Title: Dew formation reduction in global warming experiments and the potential consequences

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ABSTRACT

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

Key Words: Alpine ecosystem; Climate warming; Ecohydrology; Dew formation; Non-rainfall water; Tibetan Plateau: Warming experiments

1. Introduction

Dew, as an important contribution of non-rainfall water (NRW), is considered a vital water source in semiarid and arid areas (Agam and Berliner, 2006; Wang et al., 2017a; Beysens, 2018; Kidron and Starinsky, 2019). In such environments, water is a limiting factor and dew plays an indispensable role on plants (Benasher et al., 2010; Zhuang and Ratcliffe, 2012; Oliveira, 2013; Hill et al., 2015; Wang et al., 2019), biological crusts (Zhang et al., 2009; Fischer et al., 2012; Kidron and Temina, 2013), small animals (Steinberger et al., 1989; Zheng et al., 2010) and microorganisms (Agam and Berliner, 2006; Kidron et al., 2011; Kidron and Temina, 2013 and 2017; Kidron and Kronenfeld, 2019). Dew also determined the magnitude of water and energy flux and ecological processes during the periods of drought (Beysens et al., 2006; Zhang et al., 2019; Gotsch et al., 2015). In particular, dew has significant effects on soil-plant interactions (Munné, 1999; Kidron and Starinsky, 2012; Goldsmith et al., 2013; Wang et al., 2019), and dew influences plant foliar uptakes (Berry et al., 2019; Berry and Goldsmith, 2020), increases photosynthesis (by enhancing CO_2 uptake) and decrease transpiration (Beysens, 1995; Benasher et al., 2010; Wang et al., 2017a; Goldsmith et al., 2017).

To date, evidence suggests that dew in ecosystems alters microclimate by changing energy balance, water budget and plant water status (Tomaszkiewicz et al., 2015; Kaseke and Wang, 2018). In turn, dew formation in ecosystems is affected by many factors. Dew results from the condensation of water vapor on a surface, in contrast to fog, soil water adsorption or other non-rainfall water (Kaseke et al., 2017;

Beysens, 2018; Kidron and Starinsky, 2019; Kidron and Kronenfeld, 2020). Dew condensation process can proceed because the substrate surface cools down below the dew point temperature of surrounding air, due to the radiation deficit between surface and atmosphere (Beysens, 2016; Beysens et al., 2003). Dew formation therefore depends on the details of the condensation surface properties (e.g., substrate shape, size, emissivity and heat capacity, and surface roughness), location (e.g., angle, orientation position and height above ground, determining the sky view factor) and the characteristics of the atmospheric condition (e.g., air temperature, relative humidity and vapor pressure deficit, Kidron, 2005; Kidron and Starinsky, 2019). The dew formation processes and the influencing factors were thoroughly covered by Agam and Berliner (2006), Kidron and Starinsky (2019), Beysens (1995, 2006), and the important book of Beysens (2018). Furthermore, the above-mentioned factors (e.g., substrate properties, atmospheric condition) would change under different climatic conditions and are associated with different plant species or functional groups (Agam and Berliner, 2006; Hao et al., 2012; Liu et al., 2020). Few studies have investigated the influences of different plant functional groups on dew formations. Plant functional groups can change the micro-environment and substrates properties affecting dew amount and duration through differences in aboveground biomass, leaf area, leaf roughness and plant height (Wang et al. 2012, Xu et al. 2015, Tomaszkiewicz et al. 2016). Thus, it is expected that rapidly changing climates and different plant functional groups will significantly affect dew formation (Walther et al., 2002; Xiao et al., 2013; Li et al., 2018).

To simulate climate warming, an infrared heater warming system is widely used to address the potential impacts of climate warming on ecosystems in the field (Liu et al., 2018; Song et al., 2019; Ettinger et al., 2019). However, there are differences between infrared heater warming and natural warming (Song et al., 2019; Shaver et al., 2000). For natural warming, the extra energy should dissipate in three pathways: sensible heat, latent heat and soil heat fluxes (Shaver et al., 2000; Rustad et al. 2001). These three energy dissipation pathways are responsible for warming of the air, increasing evapotranspiration and heating the soil, respectively (Shaver et al., 2000). In terms of the three heat dissipation pathways, the infrared heater warming system is technically different from the natural warming. It will increase the air temperature and the air sensible heat radiation, which will lead to the increase of the drying degree in the micro-environment at the community scale, and will affect a number of ecosystem processes (Rustad et al. 2001, Liu et al. 2016). Therefore, the effects of infrared heater warming have the potential to influence dew formation (Wolkovich et al., 2012; Moni et al., 2019).

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

Few studies on dew research have been conducted in the context of climate change, and global warming experiments have not reported the effects of climate change or plant traits and functional groups on dew formation or even considered the effects of dew as a long-term factor affecting soils and plants as well as ecosystem processes during the course of climate change (Tomaszkiewicz et al., 2015; Li et al., 2018). On the other hand, few studies have investigated the influences of different plant traits or functional groups on dew amount and duration (Wang et al., 2012; Xu et al., 2015; Tomaszkiewicz et al., 2016). Therefore, the impacts of artificial warming, plant traits and functional groups on dew formation urgently need to be revealed to better understand the impacts of warming on ecosystem processes (Korell et al., 2019).

Experimental data from field-based climate change experiments are crucial to determine mechanistic links between simulated climate change and dew formation. This study is a part of a comprehensive warming experiment in a typical alpine grassland in Tibet Plateau (Liu et al., 2018), where we measured the dew amount and duration using the methods of the artificial condensation surface, leaf wetness sensor and *in situ* plant dew formation measurement to explore the responses of dew formation among different functional groups to simulated climate warming. The objectives of the present study were to (1) address how the widely used infrared heater warming system affects dew amount and duration and (2) elucidate whether plant functional groups, which are expected to shift under future warming, affect dew formation under ambient and warming conditions. Our results will enhance the understanding of the characteristics of dew formation under a warming climate in the future.

2. Materials and methods

2.1. Study site

The study site was located at Haibei National Field Research Station of the Alpine Grassland Ecosystem (37°36′ N, 101°19′ E, 3215 m a.s.l.) in the northeastern part of the Tibetan Plateau, China. The mean annual air temperature and precipitation were -1.2 °C and 489.0 mm during 1980-2014, respectively (Liu et al., 2018). Approximately 80% of the precipitation was concentrated in the growing season (from May to September). The ambient conditions of air temperature and precipitation distribution of study area was shown at Fig. 1. This mesic alpine grassland is dominated by *Stipa aliena*, *Elymus nutans* and *Helictotrichon tibeticum*. The soil is classified as a Mollisol according to USDA Soil Taxonomy. The average soil bulk density, organic carbon concentration and pH were 0.8 g·cm^{-3}, 63.1 g·kg^{-1} and 7.8 at the 0-10 cm soil depth, respectively (Lin et al., 2016).

