Influence of light, temperature and water stress on germination of *Hedysarum fruticosum*

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*Hedysarum fruticosum* is one of the common species for combating desertification in the semi-arid area of China, mainly because of its ability of efficient regeneration from seed and quick clonal growth. In this study, experiments were conducted to determine the effects of light intensity, constant temperature, alternating temperature and water potential (generated by PEG) on seed germination of *H. fruticosum*. It was found that under alternating temperature regimes, final percent germination increased from 87.2% to 99.2% when temperature increased from 5:15°C (night:day) to 10:20°C, then decreased with increasing temperature; germination could not take place at all under 25:35°C conditions in a 14h (215µmol m⁻² s⁻¹) photoperiod. Under dark conditions there was a similar final percent germination to that under light. The germination pattern under constant temperature conditions was similar to that under alternating temperature, and there were no significant differences in final percent germination and germination rate between alternating and constant temperature. Under varying light intensities, final percent germination of *H. fruticosum* showed no significant differences, with values always above 74.4%. When water potentials were reduced, final percent germination decreased dramatically, and few seeds could germinate at –0.2MPa. The germination rate showed a pattern similar to that of final percent germination with changing water potentials. Based on the experimental results and environmental conditions in the study area, *H. fruticosum* seeds should be dispersed from early to mid-May so that germination requirements can be fulfilled and higher germination is possible.

Introduction

*Hedysarum fruticosum* can regenerate through both clonal growth and seed germination. The two kinds of regeneration capacity, especially the quick clonal growth, make it a good candidate for fast restoration of degraded ecosystems (Zhang 1994). In addition, it can also serve as a good supplement forage for livestock after fermentation. On the Ordos plateau, China, *H. fruticosum* has been used in air seeding for a long time to rehabilitate desertified areas. Unfortunately, the seedling recruitment from *H. fruticosum* seeds was low in air seeding; however, it was still commonly used for at least two reasons: (1) expansion by clonal growth after seedling establishment (Wen 1992); (2) in order to increase the numbers of seeds germinated and seedling establishment, the quantity of seeds used in air seeding is usually increased, e.g. assuming 20% germination, seeds comprising 3–4kg need to germinate per ha, thus 15–20kg seeds of *H. fruticosum* should be used in air seeding. However, low recruitment of *H. fruticosum* is still a bottleneck for effective air seeding and research is needed to examine the causes. Based on our observations, we speculate that air seeding timing and associated environmental conditions might be relevant, since air seeding in semi-arid areas in China is usually conducted in June, when seeds often encounter soil-water deficit and temperature fluctuations, and are exposed on the sand surface; all of which could adversely affect timing for germination of *H. fruticosum*. To test this assumption and seek better timing for air seeding, this work explored the germination behaviour of *H. fruticosum* seeds through controlled laboratory experiments.

Germination responses to different environmental factors, including temperature, water potential and light (Bewley and...
Hedysarum fruticosum have been studied for a long time and considerable progress has been made for some species, e.g. effects of temperature on seed germination capacity and the germination rate of non-dormant seeds (Gummerson 1986, Dahal and Bradford 1994, Alvarado and Bradford 2002), alternating and constant temperature effects (Thompson and Grime 1983, Washitani 1985, Ghersa et al. 1992), effect of light on desert plants and their seed germination (Gutterman 1993, Khan and Ungar 1997a), effects of soil moisture or water stress, usually by applying isotonic (equal Ψs) solutions of inert osmotic media such as PEG, which cannot penetrate into the cell wall (Carpita et al. 1979) and act solely as osmoticum on seeds (Fyfield and Gregory 1989, Hardegree and Emmerich 1990).

