Effects of small rainfall events on *Haloxylon ammodendron* seedling establishment in Northwest China

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Small rainfall events (≤5 mm) account for a large proportion of rainfall amount, and may play an important role in triggering plant regeneration in arid ecosystems. However, their potential ecological importance in seedling establishment of desert shrub has been previously ignored. We conducted two parallel pot experiments to examine the effects of amount and interval of small rainfall events on seedling emergence, growth and survival of the dominant shrub species *Haloxylon ammodendron* in sand dunes of Northwest China. The results showed that: (1) decrease in rainfall amounts did not significantly lower seedling emergence, growth and survival in comparison to control, while the large increase (+20%) in rainfall amount resulted in significant increase in seedling emergence, growth and survival for both continuous and intermittent small rainfall events; (2) continuous small rainfall events were more effective than intermittent ones for triggering seedling emergence, growth and survival; (3) small rainfall events may impact the seedling establishment of *H. ammodendron* only in wet years. Our results provide insights into the effects of small rainfall events on seedling establishment processes, and highlight the inherent complexity in predicting how seedling establishment of shrub species in desert ecosystems will respond to future fluctuations in small rainfall events.

Keywords: Arid regions, *Haloxylon ammodendron*, seedling establishment, small rainfall events.

RAINFALL events in arid regions can be characterized as discrete, infrequent and largely unpredictable[1–3]. As the dominant water input regime, small rainfall events (≤5 mm) constitute a qualitatively distinct water resource for ecosystems in arid desert regions[4–6], and play an important role in determining desert plant biological processes[7,8]. For instance, small rainfall events can significantly increase soil water potential and improve the water conditions of short grass in North America[9]. They are also effective in triggering the sap flow response of desert shrubs *Nitraria sphaerocarpa* and *Elaeagnus angustifolia*, and some herbaceous species[9–11]. However, some researchers have regarded these rainfall events as ecologically unimportant in dry-land environments. This is because they affect only the shallow soil layers, and mostly evaporate rapidly back to the atmosphere[12]. They do not have any effect on plant biological processes in some desert ecosystems such as in western USA[5], and Mu Us Desert[12] and Tengger Desert[13], in China. Studies on small rainfall events have mostly focused on the physiological responses of plants after a single rainfall event. The potential ecological importance of a series of small rainfall events in the growing season has been previously ignored.

Shrubland is one of the main vegetation types in arid regions in Northwest China. Some native shrub species have been used for sand-binding to reduce wind erosion and prevent desertification. *Haloxylon ammodendron* has been chosen as a pioneer species and gradually planted in sand-dune habitats since 1970s with the help of straw checkerboards. It is of great ecological importance for restoration of degraded land[14]. After plantation, the mother plants of *H. ammodendron* can produce a large number of seeds every year. However, only a few of the seedlings could successfully establish after the following summer. Thus its population declined each year due to lack of effective regeneration. The survival of the new seedlings is mainly dependent on the characteristics of small rainfall events that make up a larger proportion of total rainfall in this region[15]. Therefore, it is expected that there is a relationship between the patterns of small rainfall events and seedling establishment in *H. ammodendron* inhabiting sand dunes of Northwest China. However, there is hardly any information about the relationship between small rainfall events and seedling establishment of *H. ammodendron*.

Therefore, the present study was conducted to test the effects of rainfall amount and interval of a series of small rainfall events on *H. ammodendron* seedling emergence, growth and survival rate in a sand-dune ecosystem. We hypothesize that (1) changes in rainfall amount can affect seedling establishment; (2) continuous rainfall events may be more beneficial than intermittent ones for seedling establishment and (3) decreased seedling establishment may affect the success of restoration efforts in the long run, especially in a future (drier and warmer) climate.

The experiment was conducted in the Chinese Ecosystem Network Research Linze Inland River Basin Comprehensive Research Station (39°21′N, 100°07′E) located at the southern edge of the Badain Jaran Desert in Northwest China. The study area has a temperate desert climate: it is dry and hot in summer, cold in winter, plenty of sunshine, very little rainfall during summer, strong winds, and frequently drifting sands. The altitude of this area is 1370 m and mean annual temperature is 7.6°C.