2.2. Warming experiment design

Our study was conducted within an experimental warming × precipitation infrastructure within an area of 50 m × 110 m that was established in July 2011 (Fig. 2a). The design of the experiment was detailed in Liu et al. (2018). In brief, the experiment manipulated the temperature (+2 °C, control) and precipitation (+50%, control, -50%) with a completely randomized design. Each treatment had six replicates, and six plots of 2.2 m × 1.8 m were randomly divided into six blocks. The warming treatment was warmed by two infrared heaters (220 V, 1200 W, 1.0 m long, 0.22 m wide and 1.2 m above the ground), which operate all the time and had been resulting in an increase of 2°C above ambient temperature at the top 5 cm layer of the soil (Ma et al., 2017). In the current study, we only compared ambient and warming conditions (Fig. 2).

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

2.3. Dew formation measurements

We used three methods to measure dew amount and duration (Fig. 3):

(1) **Artificial condensation surface:** The daily dew production was collected and measured using a preplaced plastic film, 20 cm × 20 cm in size, 15 cm above the

ground, at each plot (Vuollekoski et al., 2015; Kidron and Starinsky, 2019). The specific material is Polyethylene (PE) and its thickness is 0.05 cm. The IR emissivity of this material ranges from 0.81to 0.93 (Zhu 2007) and it is 0.91 in our study calculated by the manufacturer. Moisture and dew measurements are calculated by the difference in weight before and after dew collection. Specifically, the clean plastic films were weighed and placed at each plot at 20:00 pm (local time) the day before each measurement. At 6:00 am the next morning, the preplaced plastic films were weighed, and the differences in the weights were designated as the dew production (g) for that night. The dew amount (mm) was equal to the dew weight divided by the area of the plastic film. In this study, the dew amounts were measured by this method on sunny and windless days two times per week (total number of measurements were 42) during the peak growing seasons (from July to September) in 2012 and 2013.

(2) ***In situ* dew formation measurements on plants**: Dew formation on plants was measured by sampling the outside plots to avoid disturbing the plant community composition of each plot. Similar individuals of the same species were chosen to measure dew formation. For each species, four or five individuals were selected, weighed (fresh weight), measured plant heights and placed into floral foam to prevent wilting the day before measurement and then placed at each plot at 20:00 pm (local time). At 6:00 am the next morning, these plants were weighed after being brought back to the laboratory to attain the total weight. The dew production (g) was equal to the total weight minus the plant fresh weight. At the same time, we scanned the leaf area of plants and finally calculated the dew amount (mm) produced per unit plant

area. In this study, the dew amounts were measured by this method on sunny and windless days three times per week (total number of measurements were 40) during the peak growing season (from July to September) in 2017.

(3) **Leaf wetness sensors**: The dew amount and duration were monitored hourly using leaf wetness sensors (S-LWA-M003, Onset Computer Corporation, Bourne, MA, USA), which is 15 cm above the ground and a HOBO data logger (H21-002, Onset Computer Corporation, Bourne, MA, USA) at each plot from 2015 to 2017 (Chen 2015). The dew amount was calculated by the fitting relationship between the measured leaf wetness sensor readings and the actual condensed water amount (g). We sprayed water evenly on the leaf wetness sensors to induce water condensation on their surface, recorded the instrument reading, and established the relationship between the condensation amount and the leaf wetness sensor readings. In addition, the simulated solid condensation amount was determined using the same method in a -20 °C refrigerator to establish a relationship curve. We repeated the above steps multiple times to ensure a wide range of leaf wetness sensor readings. The relationship curve between the leaf wetness sensor readings and the condensation amount was fitted (Fig. S1), and the relationship was as follows:

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

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

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

2.4. Dew formation and aboveground biomass at the species level

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

2.5. The extra radiative distribution

The radiative flux of infrared heater and the distance from the lamp to the condenser should affect the IR energy balance and dew formation. Here the extra IR power received by the condensing surface (radiative flux per unit condensing surface, G_i [W/m^2]) at different height compared to ambient conditions were quantitatively explained by following method:

$$S_i = a_i \cdot b_i = (2tan\alpha \cdot h_i + 0.22) \cdot b_i$$

$$G_i = \frac{P}{S_i} = \frac{P}{(2tan\alpha \cdot h_i + 0.22) \cdot b_i}$$

where S_i [m^2] and P [W] are irradiated area and mean emitted power by two infrared heaters (1.0 m long, 0.22 m wide, 1200W) at the height of h_i [m], respectively. α is the angle between the lampshade and the vertical line of the infrared lamp and it equals 30° in this study plots. a_i [m] and b_i [m] are the length and width of S_i. h_i [m] is the distance from the lamp to the condenser.

2.6 Data Analysis

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

$$\mathrm{T_{dew}} = \frac{116.91 + 237.3\ln(\mathrm{e_a})}{16.78 - \ln(\mathrm{e_a})}$$

$$\mathrm{e_a} = \frac{\mathrm{RH}}{100}\mathrm{e^o(T)}$$

$$\mathrm{e^o(Ta)} = 0.6108\exp\left[\frac{17.27\mathrm{T}}{\mathrm{T}+237.3}\right],$$

where T_{dew} is dew point temperature [^{o}C], e_a is actual vapour pressure [kPa], e^o (T) is saturation vapor pressure at the air temperature T_a [kPa], and T_a is air temperature [^{o}C]. Meanwhile, the temperature differences (T_a-T_{dew}) was calculated by the difference between the air temperature (T_a) and dew point temperature (T_{dew}) to represent the difficult degrees of dew formation.

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

3. Results

3.1. Effects of warming on the dew formation

The multiple measurement methods showed decreased dew amounts under warming conditions. Warming resulted in average decreases of 91.7%, 83.9% and 41.6% in dew amount by the artificial condensation surfaces method, the *in situ* dew formation on plants and the leaf wetness sensors, respectively (linear mixed-effects model: $P < 0.001$; Fig. 4). From 2015 to 2017, warming significantly decreased the dew duration by an average of 10.3% (linear mixed-effects model: $P < 0.001$; Fig. 5a). Therefore, warming reduced the total dew formation by not only reducing the daily dew amounts (mm/day) but also the dew duration (days). The results also showed that warming significantly increased the temperature differences (T_a-T_{dew}) by 3.8% ($P < 0.001$; Fig. 5b), which made dew formation more difficult. Furthermore, the differences in the dew amount between the control and warming treatments ($D_{control}$-$D_{warming}$) showed significant differences at the seasonal scale (Fig. 5c).

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

The total aboveground biomass and dew amounts among each functional group were measured by *in situ* dew formation measurements on plants in this study. The results showed that different plant functional groups significantly differed in dew formation and warming significantly decreased the dew amount among each functional group (a reduction of 83.5%, 71.6%, 97.6% and 87.0% for sedges, forbs, grasses and all species combined, Fig. 6a), while it slightly changed the aboveground biomass of different functional groups (Fig. 6b).

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

Compared with the control treatment, the warming treatment significantly affected the relationship between plant height and dew amount ($P < 0.001$, n=60; Fig. 7). In the control treatment, linear regression revealed that the dew amount was significantly positively correlated with plant height ($R^2 = 0.35$, $P < 0.001$; Fig. 7a). However, dew amount was significantly negatively correlated with plant height ($R^2 = 0.34$, $P < 0.001$; Fig. 7b) in the warming treatment.

