

1 **Title: Infrared heater warming system markedly reduces dew**
2 **formation: An overlooked factor in arid ecosystems**

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4 Tianjiao Feng^{a,†}, Lixu Zhang^{a,†}, Qian Chen^a, Zhiyuan Ma^a, Hao Wang^b, Zijian
5 Shangguan^a, Lixin Wang^c, Jin-Sheng He^{a,b,*}

6 *^aInstitute of Ecology, College of Urban and Environmental Sciences, and Key*
7 *Laboratory for Earth Surface Processes of the Ministry of Education, Peking*
8 *University, Beijing 100871, China*

9 *^bState Key laboratory of Grassland Agro-ecosystems, College of Pastoral Agriculture*
10 *Science and Technology, Lanzhou University, Lanzhou 730020, China*

11 *^cDepartment of Earth Sciences, Indiana University–Purdue University Indianapolis*
12 *(IUPUI), Indianapolis, IN 46202, USA*

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17 *†Co-first authors: Tianjiao Feng and Lixu Zhang have equal contribution to this study.*

18 **Corresponding author: Jin-Sheng He (jshe@pku.edu.cn):*

19 *State Key laboratory of Grassland Agro-ecosystems, College of Pastoral Agriculture*
20 *Science and Technology, Lanzhou University, Lanzhou 730020, China*

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23 **ABSTRACT**

24 Dew plays a vital role in ecosystem processes in arid and semi-arid regions
25 and is expected to be affected by climate warming. Infrared heater warming
26 systems have been widely used to simulate climate warming effects on
27 ecosystem. However, how this warming system affects dew formation has been
28 long ignored and rarely addressed. In a typical alpine grassland ecosystem on the
29 Northeast of the Tibetan Plateau, we measured dew amount and duration by
30 artificial condensing surfaces, leaf wetness sensors and *in situ* dew formation on
31 plants from 2012 to 2017. We also measured plant traits related to dew
32 conditions. The results showed that (1) warming reduced the dew amount by
33 41.6%-91.1% depending on the measurement method, and reduced dew duration
34 by 32.1 days compared to the ambient condition. (2) Different plant functional
35 groups differed in dew formation. (3) Under the infrared warming treatment, the
36 dew amount decreased with plant height, while under the ambient conditions, the
37 dew amount showed the opposite trend. We concluded that warming with an
38 infrared heater system greatly reduces dew formation, and if ignored, it may lead
39 to overestimation of the effects of climate warming on ecosystem processes in
40 climate change simulation studies.

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42 *Key Words:* Alpine ecosystem; Climate warming; Dew formation; Tibetan Plateau

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44 **1. Introduction**

45 Dew is considered a vital vegetative water source in semiarid and arid areas
46 (Beysens, 1995; Agam and Berliner, 2006; Wang et al., 2017a). In such environments,
47 dew plays an indispensable role on plants (Benasher et al., 2010; Zhuang and
48 Ratcliffe, 2012; Oliveira, 2013), biological crusts (Zhang et al., 2009; Fischer et al.,
49 2012; Kidron and Temina, 2013), small animals (Steinberger et al., 1989; Zheng et al.,
50 2010) and plant-associated microorganisms (Agam and Berliner, 2006). Dew also has
51 significant effects on relative humidity, vapor pressure deficits and nutrient cycling
52 (Munné, 1999; Goldsmith et al., 2013; Wang et al., 2019), and these factors influence
53 plant photosynthesis, transpiration and other important ecological processes
54 (Benasher et al., 2010; Wang et al., 2017a).

55 Dew formation in ecosystems is affected by microclimatic parameters (e.g., air
56 temperature, relative humidity and vapor pressure deficit) and plant morphological
57 features (e.g., aboveground biomass, leaf area, leaf roughness and plant height). These
58 factors change under different climatic conditions and are associated with different
59 plant species or functional groups (Agam and Berliner, 2006; Hao et al., 2012). Thus,
60 it is expected that rapidly changing climates will significantly affect dew formation
61 (Walther et al., 2002; Xiao et al., 2013; Li et al., 2018).

62 To simulate climate warming, an infrared heater warming system is widely used
63 to address the potential impacts of climate warming on ecosystems in the field (Liu et
64 al., 2018; Song et al., 2019; Ettinger et al., 2019). However, there are differences
65 between artificial warming and natural warming (Shaver et al., 2000) and the effects

66 of artificial warming have the potential to influence dew formation (Wolkovich et al.,
67 2012; Moni et al., 2019).