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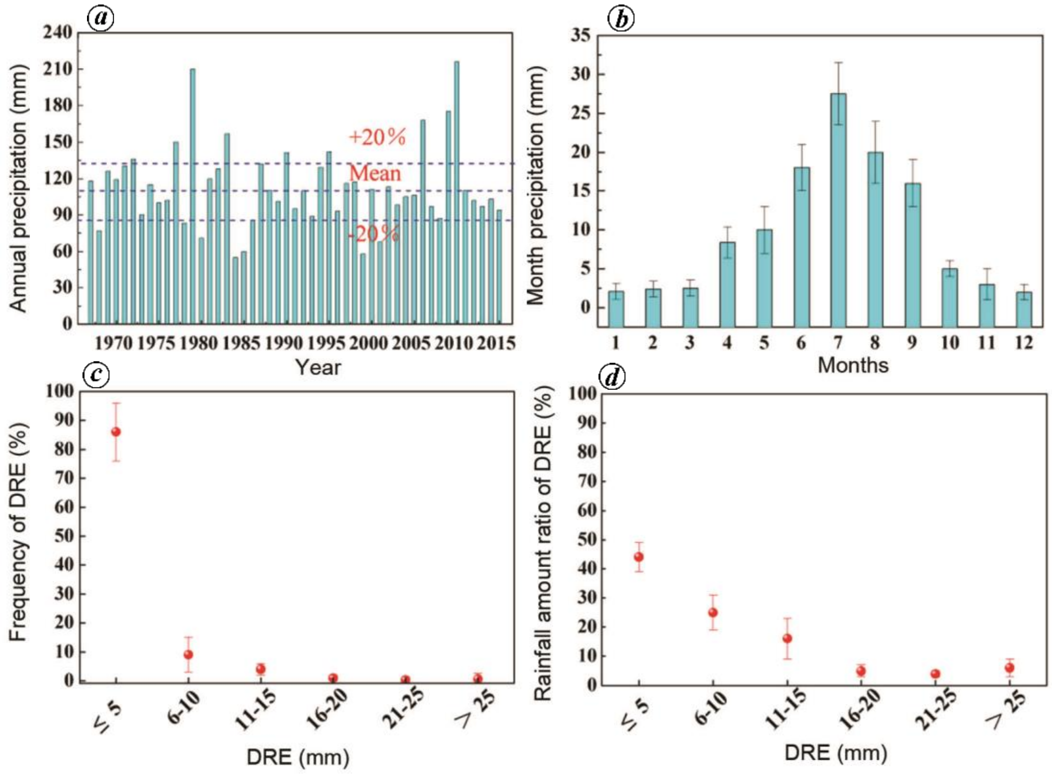

Figure 1. The characteristics of rainfall in the study area. ***a***, Distribution of annual rainfall from 1971 to 2011; amplitude of variation is 20%. ***b***, Distribution of mean precipitation amount in different months (vertical bars show standard deviation). ***c***, Frequency of different rainfall events (DRE). ***d***, Rainfall amount ratio of different rainfall events.

The mean annual potential evaporation is around 2390 mm. Mean annual wind velocity is 3.2 ms^{-1}, and prevailing wind direction is northwest. Soil is dominated mainly by blown sand with coarse texture and loose structure. The sand-binding vegetation is dominated by *H. ammodendron* with some other annual herb species such as *Suaeda glauca*, *Agriophyllum squarrosum*, *Bassia dasyphylla*, *Halogeton arachnoideus*, etc.