3.4 The radiative power distribution under inferred warming

Compared with the ambient treatment, the effects of infrared heaters on dew formation are mainly attributed to the extra IR heating radiative power received by the condensing surface at different heights. The infrared heaters are regarded as a linear light source, and their radiative area (S_i, m^2) increases with the increase of the distance from the lamps (Fig. 8a). With the constant emitting power, the extra IR power from the infrared heaters decreases gradually with the increase of the distance from the lamps (Fig. 8b). Therefore, the extra IR power increases gradually with the increase of height above ground. The relationship between extra radiative flux and the distance from the lamp was shown at Fig. 8b. The extra IR power at 10 cm from the lamps (110 cm above the ground) was 3181.8 W/m^2, while it was 436.0 W/m^2 at 120 cm from the lamps (at the surface ground). The extra IR power of infrared lamps at 10 and 20 cm above the ground were 469.7 W/m^2 and 509.2 W/m^2, respectively.

4. Discussion

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

Our study showed that warming significantly reduces dew amount using three distinct measurement methods (Fig. 4), but to different degrees. There are many methods and substrates have been used for dew harvest and they have different results even under the same climate conditions or at the same locations (Kidron and Starinsky, 2019; Groh et al., 2018). This is mostly due to different substrates properties in each method, such as shape, size, roughness, infrared emissivity, heat capacity and radiative cooling processes (Kidron, 2005; Kidron, 2010; Kidron and Starinsky, 2019). Also different collection methods involve different condensation water components such as water vapor adsorption, horizontal precipitation and guttation, which are challenging to be differentiated from one another (Kidron and Starinsky, 2019). Therefore in our study, we focus on the dew formation dynamics under warming and ambient conditions using three independent methods. The converging results enhance the robustness of our major conclusions on the impacts of infrared heating warming on dew formation. Warming can reduce dew formation in two ways: by hindering dew condensation and shortening dew retention. Warming can hinder the dew condensation processes by decreasing the air humidity and increasing evaporation (Oliveira 2013; Scheff and Frierson, 2014; Li et al., 2018). Additionally, warming changes the air temperature, dew point temperature and dew point depression (Fig. 5b), which makes it more difficult for the air temperature to approach the dew point temperature (Beysens, 1995; Jacobs et al., 2006; Mortuza et al., 2014). Warming can also accelerate the dew evaporation process (Xiao et al, 2013). Dew droplets lasted for a shorter period of time under warmer temperatures, which also led to a lower dew duration or amount (Xu et al., 2015).

In this study, we found that warming reduces dew formation (Fig. 5), which is a major contribution of NRW in water-limited ecosystems (Kidron and Starinsky, 2019). Therefore, plants growing under water stress would have higher risks of not surviving under warming conditions (Rodney et al., 2013; Tomaszkiewicz et al., 2017). On the other hand, it should be noticed that there is a regular diurnal variations in the daily dew amount and it must be influenced by rainfall distribution due to changed water vapor concentration and relative humidity in atmosphere and soil environment. Overall, under the rapidly changing climate, changes in dew formation should be considered an important environmental factor and should not be neglected in arid and cold regions.

4.2. Dew formation varied among different functional groups under warming

Functional groups create different microenvironments and have different water use strategies to influence the dew production and plant water uptake (Zhuang and Zhao, 2017; Wang et al., 2019). Dew formation is also great influenced by many factors, including substrate shape, size, emissivity and heat capacity, surface roughness, leaf angle, orientation position and plant height (Kidron and Starinsky 2019). Meanwhile, environmental conditions, such as temperature, relative humidity and wind speed, change due to various micromorphological features and distribution patterns among different functional groups (Agam and Berliner 2006), affecting dew formation and duration (Ninari and Berliner 2002). Our results showed that different functional groups had different degrees of dew formation, consistent with our expectations.

To date, few studies have investigated how biotic factors (e.g., plant traits and functional groups) affect dew formation. Here, we examined the effects of plant traits (i.e., plant height and aboveground biomass) on dew formation in different plant functional groups (sedges, forbs and grasses) and found that sedges and forbs with shorter heights are associated with less dew than grasses with taller heights under natural conditions (Fig. 6). Because under ambient conditions, the upper canopy air temperature is lower at night due to this area receiving less land-surface radiation, dew formation occurs earlier in higher leaves, such as those of grasses (Zhang et al., 2009; Wang et al., 2017a). In addition, the dominant taller species (*Stipa aliena*, *Elymus nutans*, and *Helictotrichon tibeticum*) usually have more aboveground biomass (Konrad et al., 2015; Ma et al., 2017) than shorter species, which can facilitate dew formation and retention (Pan et al., 2010). Additionally, the dew water stored within a dense canopy can be preserved for a longer period of time through the reduction in evaporation (Xiao et al., 2013).

Under warming conditions, the aboveground biomass and plant height increased, and the community composition changed with a higher prevalence of grass in the alpine ecosystems (Liu et al., 2018). Such changes should be beneficial for dew formation based on our findings under ambient conditions (i.e., results from the control plots, Fig. 7a). However, a substantial reduction in dew formation was observed under the warming treatments (Fig. 4 and Fig. 5). In addition, we found that warming resulted in a lower dew amount on taller plants, in contrast to the results under ambient conditions (Fig. 7). Warming changed the relationship between plant height and dew amount in both direct and indirect ways. Warming directly affected the air temperature profile and made dew formation more difficult (Wolkovich et al., 2012). In this case, the taller plants had less dew formation because artificial infrared heating made the temperature of the taller canopy higher than that of the lower canopy (Xiao et al., 2013). Warming indirectly caused the soil moisture to evaporate more quickly during the night (Tomaszkiewicz et al., 2015; Li et al., 2018). More importantly, according to energy balance model (Beysens, 2016), dew formation occurred with the radiative deficit power at the condensing surface (radiative emission minus radiative absorption from the environment) and the heat losses with surrounding air (Beysens, 2016; Beysens, 2018). As for artificial warming device, infrared heaters will supply extra IR power, which would be received by the condensing surface at different height. Based on the relationship between extra radiative flux of infrared heating lamp and the distance from the lamp (Fig. 8), the distance from lamp to plant should affect the IR energy balance during the dew formation process at different heights. Due to a smaller distance from the lamps, the taller plants have an increase in IR heating radiative flux under artificial warming conditions, leading to the less dew formation in this case. Therefore, the shorter plants experienced more dew collection than the higher plants during the night under warming conditions. Clearly, warming influenced the dew formation on plants and changed the ecosystem processes compared with those under natural conditions.