Although there is considerable literature on germination responses to temperature, light and water stress, little is known about their impacts on germination of H. fruticosum. Some research has been conducted on issues of hard-seededness of Hedysarum species (Sulas et al. 1999, Bell et al. 2003) which provide valuable reference material for this study, as will be discussed. In this paper, several pertinent aspects are examined concerning the germination behaviour of H. fruticosum, including: (1) germination responses to various alternating and constant temperature regimes under light and/or dark conditions; (2) germination responses to different light intensities under a specific alternating temperature regime; and (3) the degree of water stress (generated by PEG) which seeds can tolerate. It is hoped that experimental results may help understand the recruitment performance of H. fruticosum and supply experimental evidence for appropriate timing of air-seeding.

**Materials and Methods**

*Hedysarum fruticosum* of the family Leguminosae, is mainly distributed in semi-arid areas in northern China, including the Northeast, Inner Mongolia, Ninxia and Shaanxi. More detailed spatial distribution is not presently available. *H. fruticosum* is a forage legume, characterised as sub-shrub, 1–1.5m tall, stems erect, caespitose, and the racemes lax. It flowers profusely, typically in July and August, and produces heavy fruits in August and September. Seeds of *H. fruticosum* mature at the end of autumn, and germination occurs mostly in spring. The seeds of *H. fruticosum* used in this study were collected in 2000 in our study area in the Mu Us sandy land, part of the Ordsos plateau, China (Figure 1). The 1 000-seed weight was 7.3 ± 0.7g.

In the study area, annual precipitation and annual mean temperature are 345.2mm and 6.7°C (mean from 1969–1999), respectively. The monthly temperature is lower than 5°C from November to March, and falls within the range of 7.4–21.9°C from April to October. Precipitation from April to October is 321.8mm, accounting for 93.2% of the annual total. Seeds were collected randomly from the whole population to get an adequate representation of genetic diversity. They were transported to Japan, and stored at 4°C until use in 2002.

As reported by Sulas et al. (1999) and Bell et al. (2003), Hedysarum spp. seeds usually show hard-coatedness, which could decrease germination; however, the hard-seed proportion decreases linearly with time after harvest. The initial hard-seed proportion was reported at about 95% when *H. caronanum* seeds were completely ripened and, after two and half months, the proportion decreased to 74% and 80% for naked seeds and loments respectively (Sulas et al. 1999). The hard-seed proportion of *H. fruticosum* is about 85% in the season when seeds are ripened (Qi 1998). However, in our study, the seeds were stored at 4°C for over 2 years before experiments. This effectively reduced the proportion of hard-coated seeds to a negligible level of only 1.2% ± 1.9.

Germination experiments were carried out within automatic temperature- and light-controlled growth chambers. The chambers were set for daily photoperiods (14h light:10h dark) using cool white fluorescent light.

In all experiments, to avoid fungal proliferation, seeds were surface-sterilised for 1min with 0.52% sodium hypochlorite solution, and then rinsed several times with distilled water (Khan and Ungar 1984). Next, seeds were put on three-fold Toyo, No. 1 filter paper on 90mm x 15mm covered Petri dishes. The filter paper was moistened with distilled water or a solution of PEG-6000, with about half of each seed being immersed in the solution (Toye et al. 2000). A fully randomised factorial design was used in the germination tests. Each treatment had five replicates, and for each replicate, 25 randomly selected seeds were used (Gul and Weber 1999). Dishes were placed in transparent plastic boxes as an added precaution against loss of water by evaporation.

Seeds were inspected daily under 9.8 µmol m−2 s−1 light and they were scored as having germinated when the radicle emerged. Germinated seeds were discarded after counting. Germination was measured using two indices: final percent germination and germination rate. The germination rate was estimated with a modified Rozema index of germination rate (Rozema 1975),

\[
\sum_{i=0}^{\infty} \frac{100G_i}{nt_i}
\]

where \(n\) is the number of seeds used in an experiment, and \(G_i\) is the number of seeds germinated on day \(i\) (\(i = 0, 1, 2, 3, \ldots, \infty\)). Higher values represent rapid germination. Similar rate
indices have been extensively used, e.g. by Gul and Weber (1999), and Gulzar and Khan (2001).