The mean annual rainfall amount in the study area is 113 mm and variability range of annual rainfall amount is mainly in 20% (Figure 1 *a*). Over 80% of the rainfall occurs between May and September (Figure 1 *b*). The small rainfall events of ≤5 mm are the most common rainfall events during summer accounting for 86% of the frequency of rainfall events (Figure 1 *c*) and 44% of annual precipitation amount (Figure 1 *d*). Based on the rainfall amount and interval in the study area, five rainfall amount (–20%, –10%, control check (CK), +10%, +20%) and two interval (daily: interval 0 day, and intermittent: interval ≥1 day) treatments were designed. Two parallel experiments were conducted in a greenhouse, with one focusing on rainfall amount and the other on rainfall interval. To demonstrate the mean seedling emergence and survival from June to September (120 days), we set the rainfall amount as 68.0 mm (–20%), 76.1 mm (–10%), 84.5 mm (CK), 93.0 mm (+10%) and 101.4 mm (+20%). The 5 mm rainfall events were stimulated to supply water for seed germination and seedling growth in each treatment. The experiment lasted for 120 days. The interval of intermittent rainfall was calculated as follows

$$\text{Rainfall event frequency} = \text{rainfall amount}/5\ \text{mm}. \quad (1)$$

$$\text{Interval between two rainfall events} = 120/\text{rainfall event frequency}. \quad (2)$$

For continuous rainfall, the rainfall event frequency was also calculated by eq. (1), and distilled water was added to the pots from the start of the experiment continuously during the growing season. For intermittent rainfall events, the rainfall events were simulated according to the interval calculated by eq. (2).

Seeds were collected in the fall of 2012 from different mother plants of *H. ammodendron*. Next the seeds were cleaned, dried for 2–3 weeks and stored under dry, dark conditions at room temperature. In desert areas the vertical distribution of seed banks is mainly at a depth of 0–5 cm (refs 16, 17). For *H. ammodendron*, the optimal sand burial depth is 1 cm and its seedling establishment mainly occurs at this depth[18]. Thus 25 seeds were planted at 1 cm depth in plastic pots (25.5 cm diameter, 30 cm depth) filled with unsterilized sand for each treatment. There were five replicates for each treatment. To ensure no systematic effects due to position within the greenhouse, plastic pots were rearranged at random in both experiments which were conducted in the greenhouse at 24°C during the day (16 h photoperiod) and 15°C at night.

The study lasted for three months from June to September 2013. Data were collected continuously for the first 18 days, every third day for the next 14 days and every fifth day for the rest of the experiment. On the days of data collection, each study pot was scored for the total number of seedling emerged from the sand. We used radicle emergence as the criterion for seedling emergence. The seedling emergence time is defined as the time in which 50% (of the total seedling in all five replicates) of seedlings in each treatment are observed to have emerged from the burial sand. Seedling growth performance was assessed in terms of their height. The seedling survivorship was determined using the criterion that the seedlings were alive with fresh phloem both in roots and stem, or was dead with rotted tissue. The seedling emergence and survival rate were determined according to the following equations

$$\text{Seedling emergence} = [(N_1/25) + (N_2/25) + \cdots + (N_5/25)]/5. \quad (3)$$

$$\text{Seedling survival rate} = [(S_1/25) + (S_2/25) + \cdots + (S_5/25)]/5, \quad (4)$$

where $N_1, N_2, \ldots, N_5$ are the number of seedlings emerged from sand in five replicates in each rainfall treatment and $S_1, S_2, \ldots, S_5$ are the number of seedlings survived in five replicates.

Survival rate was used as an indicator of seedling establishment success. However, the survival rate is not the only indicator of potential alterations to seedling establishment as a result of changes in small rainfall pattern. Seedling growth, which is a metric describing the development of seedlings, can play an important role in seedling establishment. We extended a framework proposed by Varma *et al.*[19] to assess changes in seedling survival rate and growth (Figure 2). This framework can provide more comprehensive interpretations of the effects small rainfall events on seedling establishment. In the framework, the response space can be divided into four quadrants using log response ratios of seedling survival rate (L_{SSR}) and seedling growth (L_{SG}). Positive values of L_{SSR} and L_{SG} in the treatment groups indicate an increase in seedling survival rate and growth with respect to the control group, while negative values indicate a decline. L_{SSR} and L_{SG} were calculated using the following equations

$$L_{SSR} = \ln\,(\text{SSR treatment/SSR control}), \quad (5)$$

$$L_{SG} = \ln\,(\text{SG treatment/SG control}). \quad (6)$$

The mean values of L_{SSR} and L_{SG}, as well as their associated 95% CIs for each treatment of continuous and intermittent small rainfall events separately.

