G., Yang, S.Q., Pereira, P., 2021. Effects of long-term afforestation
425 and natural grassland recovery on soil properties and quality in Loess Plateau (China). *Sci.*
426 *Total Environ.* 770, 144833 <https://doi.org/10.1016/j.scitotenv.2020.144833>.
- 427 Wei, W., Yu, Y., Chen, L., 2015. Response of surface soil hydrology to the micro-pattern of bio-
428 crust in a dry-land Loess environment, China. *PLoS One*, 10,
429 e0133565.<https://doi.org/10.1371/journal.pone.0133565>.
- 430 Wu, G.-L., Zhang, M.-Q., Liu, Y., López-Vicente, M., 2020. Litter cover promotes biocrust
431 decomposition and surface soil functions in sandy ecosystem. *Geoderma*, 374, 114429.
432 <https://doi.org/10.1016/j.geoderma.2020.114429>
- 433 Zhao, H.-L., Guo, Y.-R., Zhou, R.-L., Drake, S., 2010. Biological biocrust and surface soil properties
434 in different vegetation types of Horqin Sand Land, China. *Catena*, 82, 70-76.
435 <https://doi.org/10.1016/j.catena.2010.05.002>.
- 436 Zhou, X. et al., 2020. Induced biological biocrusts and soil properties varied between slope aspect,
437 slope gradient and plant canopy in the Hobq desert of China. *Catena*, 190, 104559.
438 <https://doi.org/10.1016/j.catena.2020.104559>.
- 439 Zhu, J. et al., 2020. Seasonal and Interannual Variations of CO₂ Fluxes Over 10 Years in an Alpine
440 Wetland on the Qinghai-Tibetan Plateau. *Journal of Geophysical Research: Biogeosciences*,

带格式的： 缩进： 左侧： 0 厘米， 悬挂缩进： 2.5 字
符， 首行缩进： -2.5 字符

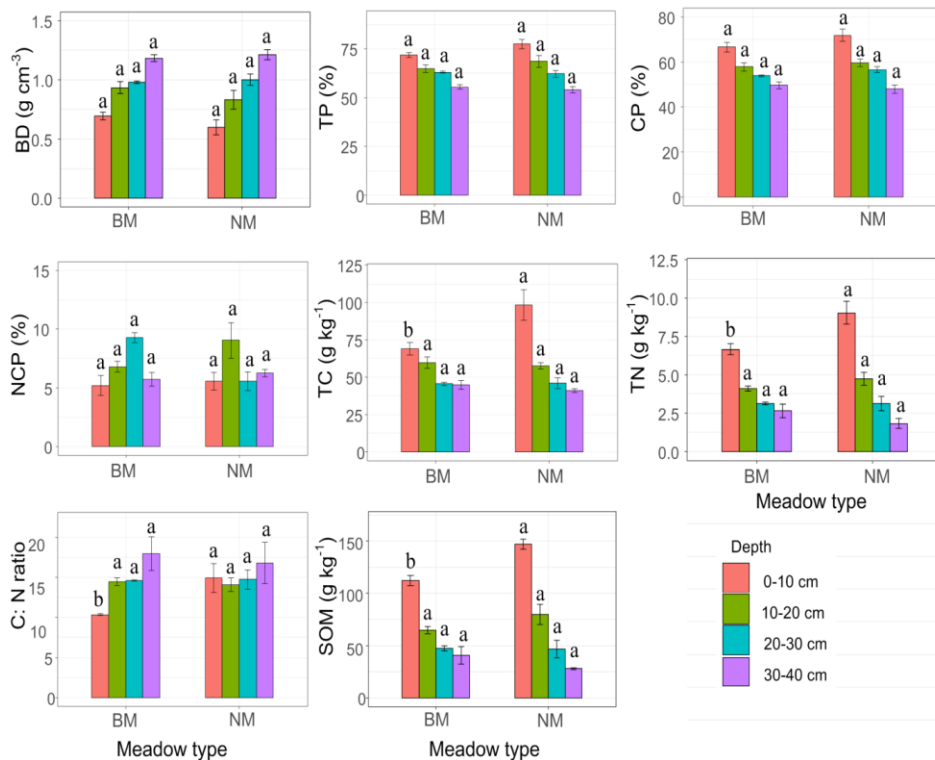


442
443 Fig.1 The study site (a) and two type meadows in this study: normal *Kobresia* meadow (b) and
444 biocrust meadow (c)
445
446
447
448
449
450
451