68 Recently, there are increasing number of studies on dew research
69 (Tomaszkiewicz et al., 2015; Wang et al., 2017a), most of which analyzed the
70 ecological effects of dew on ecosystem processes, such as plant photosynthesis and
71 transpiration in ecosystems (Ninari and Berliner, 2002; De Boeck et al., 2015; Wang
72 et al., 2019), or compared the effects of environmental factors on dew formation (Hao
73 et al., 2012; Ettinger et al., 2019; Beysens, 2016). There are also substantial efforts
74 have been made to study the potential impacts of climate warming on dryland
75 ecosystems by manipulating temperature in the field with various warming facilities
76 (Kimball et al., 2018; Moni et al., 2019; Song et al., 2019). However, the effects of
77 artificial warming on dew formation and ecosystem processes have not been
78 addressed. As a result, the observed changes in ecological processes in various
79 climate change studies are likely attributed, to some extent, to altered dew amounts,
80 misrepresenting the effects of warming on ecosystem processes.

81 Few studies on dew research have been conducted in the context of climate
82 change, and global warming experiments have not reported the effects of climate
83 change or plant traits and functional groups on dew formation or even considered the
84 effects of dew as a long-term factor affecting soils and plants as well as ecosystem
85 processes during the course of climate change (Tomaszkiewicz et al., 2015; Li et al.,
86 2018). On the other hand, few studies have investigated the influences of different
87 plant traits or functional groups on dew amount and duration (Wang et al., 2012; Xu

88 et al., 2015; Tomaszewicz et al., 2016). Therefore, the impacts of artificial warming,
89 plant traits and functional groups on dew formation urgently need to be revealed to
90 better understand the impacts of warming on ecosystem processes (Korell et al.,
91 2019).

92 Experimental data from field-based climate change experiments are crucial to
93 determine mechanistic links between simulated climate change and dew formation.
94 This study is a part of a comprehensive warming experiment in a typical alpine
95 grassland in Tibet Plateau, where we measured the dew amount and duration by the
96 methods of the artificial condensation surface, leaf wetness sensor and *in situ* plant
97 dew formation measurement to explore the responses of dew formation among
98 different functional groups to simulated climate warming. The objectives of the
99 present study were to (1) address how the widely used infrared heater warming
100 system affects dew amount and duration and (2) elucidate whether plant functional
101 groups, which are expected to shift under future warming, affect dew formation under
102 ambient and warming conditions. Our results will aid in the understanding of the
103 characteristics of dew formation under a warming climate in the future.

104

105 **2. Materials and methods**

106 *2.1. Study site*

107 The study site was located at Haibei National Field Research Station of the
108 Alpine Grassland Ecosystem (37°36' N, 101°19' E, 3215 m a.s.l.) in the northeastern
109 part of the Tibetan Plateau, China. The mean annual air temperature and precipitation

110 were $-1.2\text{ }^{\circ}\text{C}$ and 489.0 mm during 1980-2014, respectively (Liu et al., 2018).
111 Approximately 80% of the precipitation was concentrated in the growing season
112 (from May to September). This mesic alpine grassland is dominated by *Stipa aliena*,
113 *Elymus nutans* and *Helictotrichon tibeticum*. The soil is classified as a Mollisol
114 according to USDA Soil Taxonomy. The average soil bulk density, organic carbon
115 concentration and pH were $0.8\text{ g}\cdot\text{cm}^{-3}$, $63.1\text{ g}\cdot\text{kg}^{-1}$ and 7.8 at the 0-10 cm soil depth,
116 respectively (Lin et al., 2016).

117 2.2. Warming experiment design

118 Our study was conducted within an experimental warming \times precipitation
119 infrastructure within an area of $50\text{ m} \times 110\text{ m}$ that was established in July 2011. The
120 design of the experiment was detailed in Liu et al. (2018). In brief, the experiment
121 manipulated the temperature ($+2\text{ }^{\circ}\text{C}$, control) and precipitation ($+50\%$, control, -50%)
122 with a completely randomized design. Each treatment had six replications with a plot
123 area of $2.2\text{ m} \times 1.8\text{ m}$ (Liu et al., 2018). The warming treatment was applied by two
124 infrared heaters (220 V , 1200 W , 1.0 m long, and 0.22 m wide) (Ma et al., 2017). In
125 the current study, we only compared ambient and warming conditions.

126 Air temperature and relative humidity probes (VP-3, METER Group, Inc.,
127 Pullman, WA, USA) were installed 30 cm above the soil surface within each plot. All
128 data were automatically recorded hourly and stored in a data logger (EM50, METER
129 Group, Inc., Pullman, WA, USA).

130 2.3. Dew formation measurements

131 We used three methods to measure dew amount and duration:

132 (1) **Artificial condensation surface:** The daily dew production was collected
133 and measured using a preplaced plastic film, 20 cm × 20 cm in size, at each plot
134 (Vuollekoski et al., 2015). The clean plastic films were weighed and placed at each
135 plot at 20:00 pm (local time) the day before each measurement. At 6:00 am the next
136 morning, the preplaced plastic films were weighed, and the differences in the weights
137 were designated as the dew production (g) for that night. The dew amount (mm) was
138 equal to the dew weight divided by the area of the plastic film. In this study, the dew
139 amounts were measured by this method on sunny and windless days two times per
140 week during the peak growing seasons (from July to September) in 2012 and 2013.