One-way analysis of variance (ANOVA) was used to test for significant differences in the parameters of seedling establishment under different rainfall amounts with post-hoc Duncan's tests (alpha = 0.05). Analysis of covariance (ANCOVA) was used to test for significant differences in the parameters of seedling emergence, emergence time, seedling growth and survival rate between continuous and intermittent rainfall events. In the analysis, rainfall amount was used as a continuous variable and rainfall frequency as a categorical variable. Difference at $P < 0.05$ level was considered as statistically significant. All statistical analyses were performed using SPSS 16 software package.

The seedling emergence rate was significantly affected by rainfall amount for both continuous ($F = 4.343$, d.f. = 4, $P = 0.011$) and intermittent rainfall treatments ($F = 3.425$, d.f. = 4, $P = 0.027$). Seedling emergence rate reached the highest level of 74% (+20%) for continuous rainfall events and 52% (+20%) for intermittent rainfall events (Figure 3).

There was no significant effect of rainfall amount on seedling emergence time for continuous small rainfall events ($F = 0.233$, d.f. = 4, $P = 0.917$). However, seedling emergence time was significantly affected by rainfall amount for intermittent rainfall events ($F = 5.317$, d.f. = 4, $P = 0.004$), and the emergence time decreased with increasing rainfall amount (Figure 4).

Seedling height was significantly affected by rainfall amount for continuous rainfall events ($F = 33.146$, d.f. = 4, $P < 0.001$) and intermittent rainfall events ($F = 48.976$, d.f. = 4, $P < 0.001$). Seedling height reached the highest level of 22 cm (+20%) for continuous rainfall

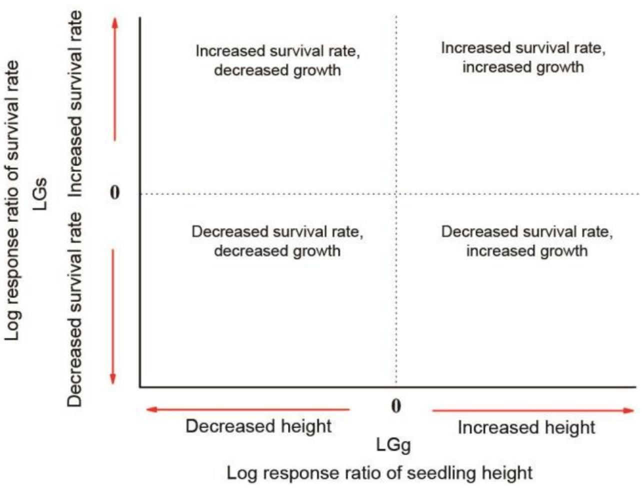

Figure 2. Framework for the combined interpretation of changes in seedling growth (LGg) and survival rate (LGs).

events and 20 cm (+20%) for intermittent rainfall events (Figure 5).

Seedling survival rate was significantly affected by rainfall amount for continuous rainfall events ($F = 5.162$, d.f. = 4, $P = 0.005$) and intermittent rainfall events ($F = 6.467$, d.f. = 4, $P = 0.008$). Seedling survival rate reached the highest level of 26% (+20%) for continuous rainfall events and 16% (+20%) for intermittent rainfall events (Figure 6).

Seedling emergence was significantly affected by small rainfall event interval ($F = 51.777$, d.f. = 1, $P < 0.001$). The mean seedling emergence proportion was 60% for continuous small rainfall events and 32% for intermittent small rainfall events (Table 1). There was significant mean difference between seedling emergence of continuous and intermittent rainfall events ($P < 0.001$, 95% CI: 0.202–0.358).