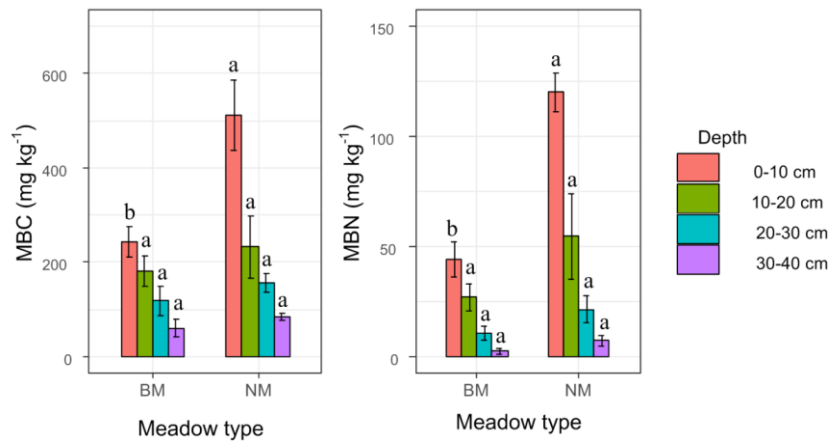


452

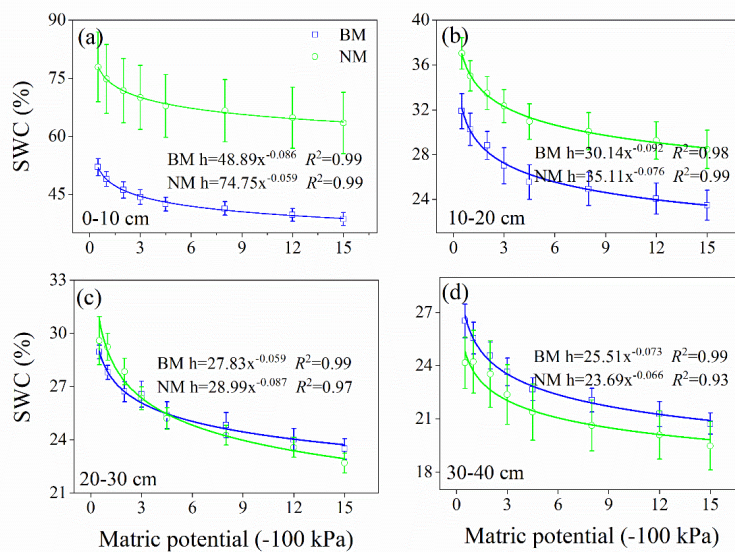
453 Fig.2 Soil textureSoil particle size distributionSoil texture among two surface soil types. Note: NM,
 454 normal *Kobresia* meadow; BM, biocrusts meadow, the different letters mean significant differences
 455 ($P < 0.05$) between normal *Kobresia* meadow and crust meadow at the same soil layer.



456
 457 Fig.3 The soil physicochemical among two surface soil types, BD: soil bulk density, TP: soil total
 458 porosity, CP: soil capillary porosity, NCP: non-capillary porosity, TN: soil total nitrogen, TC: soil
 459 total carbon, C:N: soil C: N ratio, SOM: soil organic matter, the different letters mean significant
 460 differences ($P < 0.05$) between normal *Kobresia* meadow and crust meadow at the same soil layer
 461
 462

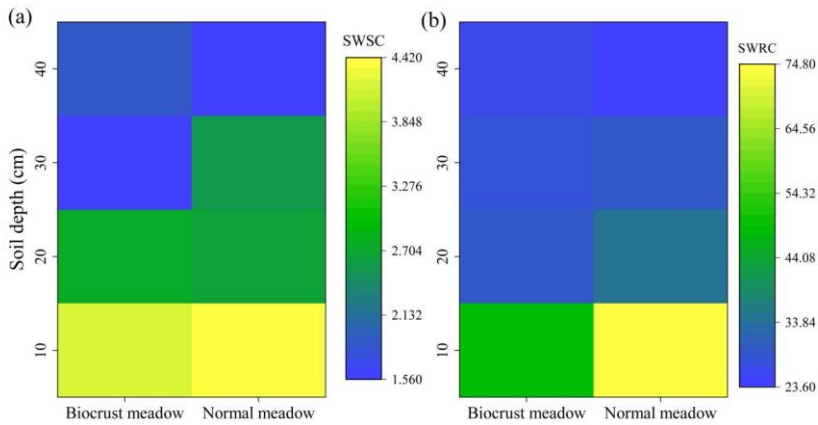


463
 464 Fig. 4 Soil microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) among two
 465 surface soil types, the different letters mean significant differences ($P < 0.05$) between normal
 466 *Kobresia* meadow and crust meadow at the same soil layer
 467