Germination values (including final percent germination and germination rate) were arcsine square-root transformed before statistical analysis to ensure homogeneity of variance (Gulzar and Khan 2001). The transformed values were analysed using two-way or one-way analysis of variance (ANOVA) procedures. Differences between mean values for treatments were tested by Tukey's test. All statistical analyses, including the test for homogeneity of variance, were performed using the SPSS 10.0 package (SPSS 2000).

Three experiments were conducted to examine some of the major germination requirements of *H. fruticosum*.

**Experiment 1: Effects of alternating temperature regimes on germination at a specific light intensity or in constant dark**

The effect of temperature on germination was determined for five alternating temperature regimes: viz. 5:15°C, 10:20°C, 15:25°C, 20:30°C and 25:35°C (night temperature:day temperature; the same notation is used in following sections) in a randomised complete block design. The five temperature regimes closely approximate the spring and summer germination conditions in semi-arid areas in China, based on 30 years of observations of micro-environments. Two light intensity regimes were applied, 215µmol m–2 s–1 (14h light:10h dark) and dark (24h). Seeds were assessed daily, as described above. The tests continued until germination percentage became effectively constant.

**Experiment 2: Effects of light intensity on germination under a specific temperature regime**

The light intensity regimes included 400, 100, 25µmol m–2 s–1, and dark, with temperatures being 10:20°C (night:day). Various light intensities (measured using a light sensor) were achieved by wrapping plastic boxes externally with different layers of white and black plastic nets. Black boxes were used to approximate completely dark environments, two sides of each box being made of two-layer wooden boards. For free airflow, but avoiding any light exposure, a long narrow aperture was made in each layer but at different places. Seeds were checked daily for different light intensity treatments. For the dark treatment, seeds were inspected only on the last day. The tests continued until the germination percentage became effectively constant.

**Experiment 3: Effects of moisture stress (generated through PEG solution) on germination**

Seeds were moistened using solutions of PEG-6000 with known water potential (Ψw), the solutions being prepared according to the equations of Michel and Kaufmann (1973). About two-thirds (volume) of the water or solution in each Petri dish was replaced daily to avoid a change in the Ψw of the solution (Tobe et al. 2000).

All experiments were performed in the dark. Five constant temperature regimes were used, viz. 10°C, 15°C, 20°C, 25°C and 30°C. Water potentials achieved were 0, −0.2, −0.4, −0.6, −0.8, −1.0, −1.2, −1.4, −1.6, −1.8 and −2.0Mpa. The experiment was designed as a randomised complete block. Seeds were checked daily under 9.8µmol m–2 s–1 light. The tests continued until the germination percentage became effectively constant.

**Results**

**Effects of alternating temperature regimes on germination at a specific light intensity, or in the dark**

Under the 14h light:10h dark photoperiod conditions, the final percent germination of *H. fruticosum* seeds increased slightly from 87.2% at 5:15°C to 99.2% at 10:20°C, then decreased sharply to 10.3% at 20:30°C. When the temperature regime was 25:35°C, no *H. fruticosum* seeds germinated (Figure 2a). The final percent germination was lower under continuous dark conditions than under the 14h:10h photoperiod irrespective of the temperature regime; however, the difference was insignificant.

Under the same photoperiod conditions, germination rate varied significantly with different temperature regimes and showed a similar pattern as final percent germination. Rate first increased with increasing temperatures, reaching a maximum at 10:20°C, then decreased dramatically as temperature increased further. There were significant differences between germination rates under the various temperature conditions (Figure 2c), no matter whether light was provided or under dark conditions. However, for any temperature regime, germination rate was not significantly different between light and dark treatments for any temperature regime.

**Effects of constant temperature regimes on germination under dark conditions**

In the dark, when seeds were subjected to constant temperatures (10°C, 15°C, 20°C, 25°C, 30°C), they germinated well at lower temperatures. However germination was significantly lower at 20°C (for data at constant temperatures, both final percent germination and germination rate were based on data collected at 0MPa of experiment 3). The final percent germination increased slightly from 70.9% at 10°C to 79.1% at 15°C, then decreased sharply to 24.5% at 20°C. No seeds germinated at 25°C and 35°C (Figure 2b).