Seedling emergence time was significantly affected by small rainfall event interval ($F = 52.657$, d.f. = 1, $P < 0.001$). The seedling emergence time was 5 days for continuous small rainfall events and 7 days for intermittent small rainfall events (Table 1). There was significant

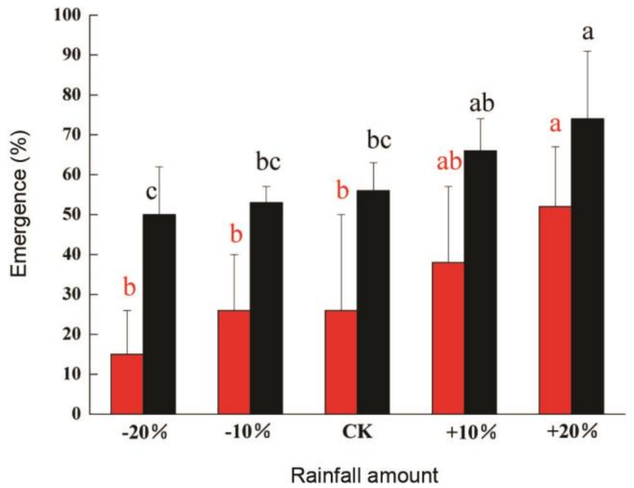

Figure 3. Seedling emergence rate varies significantly under different rainfall amounts. Red bar represents intermittent, small rainfall events and black bar represents continuous, small rainfall events. Means (±1 SD) with different letters within each rainfall amount regime indicate significant difference ($P < 0.05$ from ANOVA followed by Duncan's test).

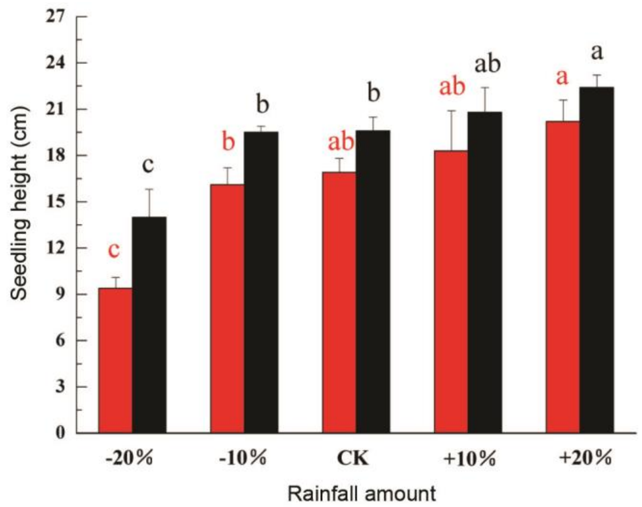

Figure 5. Seedling height varies significantly under different rainfall amounts for intermittent rainfall events. Red bar represents intermittent small rainfall events and black bar represents continuous small rainfall events. Means (±1 SD) with different letters within each rainfall amount regime indicate significant difference ($P < 0.05$ from ANOVA followed by Duncan's test).

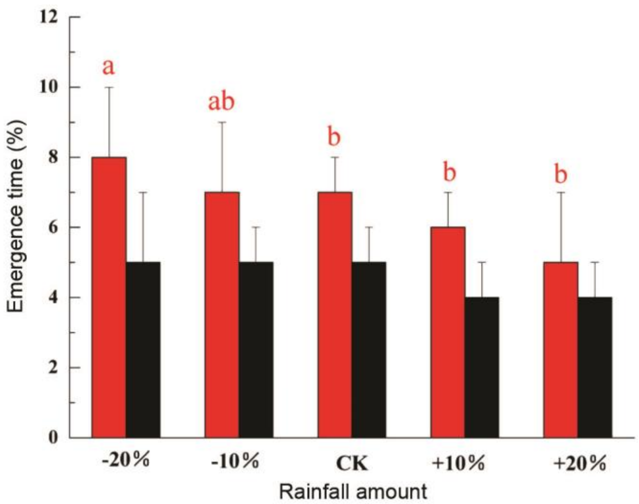

Figure 4. Seedling emergence time varies significantly under different rainfall amounts for intermittent rainfall events. Red bar represents intermittent small rainfall events and black bar represents continuous small rainfall events. Means (±1 SD) with different letters within each rainfall amount regime indicate significant difference ($P < 0.05$ from ANOVA followed by Duncan's test).