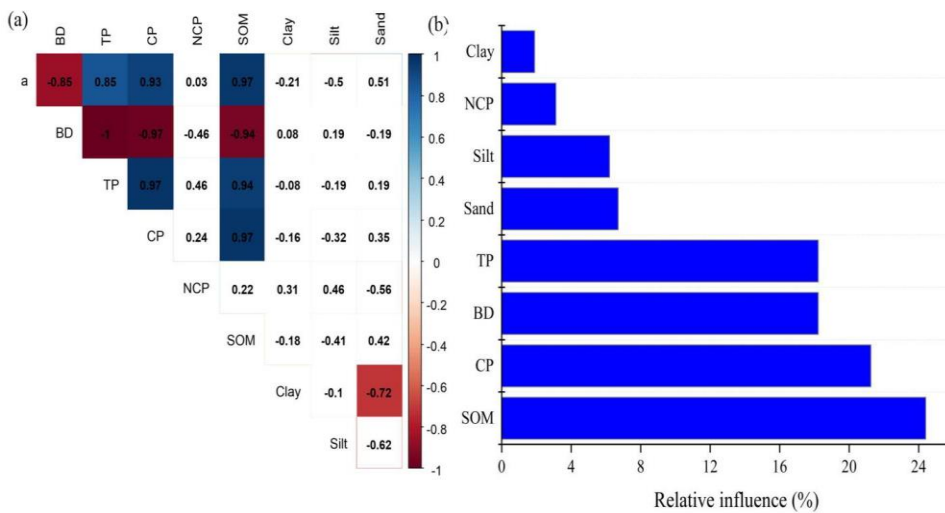


468
 469 Fig.5 Soil water retention curve of different soil layer (a: 0-10 cm, b: 10-20 cm, c: 20-30 cm, d: 30-
 470 40 cm) among two surface soil types between soil water content (SWC) and matric potential. Note:
 471 NM, normal *Kobresia* meadow; BM, biocrusts meadow, the soil water retention curve was fitted by
 24

472 Gardner model (i.e. $h = A\theta^B$), A and B are the fitting parameters; a higher value of A indicated a
 473 higher soil water-holding capacity.
 474



475
 476 Fig.6 Soil water supply capacity (SWSC) (a) and soil water retention capacity (SWRC) (b)of
 477 different soil layer among two surface soil types, the SWSC was represent the A*B from Gardner
 478 model, the SWRC represent the A from Gardner model, a higher value of A*B and A indicated a
 479 higher soil water supply capacity and soil water retention capacity, respectively.
 480

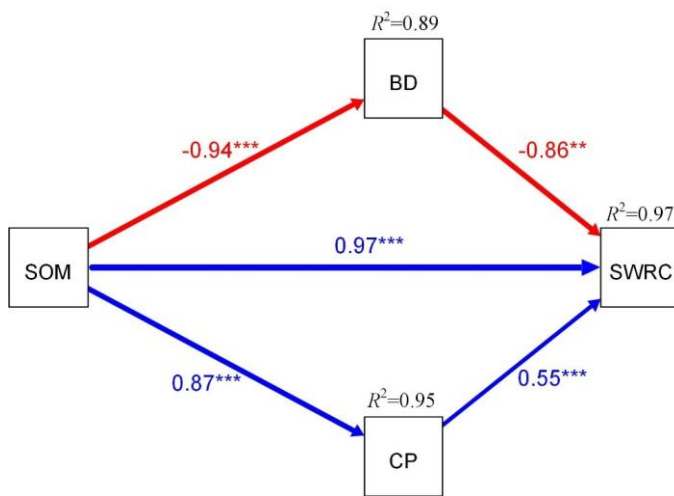


481
 482 Fig. 7 Pearson correlation between soil water retention and soil properties (a) among two surface
 25

483 soil types, and the relative influence of soil properties on soil water retention (b). Note: the “*”,
 484 “***” and “****” indicated significant at 0.05, 0.01 and 0.001 level, respectively. Note: a: the
 485 parameter fitted by Gardner model, BD: soil bulk density, TP: soil total porosity, CP: capillary
 486 porosity, NCP: non-capillary porosity, SOM: soil organic matter.

487

488



489

490 Fig. 8 Structural equation modeling of the direct and indirect effects of soil properties on soil water
 491 retention capacity (SWRC) among two surface soil types. Standardized path coefficients, adjacent
 492 to arrows, are analogous to partial correlation coefficients, and indicative of the effect size of the
 493 relationship. Continuous blue and red lines represent positive and negative correlations, respectively.
 494 Model fit: Fisher.C=5.48, $df=2$, P -value=0.065.

495

496

497

498

499

500

501

502

503 Table 1 The soil saturated hydraulic conductivity, soil water content and root density across two
 504 type meadow
 505

	NM	BM
K_s (mm min ⁻¹)	1.36	0.80
Soil water content (%)		
0-10 cm	41.58	18.77
10-20 cm	41.88	27.70
20-30 cm	35.93	29.45
30-40 cm	29.34	29.59
Root density (g m ⁻²)		
0-10 cm	3012.62	4917.89
10-20 cm	622.63	1431.53
20-30 cm	154.18	194.25
30-40 cm	93.01	142.02

506 Note: NM, normal Kobresia meadow; BM, biocrusts meadow

507

508

509

510