Germination rate showed a similar pattern to final percent germination, initially increasing and then decreasing with increasing temperature. The most suitable constant temperature was 15°C (Figure 2d).

**Effects of light intensity on germination under a specific temperature regime**

There were no significant differences among final percent germination of *H. fruticosum* seeds under varied light intensities (including constant darkness). The final percent germination was above 74% under all experimental light intensities (Figure 3a).

Germination rate was not significantly different at the various light intensities, although it was slightly lower under 25 and 100µmol m–2 s–1 than under 400µmol m–2 s–1 (Figure 3b).
Effects of PEG solution on germination

The final percent germination and germination rate of *H. fruticosum* significantly decreased with lowered water potentials. It was relatively high in distilled water, but few seeds germinated even at –0.2MPa.

Discussion

Although clonal regeneration is the major recruitment strategy for *H. fruticosum* populations, poor seed germination is still a significant concern. This is because *H. fruticosum* is one of the important species on the Ordos plateau, China, where serious desertification is ongoing, and air seeding is one of the most feasible rehabilitation technologies.

Our study found that under alternating or constant temperatures, both final percent germination and germination rate of *H. fruticosum* first increased with temperatures, and then decreased sharply from the maximum value. The optimal alternating and constant temperatures were 10:20°C and 15°C, respectively, and germination did not occur at alternating temperatures of 25:35°C or the constant temperatures of 25°C and 30°C (Figure 2). This pattern is similar to the findings of Agami (1986), who reported that germination of *Zygophyllum dumosum* seeds was independent of temperature in the range of 10–25°C, but was strongly inhibited at 30°C and 35°C. Similar results were also documented for perennials such as *Haloxylon recurvum* (Khan and Ungar 1996, 1997b, 1997c), *Salicornia pacifica var. utahensis* (Khan and Weber 1986), *Allenrolfea occidentalis* (Gold 1939, Young et al. 1995) and other halophytes such as *Triglochin bulbosa* (Naidoo and Naicker 1992). Cluff et al. (1983) found that a temperature regime of 10:40°C (16:8h) was optimal for seed germination of *Distichlis spicata*, while –5°C and 50°C were the lower and upper threshold temperatures, although it appears that *D. spicata* had a wider optimal temperature variation than *H. fruticosum*. It should be pointed out that as a general rule, seeds exhibit a base or minimum temperature for germination (*Tb*), an optimal temperature at which germination is most rapid (*To*), and a maximum or ceiling temperature at which germination is prevented (*Tc*) (Alvarado and Bradford 2002). However, the minimum temperature for germination of *H. fruticosum* was not a subject of the present study.

The final percent germination in our experiments was somewhat higher under alternating temperature conditions than that at constant temperature. Although the difference was not significant, it is consistent with the report that diurnal temperature fluctuations could stimulate seed germination.

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**Figure 2:** Final percent germination (±SE) (a) and germination rate (±SE) (c) of *Hedysarum fruticosum* in light (215µmol m⁻² s⁻¹) and dark under alternating temperature conditions (5:15°C, 10:20°C, 15:25°C, 20:30°C, 25:35°C) (night:day), and final percent germination (±SE) (b) and germination rate (±SE) (d) of *H. fruticosum* in dark under constant temperature conditions (10°C, 15°C, 20°C, 25°C, 30°C). Each bar represents the mean of five replicates; bars with different letters are significantly different from each other at P < 0.05 (Tukey test)
compared with 90% in the light for Naicker (1992) reported only 10% germination in the dark with that in the light (Khan and Weber 1986). Naidoo and pacifica (Morinaga 1926, Warington 1936, Thompson 1968, 1974a, South African Journal of Botany 2005, 71(2): 167–172 conditions. A 50% reduction in dark germination of species germinated equally well under light or dark germination in 20 and 10 species respectively, while 11