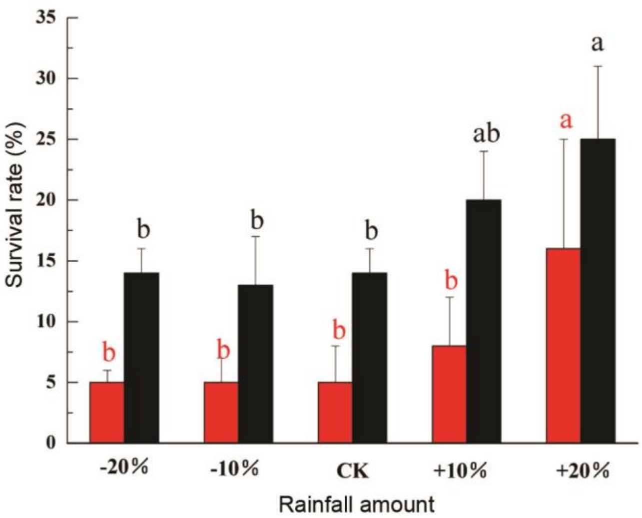

Figure 6. Seedling survival rate varies significantly under different rainfall amounts. Red bar represents intermittent small rainfall events and black bar represents continuous small rainfall events. Means (±1 SD) with different letters within each rainfall amount regime indicate significant difference ($P < 0.05$ from ANOVA followed by Duncan's test).

Table 1. Log response ratios and associated 95% confidence intervals (CIs) for changes in seedling survival (LGs) and growth (LGg) of continuous and intermittent small rainfall events

	Emergence proportion			Emergence time			Seedling height			Seedling survival rate		
Treatment	Mean	Lower CI	Upper CI	Mean (days)	Lower CI	Upper CI	Mean (cm)	Lower CI	Upper CI	Mean	Lower CI	Upper CI
Continuous rainfall	0.597*	0.541	0.652	**4.200***	3.769	4.631	**19.151***	17.621	20.681	**0.171***	0.143	0.200
Intermittent rainfall	0.317*	0.261	0.372	**6.400***	5.969	6.831	**14.316***	12.786	15.846	**0.075***	0.047	0.104

Asterisks (*) and bold type face indicate log response ratios where 95% CIs do not overlap.

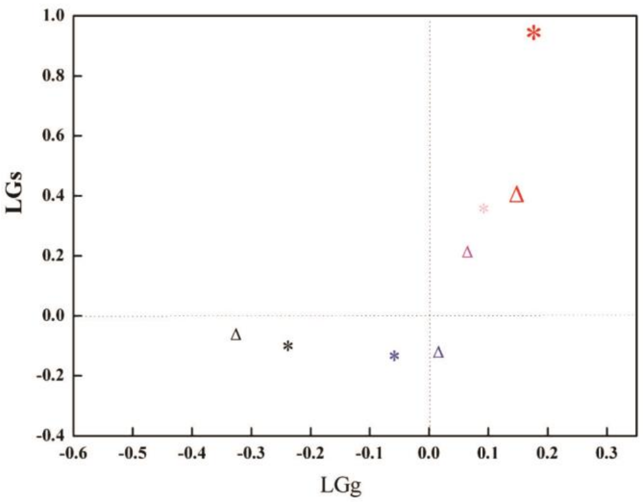

Figure 7. Seedling growth (LGg) and survival rate (LGs) response space for small rainfall events with different rainfall amounts. Continuous and intermittent small rainfall events are represented by Δ and * with different colours respectively (from left to right –20%, –10%, +10%, +20%). For clarity, 95% CIs around log response ratios are listed in Supplementary Table 1.

mean difference ($P < 0.001$, 95% CI: –2.810 to –1.590) between seedling emergence time of continuous and intermittent rainfall events.