141 (2) ***In situ* dew formation measurements on plants:** Dew formation on
142 plants was measured by sampling the outside plots to avoid disturbing the plant
143 community composition of each plot. Similar individuals of the same species were
144 chosen to measure dew formation. For each species, four or five individuals were
145 selected, weighed, measured plant heights and placed into floral foam to prevent
146 wilting the day before measurement and then placed at each plot at 20:00 pm (local
147 time). At 6:00 am the next morning, these plants were weighed after being brought
148 back to the laboratory to attain the total weight. The dew production (g) was equal to
149 the total weight minus the plant fresh weight. At the same time, we scanned the leaf
150 area of plants and finally calculated the dew amount (mm) produced per unit plant
151 area. In this study, the dew amounts were measured by this method on sunny and
152 windless days three times per week during the peak growing season (from July to
153 September) in 2017.

154 (3) **Leaf wetness sensors:** The dew amount and duration were monitored hourly
155 using leaf wetness sensors (S-LWA-M003, Onset Computer Corporation, Bourne,
156 MA, USA) and a HOBO data logger (H21-002, Onset Computer Corporation,
157 Bourne, MA, USA) at each plot from 2015 to 2017 (Chen 2015). The dew amount
158 was calculated by the fitting relationship between the measured leaf wetness sensor
159 readings and the actual condensed water amount (g). We sprayed water evenly on the
160 leaf wetness sensors to induce water condensation on their surface, recorded the
161 instrument reading, and established the relationship between the condensation amount
162 and the leaf wetness sensor readings. In addition, the simulated solid condensation
163 amount was determined using the same method in a -20 °C refrigerator to establish a
164 relationship curve. We repeated the above steps multiple times to ensure a wide range
165 of leaf wetness sensor readings. The relationship curve between the leaf wetness
166 sensor readings and the condensation amount was fitted (Fig. S1), and the relationship
167 was as follows:

$$168 \quad D = (0.00005 \times Rl^2 + 0.0001 \times Rl) / S, R^2 = 0.71, p < 0.001,$$

169 where D is the dew amount (mm), Rl is the leaf wetness sensor reading and S is
170 the area of the leaf wetness sensor, which was 4.7 cm × 5.1 cm.

171 In our study, the former two measurement methods focused on dew amount,
172 while only the leaf wetness sensor method measured the dew duration. The data were
173 automatically recorded hourly, and dew duration was calculated as the number of days
174 for which dew was recorded between 8:00 p.m. and 6:00 a.m. of the next morning
175 during the measuring periods.

176 2.4. Dew formation and aboveground biomass at the species level

177 In total, we measured dew formation at the species level for 10 species. These
178 ten species accounted for approximately 72% of the total community biomass (Liu et
179 al., 2018). We divided these plant species into three functional groups, i.e., grasses
180 (*Stipa aliena*, *Elymus nutans* and *Helictotrichon tibeticum*), forbs (*Tibetia himalaica*,
181 *Oxytropis ochrocephala*, *Medicago ruthenica*, *Gentiana straminea* and *Saussurea*
182 *pulchra*), and sedges (*Kobresia humilis* and *Carex przewalskii*) and separately
183 analyzed their dew formation responses to warming. The aboveground biomass was
184 separated into grasses, sedges, and forbs, harvested and oven-dried at 65 °C to a
185 constant weight. Plant height was measured using five selected individuals per species
186 in each plot before dew formation measurement during the experimental periods.

187 2.5. Data Analysis

188 Based on long-term meteorological observations, the dew point temperature was
189 calculated by Penman-Monteith equation with the following function (Allen et al.,
190 1998):

$$\begin{aligned} 191 \quad T_{\text{dew}} &= \frac{116.91 + 237.3 \ln(e_a)}{16.78 - \ln(e_a)} \\ 192 \quad e_a &= \frac{\text{RH}}{100} e^o(T) \\ 193 \quad e^o(T_a) &= 0.6108 \exp\left[\frac{17.27T}{T+237.3}\right], \end{aligned}$$

194 where T_{dew} is dew point temperature [°C], e_a is actual vapour pressure [kPa], e^o
195 (T) is saturation vapor pressure at the air temperature T_a [kPa], and T_a is air
196 temperature [°C]. Meanwhile, the temperature differences ($T_a - T_{\text{dew}}$) was calculated by
197 the difference between the air temperature (T_a) and dew point temperature (T_{dew}) to

198 represent the difficult degrees of dew formation.