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

There have been many studies about the response of ecosystem processes to climate change using various artificial warming methods in dry ecosystems (Kimball et al., 2018; Song et al., 2019; Korell et al., 2019), but the possible impacts from the differences between artificial and natural warming on the experimental results have often been overlooked. Our results showed that artificial warming (with an infrared heater warming system) affects dew formation, which likely affects ecosystem processes (Liu et al., 2016). However, it is worth noting that natural climate warming and the infrared heater warming system differ in terms of their heat-dissipating pathways (Korell et al., 2019). Artificial warming generates more heat radiation in the air and drier micro-environments than natural warming (Liu et al., 2018). This difference will affect a number of ecosystem processes and is often overlooked across simulated climate change experiments. Warming makes plants grow taller (Liu et al., 2018), but taller plants produced less dew under warming in our study (Fig. 6). This indicates that the dew formation was significantly reduced under the experimental warming conditions. In addition, the relationship between dew formation and plant height changed being positively correlated under the control treatment to being negatively correlated under the warming treatment (Fig. 7). For such cases, the conclusions of the impacts of warming obtained by artificial warming experiments may deviate from the actual impacts of warming on ecosystem processes. Under future climate warming, the changes in water condensation will also have an especially profound impact on the ecosystem patterns and processes in dryland ecosystems (Li et al., 2018; Wang et al., 2017b). Therefore, we suggest that the impact of experimental warming on dew formation should be considered an important environmental factor affecting ecosystems processes during climate warming.

5. Conclusions

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

Declaration of Competing Interest

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

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Figure Captions

Fig. 1. The daily air temperature and precipitation distribution of study area

Fig. 2. The photos of study sites and diagram of experiment plots. (a) The overall view of the “warming × precipitation” platform; (b) photo of study sites; (c)diagram of warming experimental plots; (d) Thermal image of the warming pattern produced by the infrared heaters; (e) Daily average soil temperature under warming and control plots.

Fig. 3. The photos of dew collecting devices. (a) Artificial condensation surface; (b) *In situ* dew formation measurements on plants; (c) Leaf wetness sensors.

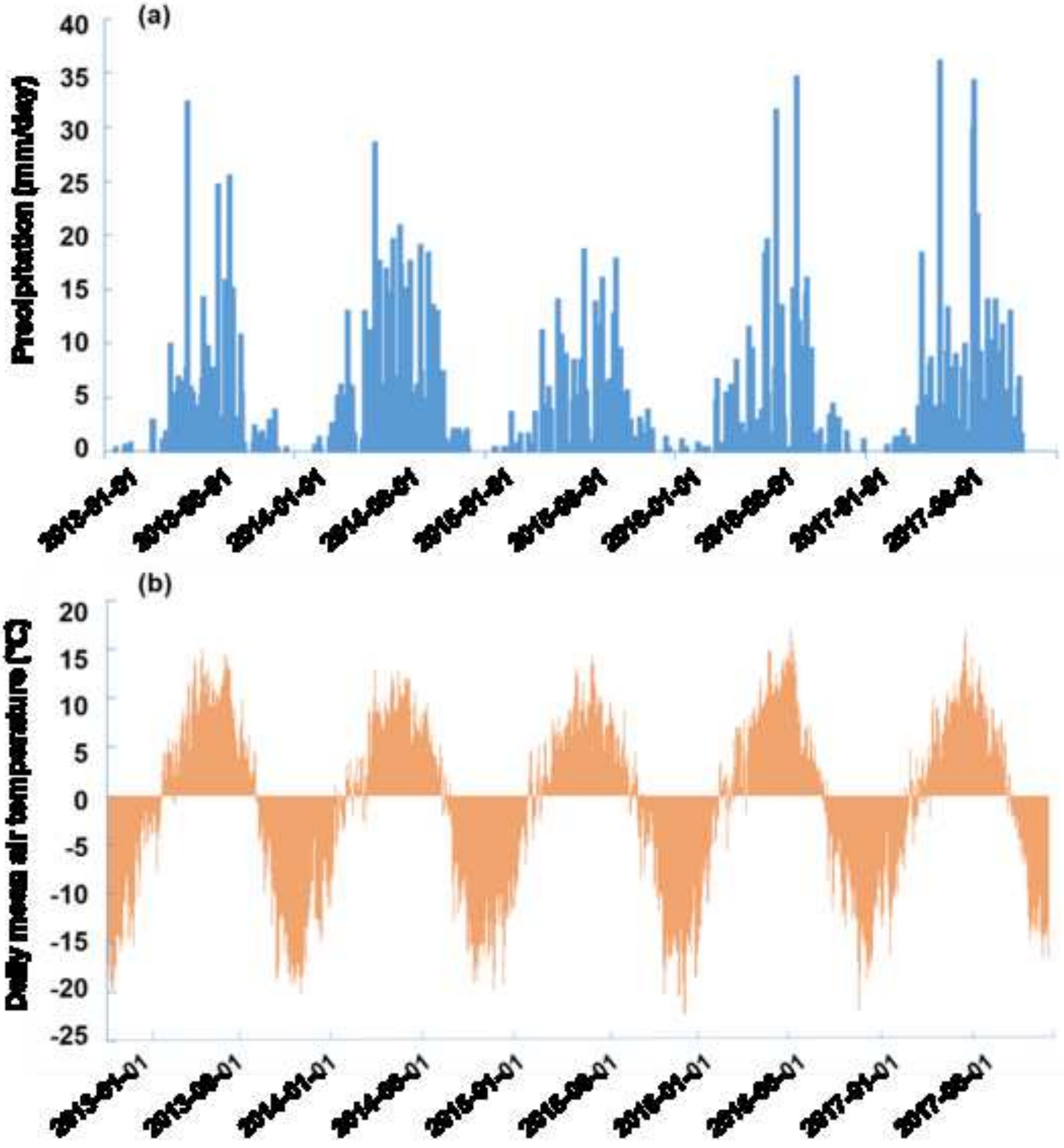
Fig.4. The dew amount measured by (a) artificial condensation surface, (b) *in situ* dew formation on plants and (c) leaf wetness sensors in control and warming treatments during the experimental period.