Seedling height was significantly affected by small rainfall event interval ($F = 20.201$, d.f. = 1, $P < 0.001$). The seedling height was 19 cm for continuous small rainfall events, and 14 cm for intermittent small rainfall events (Table 1). There was significant difference ($P < 0.001$, 95% CI: 2.671–6.999) between seedling growth of continuous and intermittent rainfall events.

Seedling survival rate was significantly affected by rainfall event interval ($F = 23.071$, d.f. = 1, $P < 0.001$). The mean seedling survival rate was 17% for continuous rainfall events and 8% for intermittent rainfall events (Table 1). There was significant difference ($P < 0.001$, 95% CI: 0.056–0.136) between seedling survival rate of continuous and intermittent rainfall events.

Successful seedling establishment on sand dunes is constrained by its emergence, growth and survival. As one of the most frequent rainfall events in water-limited ecosystems, small rainfall events play a critical role in plant regeneration processes, and complex linkages exist between small rainfall events and seedling establishment[20,21]. Our experiments showed that both amount and interval of small rainfall events significantly affect the seedling establishment of *H. ammodendron*. These results highlight the importance of variability in small rainfall events to plant regeneration of sand-binding shrub species in the context of climate change.

The results of this study show that the amount of small rainfall events significantly affects the seedling emergence rate. One main reason for this is that increased rainfall amount leads to enhanced infiltration of soil moisture and depletion of soil evaporation in the hot growing season during summer[7]. The seedling emergence rate could be also related to the physiological dormancy of *H. ammodendron* seeds. Most of the seeds of *H. ammodendron* are dry and physiological quiescent after maturation in autumn. Meanwhile they can keep their viability. In the next summer, some amount of water is needed by the seeds to break dormancy[18]. We observed that *H. ammodendron* seedlings gradually emerged after a series of small rainfall events of 5 mm, showing that such events are ecological effective in triggering the seeds of *H. ammodendron* to germinate. However, only a small proportion of seeds germinated after a single small rainfall event because the amount of water from a single small rainfall event is too limited for germinating all the seeds. Especially for some seeds with thick and hard pericarp, they need a large amount of water to germinate[22]. Thus seedling emergence increases with increasing rainfall amount. However, the significant increase in seedling emergence can only be observed when rainfall amount increases by 20%; this explains why a large number of seedlings only emerge in wet years. Most seeds of desert plant species keep dormant after small rainfall events[22,23]. Most importantly, the number of emerged seedlings is minimized under lower rainfall amount and most of the seeds are stored in a seed bank till the next effective rainfall to germinate.

We found that higher rainfall amount also significantly increased the growth and survival rate, while lower rainfall amount did not significantly affect seedling growth and survival in comparison to controls. Knapp *et al.*[24] reported that plant biomass in grassland systems did not strongly decline in dry years, but strongly increased in wet years. Collectively, these results suggest that a threshold amount of rainfall events is needed: if the amount falls below a certain critical level, it has no significant effect on plant growth and survival. However, the specific thresholds of rainfall amount were found to vary in different species, or in the same species in different areas[25,26]. Our experimental results demonstrate that only when rainfall amount increases by 20% (110 mm), can a series of small rainfall events significantly affect seedling establishment ($P < 0.001$). Thus 20% is the largest variability range for the annual rainfall amount in the study area. This suggests that the successful seedling establishment only occurs in extreme wet years. This threshold rainfall amount is much higher than that for a short-grass in North America, where rainfall amount of 15–30 mm had maximum effect on its growth[27]. The larger threshold in our study is most likely the result of higher water demand in the sand-dune environment, caused by lower soil water-holding capacity and higher evaporation rate.