199 The dew point temperature was calculated using long-term meteorological
200 observations. Linear regression was used to test the relationship between plant height
201 and dew amount in the control and warming treatments. To test the warming effect,
202 one-way analysis of variance (ANOVA) and Tukey's HSD test were used to
203 determine differences in dew amount and duration between the control and warming
204 plots. All statistical analyses were conducted using R 3.2.2 software (R Foundation
205 for Statistical Computing, Vienna, Austria, 2013). Differences were considered
206 significant at $P < 0.05$ unless otherwise stated.

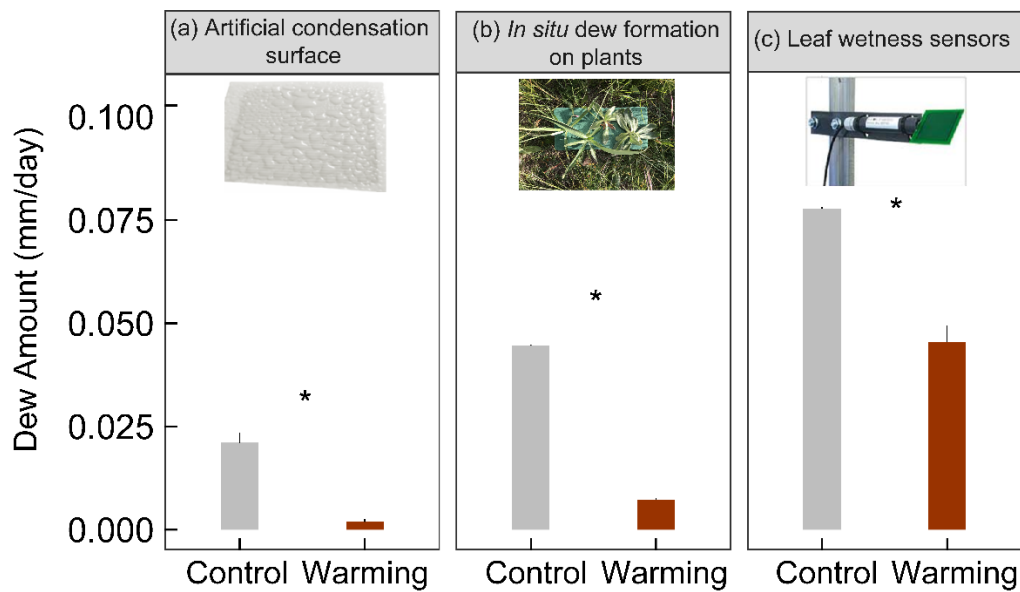
207

208 **3. Results**

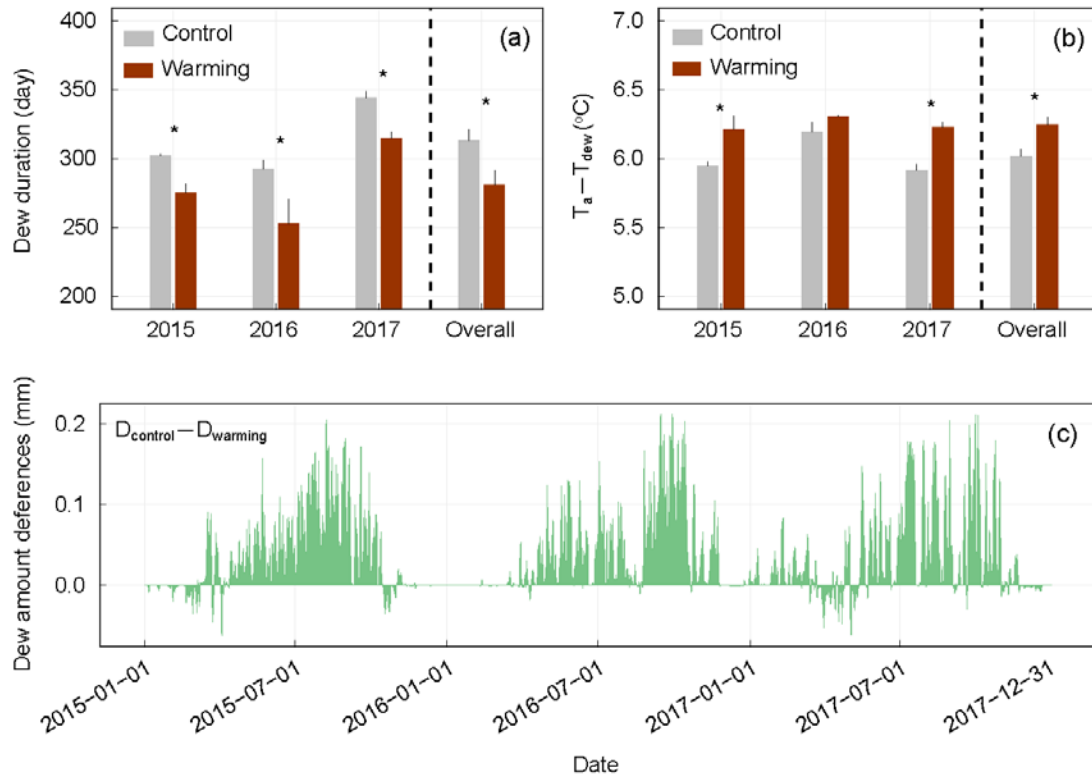
209 *3.1. Effects of warming on the dew formation*