Secondary dormancy during the burial period and then develop a light requirement to trigger germination (Gul and Baskin 1995, Benvenuti 1995, Khan and Ungar 1997c) because seeds may undergo a transition from primary to hard-coatedness, is that seeds should be stored in cool facilities and necessary equipment. The National Institute for Environment Studies kindly supplied laboratory appreciating the assistance of the Association of International Research Programs (G2000018600) and the China NSFC Key Project (49835010) for their support of seed collection in China. The authors also greatly acknowledge the Fund of the President of the Chinese Academy of Sciences, the National Key Basic Research — The authors thank the Fund of the President of the Chinese Academy of Sciences, the National Key Basic Research Program (G2000018600) and the China NSFC Key Project (49835010) for their support of seed collection in China. The authors also greatly appreciate the assistance of the Association of International Research Initiatives for Environmental Studies, Japan, in funding this research. The National Institute for Environment Studies kindly supplied laboratory facilities and necessary equipment.

Various studies have shown that light is another important factor for seed germination in many species (Baskin and Baskin 1995, Benvenuti 1995, Khan and Ungar 1997c) because seeds may undergo a transition from primary to secondary dormancy during the burial period and then develop a light requirement to trigger germination (Gul and Weber 1999). Baskin and Baskin (1995) reported that out of 41 species of halophytes, light and dark promoted germination in 20 and 10 species respectively, while 11 species germinated equally well under light or dark conditions. A 50% reduction in dark germination of S. pacifica var. utahensis seeds was recorded in comparison with that in the light (Khan and Weber 1986). Naidoo and Naicker (1992) reported only 10% germination in the dark compared with 90% in the light for T. bulbosa and T. striata. In this study, no significant effects of light were found on germination of H. fruticosum in terms of final percent germination or germination rate.

With regard to effects of water stress on germination, some research reveals that germination rate and final germination percentage both decrease with decreasing soil-water potential, and species may have characteristic threshold water potentials below which germination cannot occur (Fyfield and Gregory 1989). In our experiments, even a water potential of –0.2MPa significantly decreased germination. This might indicate why H. fruticosum populations regenerate through clonal growth, i.e. because water potential of the sandy soil is usually lower than –0.2MPa.

Finally, our findings could be useful for designing more effective timing for air seeding. As presently shown, germination conditions necessary for H. fruticosum include relatively low temperatures and moist soil, which usually occur over a short period from late May to mid-June, when the area concerned enters the rainy season, coupled with suitable temperature combinations about 10:20°C. In addition, H. fruticosum seeds need to be buried by sand for favourable soil water conditions in the late spring. Although light exposure will not inhibit germination, the surface sands quickly dry after rain, and the higher temperatures when air seeding conventionally takes place could easily damage the shallowly-rooted seedlings developed from unburied seeds (Qi 1998). If the timing of air seeding were earlier, seed burial could be conveniently facilitated by the prevailing winds that occur from early to late spring. For H. fruticosum, the maximum burial depth, from which seedlings are able to emerge, was reported to be 50mm (Wen 1992). In order to avoid burial that is too deep, air seeding should not be earlier, when winds are still very strong. On the other hand, seed germination should not take place too late otherwise seedlings may not avoid frost damage in autumn, at the end of a frost-free period.

Considering all these factors, suitable timing for dispersing H. fruticosum seeds should be early to mid-May. Further, our experiments showed that after storage for 2 years at 4°C, hard-coatedness was negligible. Although the appropriate storage time and temperature remain to be ascertained, a general recommendation to reduce the adverse impacts of hard-coatedness, is that seeds should be stored in cool conditions for several months.

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Figure 3: Final percent germination (±SE) and germination rate (±SE) of Hedysarum fruticosum in various light intensities (dark, 25, 100, 400µmol m−2 s−1) at 10:20°C (night:day) temperature. Each bar represents the mean of five replicates; bars with different letters are significantly different from each other at P < 0.05 (Tukey test) (Morinaga 1926, Warington 1936, Thompson 1968, 1974a, 1974b).
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