Rainfall interval also significantly affected seedling establishment. The seedling emergence, growth and survival under continuous small rainfall events were significantly larger than intermittent events. In fact, the processes of seedling establishment are not a direct consequence of rainfall, but rather more closely linked to changes in soil moisture. Soil moisture has a 'memory' of past rainfall events and the duration of this memory is mainly related to rainfall and soil characteristics[28]. For instance, the interval between rainfall events determines the water availability of small rainfall events[7]. Intermittent small rainfall events affect only the shallowest depths in soil layers[9]. This is because the soil infiltration rate of intermittent rainfall events is much lower than the continuous ones, and most of the water from rainfall is often rapidly evaporated back to the atmosphere. Thus the soil can 'remember' these rainfall events for no more than a few days without incoming rainfall event due to high rate of evapotranspiration[6]. However, a series of continuous rainfall events that percolate into the much deeper soil profile, may result in much higher available soil water and make soil moisture memory last much longer[29]. Our results indicate that continuous small rainfall events could provide an effective water source that can be utilized by the seedlings of *H. ammodendron*. Wiegand *et al*.[30] also found that continuous small rainfall events were equally important as large, rare rainfall events for population maintenance by studying *Acacia* population dynamics in the Negev Desert in Israel. In addition, we found that rainfall with shorter intervals greatly decreases seedling emergence time. This means that the seedlings under continuous rainfall have more time for growth in a distinct growing season and bigger sizes. It also implies that these seedlings may emerge into a community where potential competitors may have not already germinated and would, therefore, be better equipped to exploit local resource availability, and grow and establish properly by the end of the growing season.

In conclusion, we found that seedling emergence, growth and survival have significant response to small rainfall events of 5 mm, when the rainfall amount increases by 20%. The continuous small rainfall events are more effective than intermittent ones for seedling establishment. These results would help understand the seedling establishment and plant regeneration processes in a changing climate with increased risk of drought and rainfall variability.

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ACKNOWLEDGEMENTS. This study was supported by the National Natural Science Foundation of China (Grant No. 41701045) and Opening Fund of Key Laboratory of Ecohydrology of Inland River Basin, Chinese Academy of Sciences, Project No. KLEIRB-ZS-16-05. We thank the anonymous reviewers for their constructive comments which helped improve the manuscript.

Received 7 December 2017; revised accepted 30 August 2018

doi: 10.18520/cs/v116/i1/121-127

Assessment of ergonomic parameters of coconut climbing devices for women

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At present there are different models of coconut climbing devices available in the market. The safety and efficiency aspects of coconut climbing devices are not being studied for women. Therefore, a study was undertaken to evaluate the existing models of five coconut climbing devices, sit and climb type (TNAU model), standing type (Chemberi model), KAU coconut palm climber (developed at KCAET, Tavanur, KAU), Kerasureksha (model developed at ARS, Mannuthy, KAU) and CPCRI model coconut climbing device on ergonomic basis for women operators. Minimum heart rate and energy expenditure was observed for KAU coconut palm climber than other models. The subjects felt less safety in operating TNAU model and standing type (Chemberi model). Sit and climb type (TNAU model) was found difficult to operate compared to other devices. On basis of these results it was found that KAU coconut palm climber was more suitable and ergonomically comfortable for the women operators.

Keywords: Coconut climbing devices, ergonomics, heart rate, energy expenditure, women workers.

KERALA derives its name from the word ‘Kera’ which refers to coconut tree, the most important plantation crop of the state. The farming sector of Kerala has problems like shortage of labour, lack of trained labour and high cost of available labour. Mechanization is considered a remedy to the growing labour scarcity and uneconomic nature of farming. In the case of coconut cultivation, harvesting the nuts and plant protection are major problems. Majority of coconuts are harvested by climbing the palm and cutting bunches down by knife. This process may seem simple but it is quite dangerous and time-consuming. Coconut palms are very tall; any fall from the top of the palm can result in severe injury, even death. Due to the strenuous nature of work and risk involved, professional coconut climbers are now very few in number and timely harvest of the nuts forms a severe constraint in coconut farming. In response, there is a genuine need to develop safe and efficient devices to facilitate easy climbing. Mechanization is the available option and several coconut climbing devices have been developed that help climbers.

Women play a vital role in agriculture. According to the 2011 census, women constitute 37% of the total work

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