210 The multiple measurement methods showed decreased dew amounts under
211 warming conditions. Warming resulted in average decreases of 91.7%, 83.9% and
212 41.6% in dew amount by the artificial condensation surface method, the in situ dew
213 formation on plants and the leaf wetness sensors, respectively (linear mixed-effects
214 model: $P < 0.001$; Fig. 1). From 2015 to 2017, warming significantly decreased the
215 dew duration by an average of 10.3% (linear mixed-effects model: $P < 0.001$; Fig.
216 2a). Therefore, warming reduced the total dew formation by not only reducing the
217 daily dew amounts (mm/day) but also the dew duration (days). The results also
218 showed that warming significantly increased the temperature differences ($T_a - T_{dew}$) by
219 3.8% ($P < 0.001$; Fig. 2b), which made dew formation more difficult. Furthermore,

220 the differences in the dew amount between the control and warming treatments
221 ($D_{\text{control}} - D_{\text{warming}}$) showed significant differences at the seasonal scale (Fig. 2c). The
222 dew amounts under the warming treatment decreased by an average of 0.05 mm (up
223 to 64.5%) during the growing seasons and only decreased by an average of 0.006 mm
224 (only 27.5%) in non-growing seasons (Fig. 2c).



225
226 Fig. 1. The dew amount measured by (a) artificial condensation surface, (b) *in situ*
227 dew formation on plants and (c) leaf wetness sensors in control and warming
228 treatments during the experimental period.



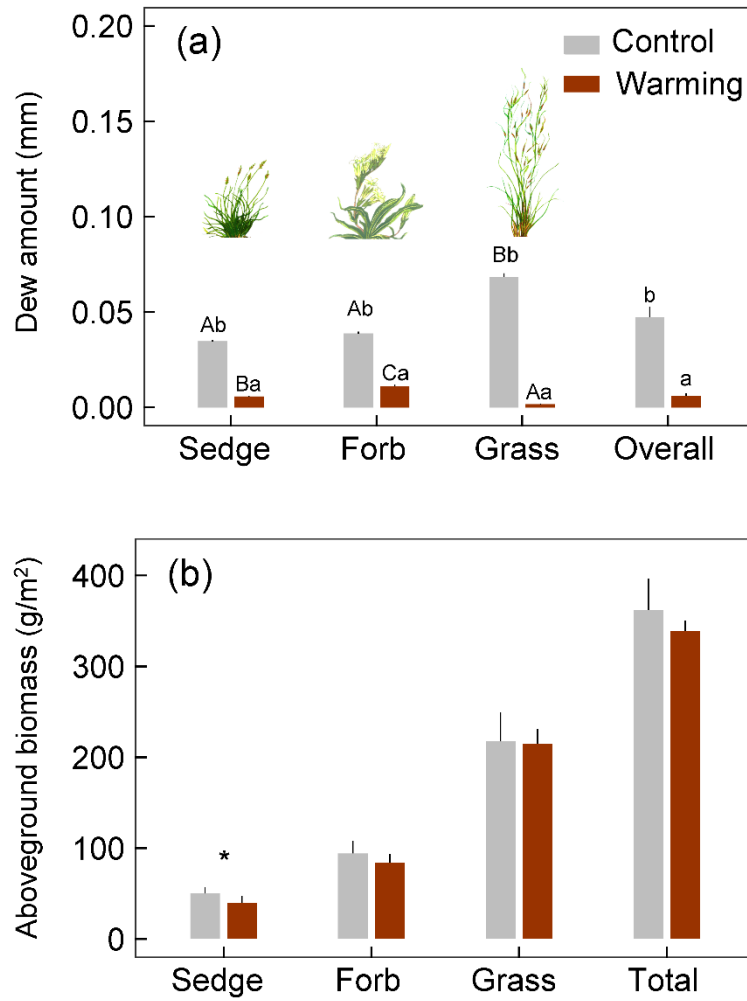
229

230 Fig. 2. Warming effects on (a) dew duration, (b) the difference between the air
231 temperature (T_a) and dew point temperature (T_{dew}) and (c) the differences of dew
232 amount between the control and warming treatment. * indicates statistically
233 significant at $P < 0.001$.