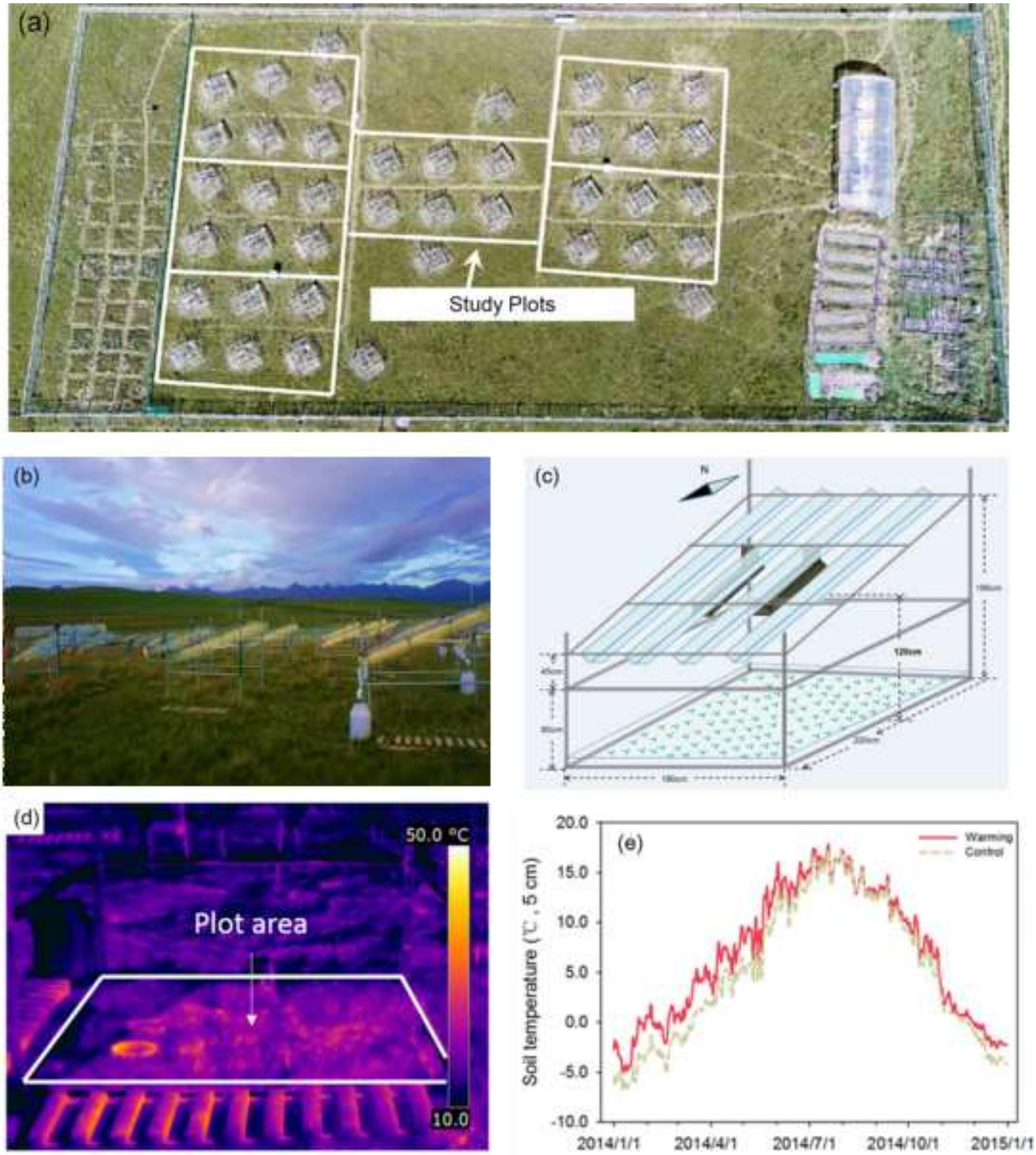
Fig. 5. Warming effects on (a) dew duration, (b) the difference between the air temperature (T_a) and dew point temperature (T_{dew}) and (c) the differences of dew amount between the control and warming treatment. * indicates statistically significant at $P < 0.001$.

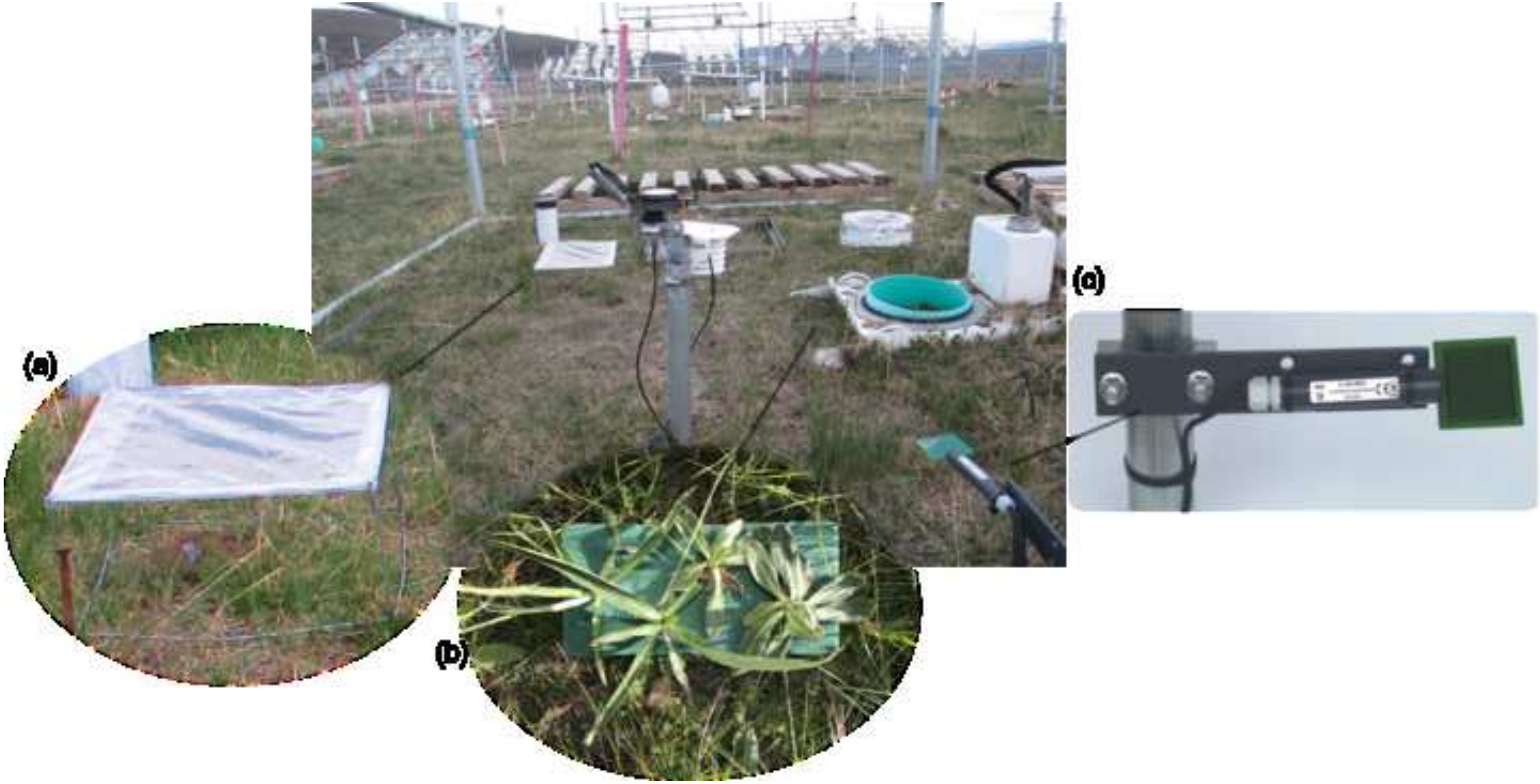
Fig. 6. Warming effects on (a) dew amount and (b) aboveground biomass of different functional groups. Different uppercase letters indicate significant difference in different functional groups ($P<0.05$) and different lowercase letters indicate significant difference in control and warming treatments ($P<0.05$).