234 3.2. *Effects of warming on dew amount among different functional groups*

235 The total aboveground biomass and dew amounts among each functional group
236 were measured by *in situ* dew formation measurements on plants in this study. The
237 results showed that different plant functional groups significantly differed in dew
238 formation and warming significantly decreased the dew amount among each
239 functional group (a reduction of 83.5%, 71.6%, 97.6% and 87.0% for sedges, forbs,
240 grasses and all species combined, Fig. 3a), while it slightly changed the aboveground
241 biomass of different functional groups (Fig. 3b).

242



243

244 Fig. 3. Warming effects on (a) dew amount and (b) aboveground biomass of different

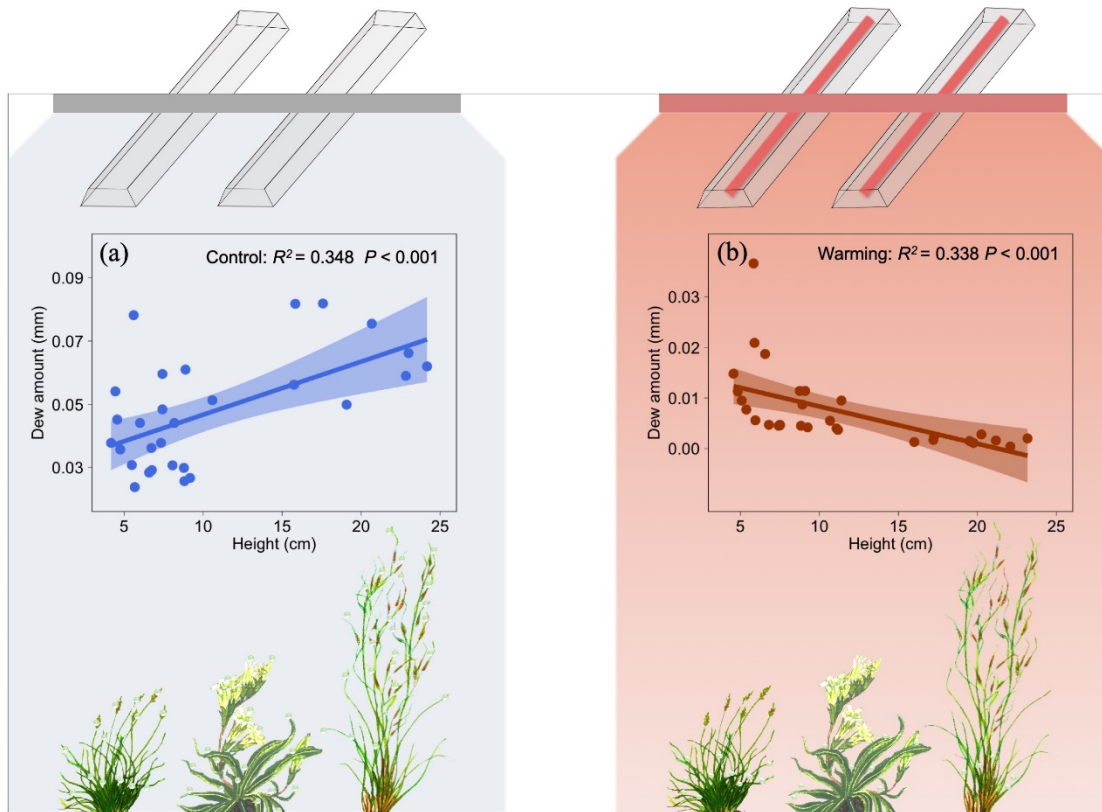
245 functional groups. Different uppercase letters indicate significant difference in

246 different functional groups ($P < 0.05$) and different lowercase letters indicate

247 significant difference in control and warming treatments ($P < 0.05$).

248 3.3. Effects of warming on the relationships between plant height and
249 dew amount

250 Compared with the control treatment, the warming treatment significantly
251 affected the relationship between plant height and dew amount ($P < 0.001$, $n=60$; Fig.
252 4). In the control treatment, linear regression revealed that the dew amount was
253 significantly positively correlated with plant height ($R^2 = 0.35$, $P < 0.001$; Fig. 4a).
254 However, dew amount was significantly negatively correlated with plant height ($R^2 =$
255 0.34 , $P < 0.001$; Fig. 4b) in the warming treatment.



256
257 Fig. 4. The relationships between plant height and dew amount in control and
258 warming plots.

259

260 **4. Discussion**

261 *4.1. Warming reduces dew amount and changes seasonal patterns of dew* 262 *formation*

263 Using three distinct measurement methods, our study showed that warming
264 significantly reduces dew amount (Fig. 1), which may have substantial impacts on
265 plant growth especially during the dry period in the alpine and dryland ecosystems
266 (Stone, 1957; Jacobs et al., 2006; Benasher et al., 2010; Rodney et al., 2013).
267 Warming can reduce dew formation in two ways: by hindering dew condensation and
268 shortening dew retention. Warming can hinder the dew condensation processes by
269 decreasing the air humidity and increasing evaporation (Oliveira 2013; Scheff and
270 Frierson, 2014; Li et al., 2018). Additionally, warming changes the air temperature,
271 dew point temperature and dew point depression (Fig. 2b), which makes it more
272 difficult for the air temperature to approach the dew point temperature (Beysens,
273 1995; Jacobs et al., 2006; Mortuza et al., 2014). Warming can also accelerate the dew
274 evaporation process (Xiao et al, 2013). Dew droplets lasted for a shorter period of
275 time under warmer temperatures, which also led to a lower dew duration or amount
276 (Xu et al., 2015).

277 In this study, we found that warming not only reduces dew formation but also
278 changes its seasonal variation (Fig. 2). Therefore, plants growing under water stress
279 would have higher risks of not surviving under warming conditions (Rodney et al.,
280 2013; Tomaszewicz et al., 2017). Overall, under the rapidly changing climate,
281 changes in dew formation should be considered an important environmental factor

282 and should not be neglected in arid and cold regions.

283 *4.2. Dew formation varied among different functional groups under*
284 *warming*

285 Functional groups create different microenvironments and have different water
286 use strategies to influence the dew production and absorption by plants (Zhuang and
287 Zhao, 2017; Wang et al., 2019). Environmental conditions, such as temperature,
288 relative humidity and wind speed, change due to various micromorphological features
289 and distribution patterns among different functional groups (Agam and Berliner
290 2006), affecting dew formation and duration (Ninari and Berliner 2002). Our results
291 showed that different functional groups had different degrees of dew formation,
292 consistent with our expectations.

293 To date, few studies have investigated how biotic factors (e.g., plant traits and
294 functional groups) affect dew formation. Here, we examined the effects of plant traits
295 (i.e., plant height and aboveground biomass) on dew formation in different plant
296 functional groups (sedges, forbs and grasses) and found that sedges and forbs with
297 shorter heights are associated with less dew than grasses with taller heights under
298 natural conditions (Fig. 3). Because under ambient conditions, the upper canopy air
299 temperature is lower at night due to this area receiving less land-surface radiation,
300 dew formation occurs earlier in higher leaves, such as those of grasses (Zhang et al.,
301 2009; Wang et al., 2017a). In addition, the dominant taller species (*Stipa aliena*,
302 *Elymus nutans*, and *Helictotrichon tibeticum*) usually have more aboveground
303 biomass (Konrad et al., 2015; Ma et al., 2017) than shorter species, which can

304 facilitate dew formation and retention (Pan et al., 2010). Additionally, the dew water
305 stored within a dense canopy can be preserved for a longer period of time through the
306 reduction in evaporation (Xiao et al., 2013).

307 Under warming conditions, the aboveground biomass and plant height increased,
308 and the community composition changed with a higher prevalence of grass in the
309 alpine ecosystems (Liu et al., 2018). Such changes should be beneficial for dew
310 formation based on our findings under ambient conditions (i.e., results from the
311 control plots, Fig. 4a). However, a substantial reduction in dew formation was
312 observed under the warming treatments (Fig. 1 and Fig. 2). In addition, we found that
313 warming resulted in a lower dew amount on taller plants, in contrast to the results
314 under ambient conditions (Fig. 4). Warming changed the relationship between plant
315 height and dew amount in both direct and indirect ways. Warming directly affected
316 the air temperature profile and made dew formation more difficult (Wolkovich et al.,
317 2012). In this case, the taller plants had less dew formation because artificial infrared
318 heating made the temperature of the taller canopy higher than that of the lower
319 canopy (Xiao et al., 2013). Warming indirectly caused the soil moisture to evaporate
320 more quickly during the night (Tomaszkiewicz et al., 2015; Li et al., 2018). Therefore,
321 the shorter plants experienced more dew collection than the higher plants during the
322 night under warming conditions. Clearly, warming influenced the dew formation on
323 plants and changed the ecosystem processes compared with those under natural
324 conditions.