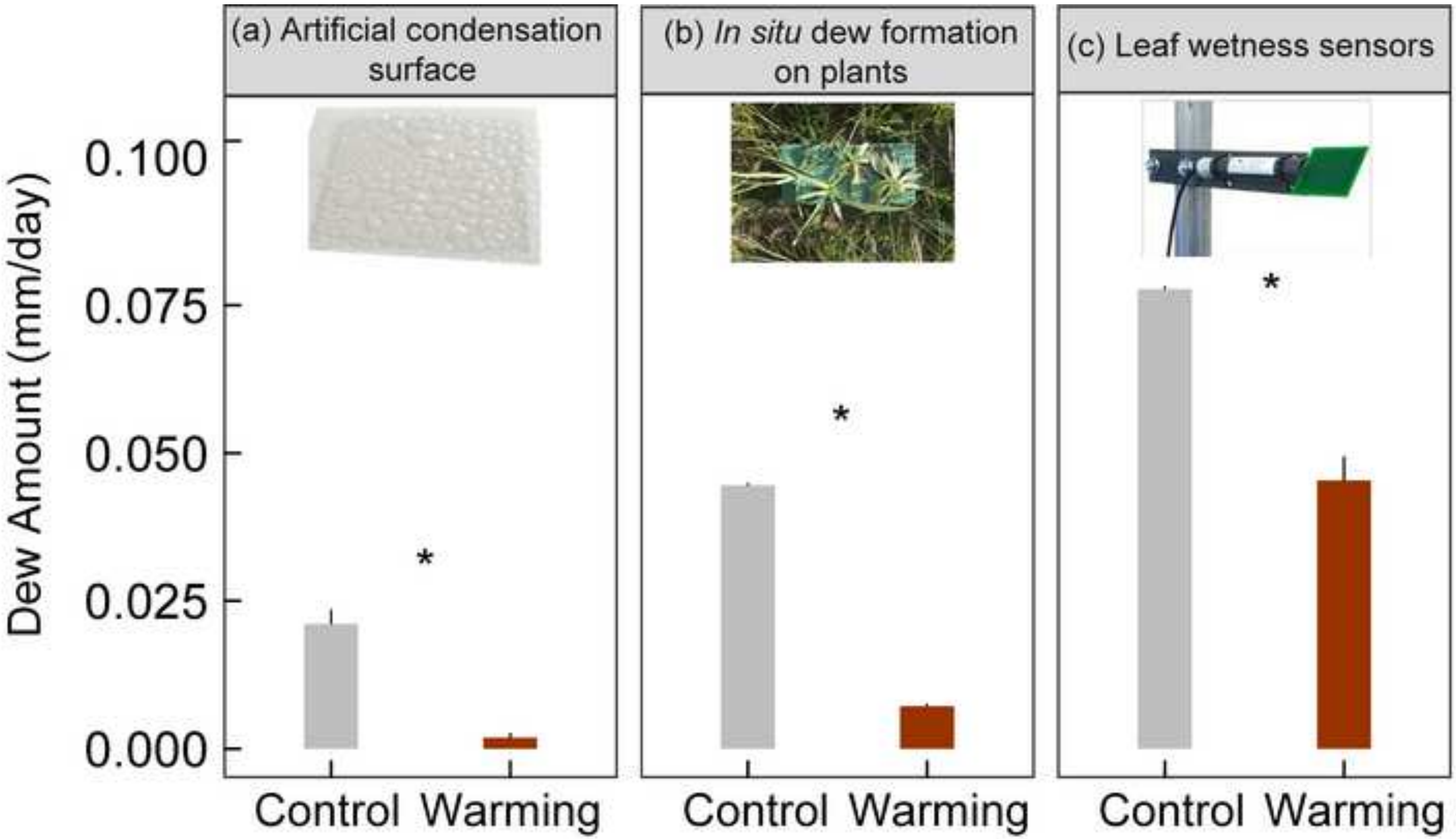
Fig. 7. The relationships between plant height and dew amount in control and warming plots.

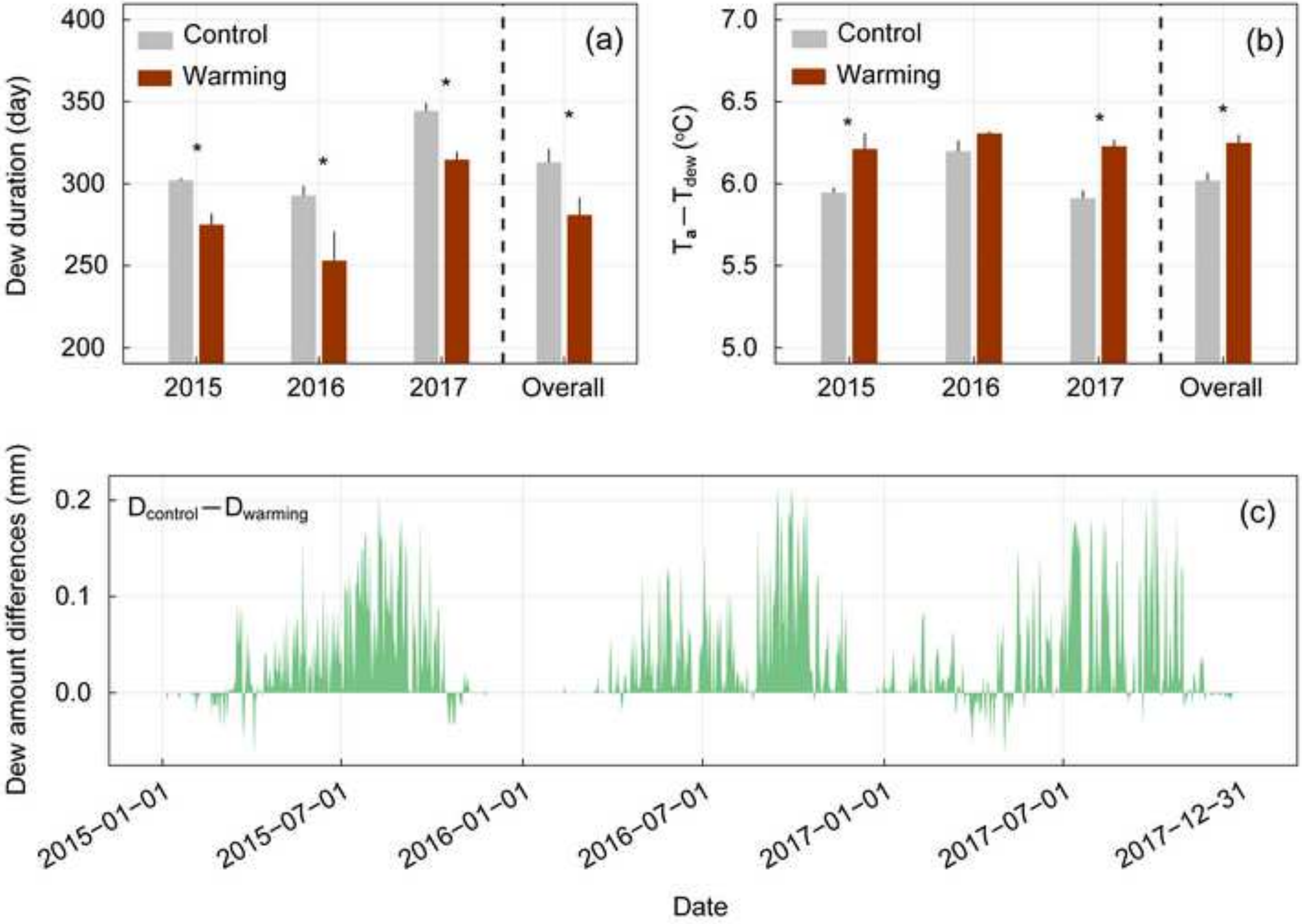
Fig. 8. The extra radiative flux by the infrared heaters. (a) The diagram of the radiation area by infrared heaters. (b) The relationship between extra radiative flux and the distance from the lamp.

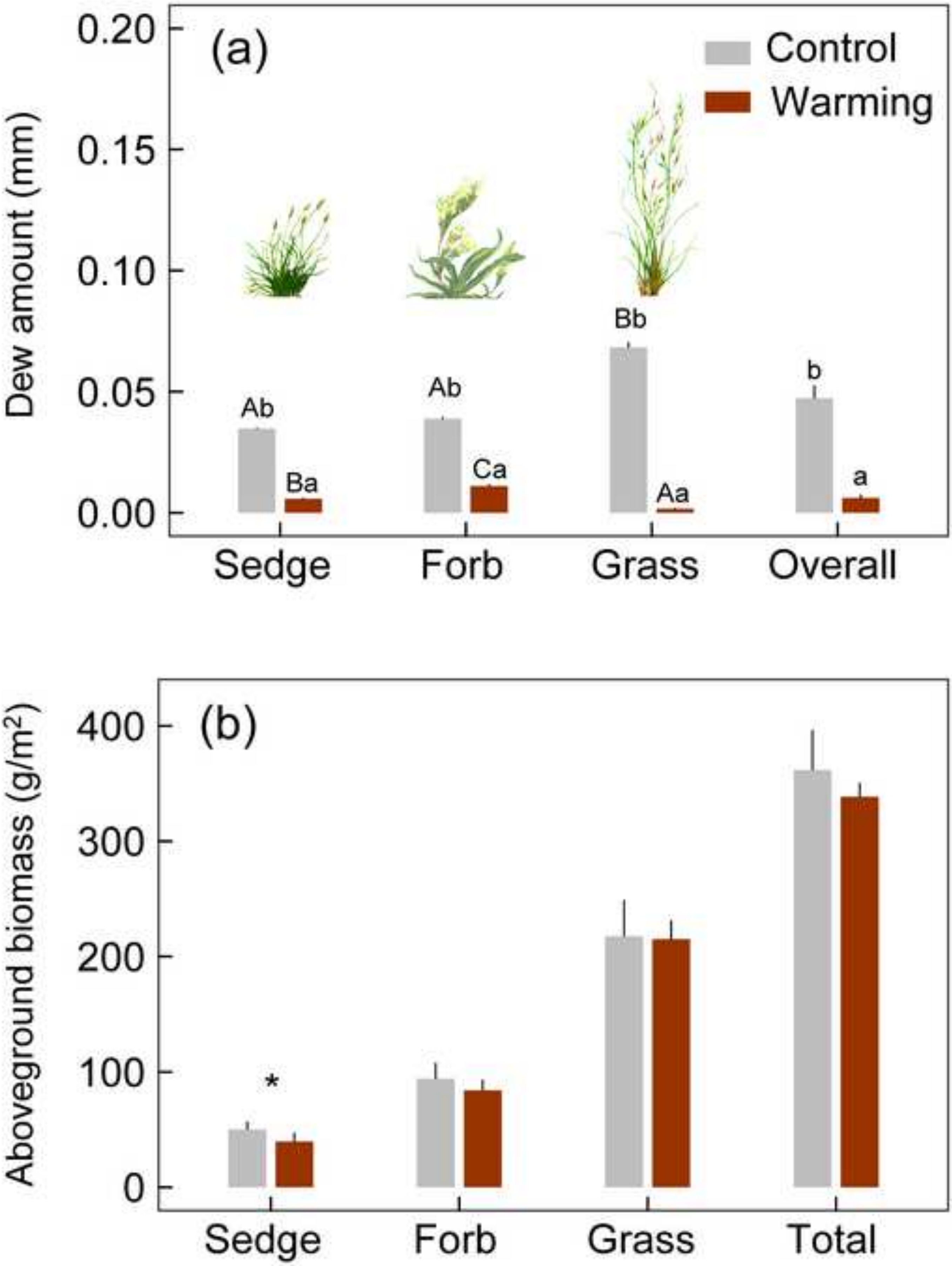

(a)
Precipitation (mm/day)
0
5
10
15
20
25
30
35
40
2013-01-01
2013-08-01
2014-01-01
2014-08-01
2015-01-01
2015-08-01
2016-01-01
2016-08-01
2017-01-01
2017-08-01
(b)
Daily mean air temperature (°C)
-25
-20
-15
-10
-5
0
5
10
15
20
2013-01-01
2013-08-01
2014-01-01
2014-08-01
2015-01-01
2015-08-01
2016-01-01
2016-08-01
2017-01-01
2017-08-01