325 *4.3. Infrared heater warming system reduces dew formation: An*
326 *overlooked factor in climate change studies*

327 There have been many studies about the response of ecosystem processes to
328 climate change using various artificial warming methods in dry ecosystems (Kimball
329 et al., 2018; Song et al., 2019; Korell et al., 2019), but the possible impacts from the
330 differences between artificial and natural warming on the experimental results have
331 often been overlooked. Our results showed that artificial warming (with an infrared
332 heater warming system) affects dew formation, which likely affects ecosystem
333 processes (Liu et al., 2016). However, it is worth noting that natural climate warming
334 and the infrared heater warming system differ in terms of their heat-dissipating
335 pathways (Korell et al., 2019). Artificial warming generates more heat radiation in the
336 air and drier micro-environments than natural warming (Liu et al., 2018). This
337 difference will affect a number of ecosystem processes and is often overlooked across
338 simulated climate change experiments. Warming makes plants grow taller (Liu et al.,
339 2018), but taller plants produced less dew under warming in our study (Fig. 3). This
340 indicates that the dew formation was significantly reduced under the experimental
341 warming conditions. In addition, the relationship between dew formation and plant
342 height changed being positively correlated under the control treatment to being
343 negatively correlated under the warming treatment (Fig. 4). For such cases, the
344 conclusions of the impacts of warming obtained by artificial warming experiments
345 may deviate from the actual impacts of warming on ecosystem processes. Under
346 future climate warming, the changes in water condensation will also have an

347 especially profound impact on the ecosystem patterns and processes in dryland
348 ecosystems (Li et al., 2018; Wang et al., 2017b). Therefore, we suggest that the
349 impact of experimental warming on dew formation should be considered an important
350 environmental factor affecting ecosystems processes during climate warming.

351

352 **5. Conclusions**

353 Using three measurement methods, we observed that warming significantly
354 reduced the dew amount and duration and changed its seasonal patterns. Different
355 plant functional groups had different effects on dew formation due to their associated
356 microclimates and plant heights, resulting in taller plants experiencing more dew
357 formation. However, artificial warming caused the taller plants to have less dew
358 formation due to the associated heat radiation. We also found that infrared heater
359 warming systems markedly reduced dew formation, which should be addressed to
360 avoid overestimating the impact of climate warming on ecosystems during global
361 change studies. Our study demonstrates that dew condensation responds to climate
362 warming and highlights that microhabitat conditions and plant traits mediate dew
363 formation under warming conditions, having an important potential effect on
364 ecosystems processes in the future.

365

366 **Authors' contributions**

367 Jin-sheng He conceived the ideas and designed methodology; Lixu Zhang and
368 Qian Chen collected the data; Lixu Zhang, Zhiyuan Ma, Zijian Shangguan, Hao Wang

369 and Tianjiao Feng analysed the data; Lixu Zhang and Tianjiao Feng led the writing of
370 the manuscript with the assistances from Lixin Wang. All authors contributed
371 critically to the drafts and gave final approval for publication.

372

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378

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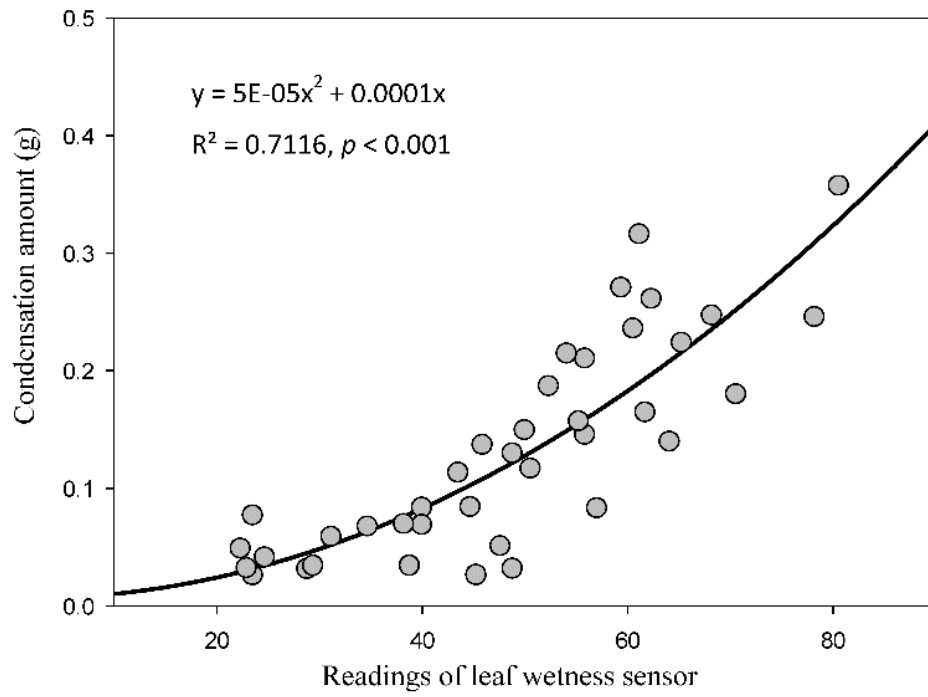
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541 Fig. S1 Fitting curve of the readings of leaf wetness sensor and condensation amount

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