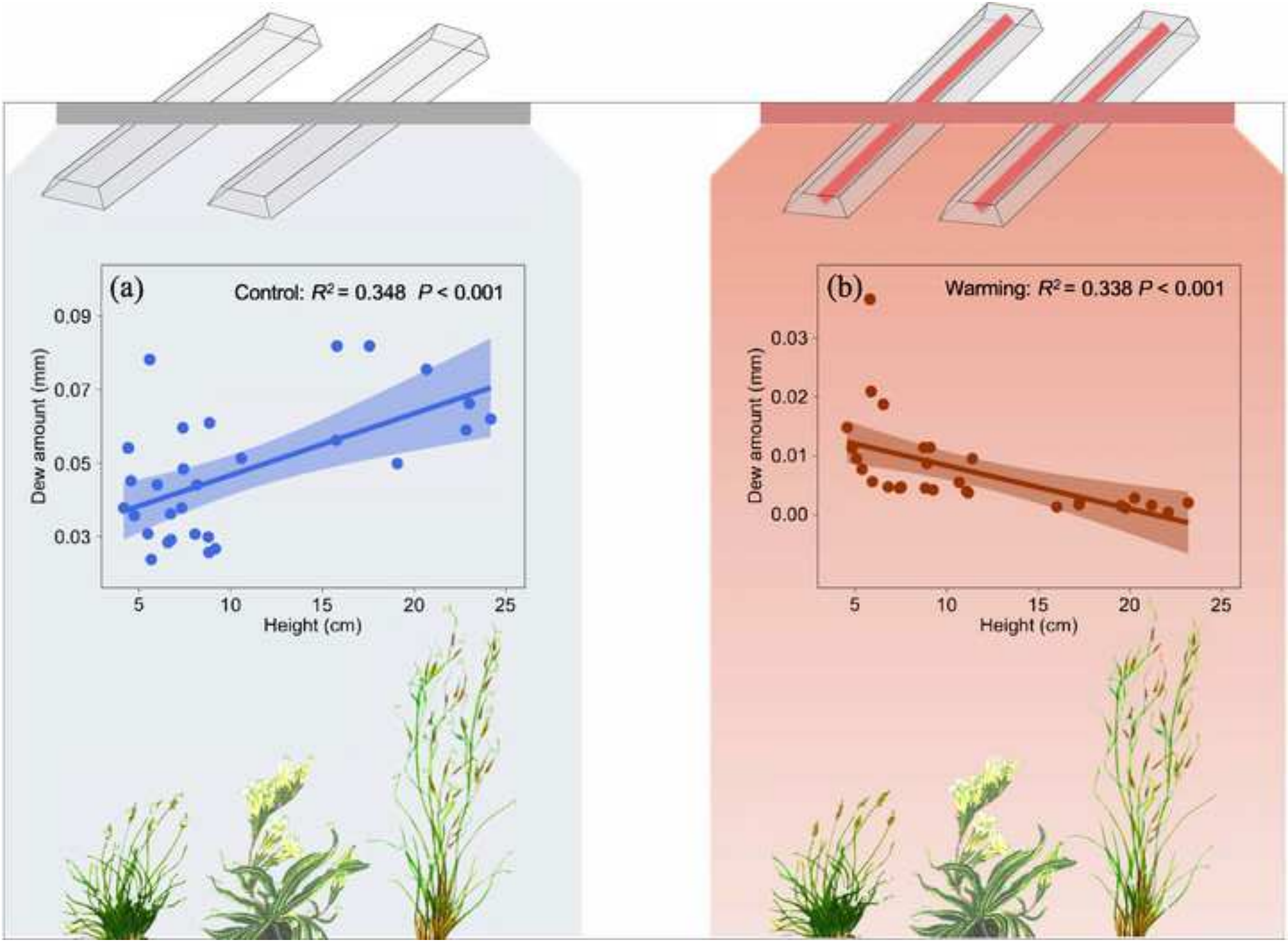

(a)
Study Plots
(b)
(c)
N
120cm
(d)
50.0 °C
Plot area
10.0
(e)
Warming
Control
Soil temperature (℃ , 5 cm)
20.0
15.0
10.0
5.0
0.0
-5.0
-10.0
2014/1/1
2014/4/1
2014/7/1
2014/10/1
2015/1/1


(a)
(b)
(c)

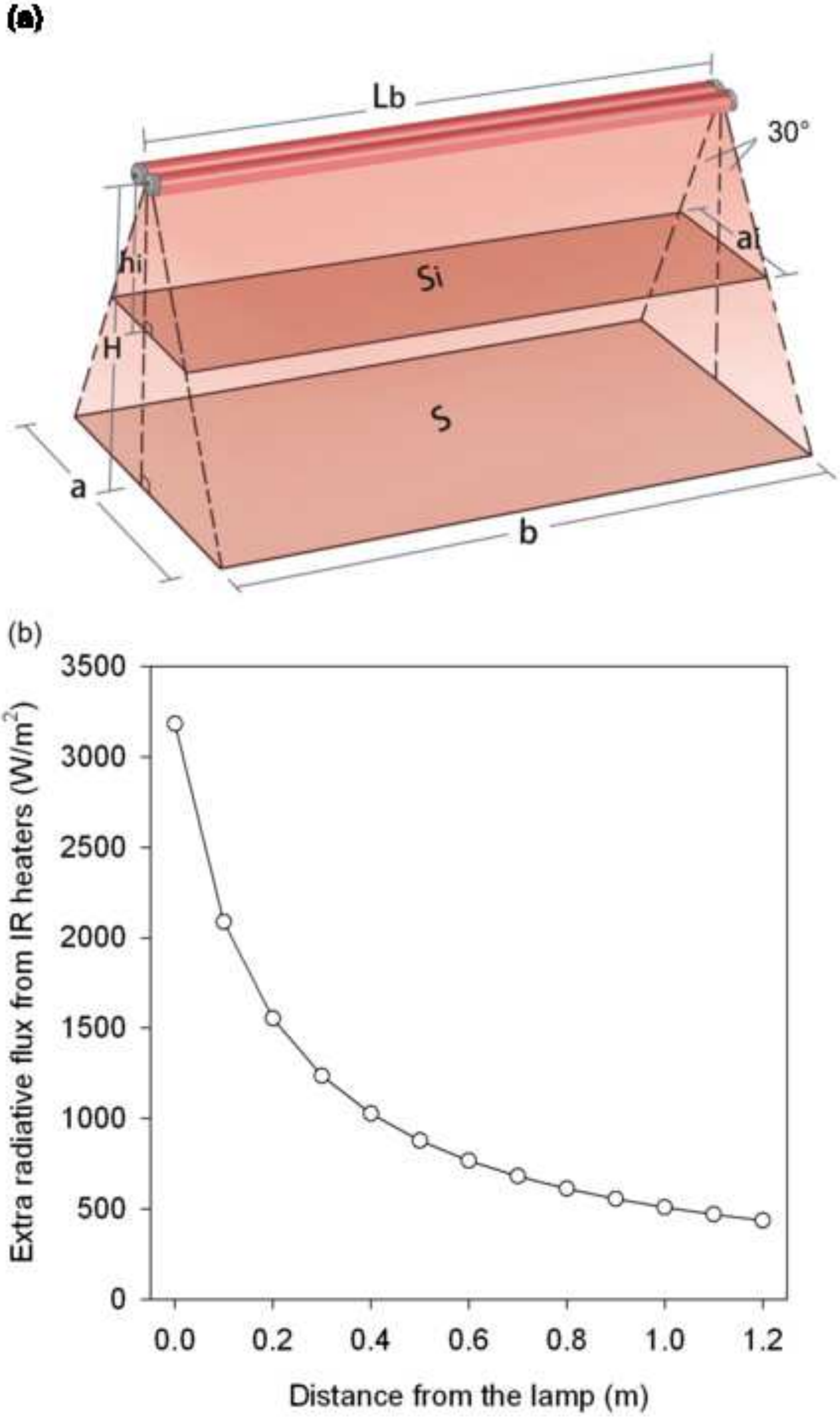

(a) Artificial condensation surface
(b) *In situ* dew formation on plants
(c) Leaf wetness sensors
Dew Amount (mm/day)
0.100
0.075
0.050
0.025
0.000
*
*
*
Control
Warming
Control
Warming
Control
Warming


Dew duration (day)
400
350
300
250
200
Control
Warming
(a)
*
*
*
*
2015
2016
2017
Overall
$T_a - T_{dew}$ (°C)
7.0
6.5
6.0
5.5
5.0
Control
Warming
(b)
*
*
*
2015
2016
2017
Overall
Dew amount differences (mm)
0.2
0.1
0.0
$D_{control} - D_{warming}$
(c)
2015−01−01
2015−07−01
2016−01−01
2016−07−01
2017−01−01
2017−07−01
2017−12−31
Date


(a)
Dew amount (mm)
0.20
0.15
0.10
0.05
0.00
Control
Warming
Ab
Ba
Ab
Ca
Bb
Aa
b
a
Sedge
Forb
Grass
Overall
(b)
Aboveground biomass (g/m²)
400
300
200
100
0
*
Sedge
Forb
Grass
Total



(a)
Control: $R^2 = 0.348$ $P < 0.001$
Dew amount (mm)
0.09
0.07
0.05
0.03
5
10
15
20
25
Height (cm)
(b)
Warming: $R^2 = 0.338$ $P < 0.001$
Dew amount (mm)
0.03
0.02
0.01
0.00
5
10
15
20
25
Height (cm)


(a)
Lb
30°
hi
ai
Si
H
S
a
b
(b)
Extra radiative flux from IR heaters (W/m²)
3500
3000
2500
2000
1500
1000
500
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Distance from the lamp (m)