Weed Science

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Research Article

Cite this article: Mahajan G, Prasad A, Chauhan BS (2021) Seed germination ecology of Sumatran fleabane (*Conyza sumatrensis*) in relations to various environmental parameters. Weed Sci. **69**: 687–694. doi: 10.1017/wsc.2021.56

Received: 28 May 2021
Revised: 18 July 2021
Accepted: 2 August 2021
First published online: 9 August 2021

Associate Editor:
Nathan S. Boyd, Gulf Coast Research and Education Center

Keywords:
Burial depth; emergence; light; salt stress; seed; shade; temperature; water stress

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*This article has been updated since its original publication. See https://doi.org/10.1017/wsc.2021.63.

Seed germination ecology of Sumatran fleabane (*Conyza sumatrensis*) in relations to various environmental parameters*

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Abstract

Sumatran fleabane [*Conyza sumatrensis* (Retz.) Walker] is an emerging weed in the Australian cropping region. Populations resistant to glyphosate have evolved in Australia, creating the demand for information regarding the seed germination ecology of glyphosate-resistant (R) and glyphosate-susceptible (S) populations of *C. sumatrensis*. A study was conducted to examine the effects of temperature, light intensity, salt stress, osmotic stress, and burial depth on the germination and emergence of two populations (R and S) of *C. sumatrensis*. Both populations were able to germinate over a wide range of alternating day/night temperatures (15/5 to 35/25 C). In light/dark conditions, the R population had higher germination than the S population at 20/10 and 35/25 C. In the dark, the R population had higher germination than the S population at 25/15 C. In the dark, germination was inhibited at 30/20 C and above. Averaged over populations, seed germination of *C. sumatrensis* was reduced by 97% at zero light intensity (completely dark conditions) compared with full light intensity. Seed germination of *C. sumatrensis* was reduced by 17% and 85% at osmotic potentials of −0.4, and −0.8 MPa, respectively, compared with the control treatment. The R population had lower germination (57%) than the S population (72%) at a sodium chloride concentration of 80 mM. Seed germination was highest on the soil surface and emergence was reduced by 87% and 90% at burial depths of 0.5 and 1.0 cm, respectively. Knowledge gained from this study suggests that a shallow-tillage operation to bury weed seeds in conventional tillage systems and retention of high residue cover on the soil surface in zero-till systems may inhibit the germination of *C. sumatrensis*. This study also warrants that the R population may have a greater risk of invasion over a greater part of a year due to germination over a broader temperature range.

Introduction

Sumatran fleabane [*Conyza sumatrensis* (Retz.) Walker; name recently changed to *Erigeron sumatrensis* Retz.] is a short-lived (i.e., annual or biennial) weed of the Asteraceae family. It is native to Indonesia but is now widely distributed worldwide (Thebaud and Abbott 1995). About 150 species of *Conyza* have been documented worldwide (Holm 1997). Invasive weeds of the *Conyza* genus are found in 65 nations (Roskov et al. 2016). Out of 150 species of *Conyza*, three species, namely *C. sumatrensis*, horseweed [*Conyza canadensis* (L.) Cronquist], and hairy fleabane [*Conyza bonariensis* (L.) Cronquist], are very common in the cropping regions of Australia. In Australia, *C. sumatrensis* is a problematic weed and can be seen in spring- and summer-season crops (Storrie 2020). The occurrence of *C. sumatrensis* can be seen in crop fields, especially cotton (*Gossypium hirsutum* L.), horticultural crops, and fallow fields, as well as along roadsides and railway lines (Diez de Ulzurrun et al. 2020; Everett 1990; Thebaud and Abbott 1995). It is widely naturalized in southeastern Queensland, New South Wales, the Australian Capital Territory, Victoria, Tasmania, South Australia, and Western Australia (AVH 2010).

Conyza sumatrensis seeds are reported to remain viable for 2 to 3 yr in the soil (Hayashi 1979). The seed production level for *C. sumatrensis* has been reported to be up to 60,000 seeds per plant (Hao et al. 2009). A previous study reported that *C. sumatrensis* could produce 95 florets per head (Thebaud and Abbott 1995). These authors also reported that within a competitive environment, *C. sumatrensis* has a greater ability to absorb and utilize both water and nutrient sources than *C. canadensis*. *C. sumatrensis* populations have been reported to be resistant to multiple herbicides with different modes of action: acetolactate synthase inhibitors

(Group 2); photosystem I and II inhibitors, urea, and amide (Group 5, 6, 7); and glycines (Group 9) (Heap 2021). Resistant populations of *C. sumatrensis* have been found in Japan, Spain, Taiwan, Sri Lanka, Malaysia, and Australia (Heap 2021; Osuna and De Prado 2003). *Conyza sumatrensis* is a self-pollinated weed, and the spread of resistance could be due to the wind-mediated dispersal movement of seeds. High seed production and broad dispersal may cause high infestations of *C. sumatrensis* (Andersen 1993; Diez de Ulzurrun et al. 2020; Hao et al. 2009; Smisek et al. 1998).

The adoption of conservation farming systems in Australia and the evolution of resistance to multiple herbicides with different modes of action have made *C. sumatrensis* a more problematic weed in Australia (Green 2010). It was suggested that integrated weed management strategies based on knowledge of weed biology could play an important role in weed control and may help in mitigating herbicide resistance in weeds (Mahajan and Chauhan 2020). Therefore, knowledge of seed germination biology could be useful for developing integrated weed management strategies for *C. sumatrensis*. Previous studies suggest that environmental factors such as temperature, light, soil salinity, and water stress may alter the germination behavior of weeds (Loura et al. 2020; Mahajan et al. 2018; Singh et al. 2021).

Temperature is an important factor that influences seed germination by affecting moisture uptake, which enhances physiological and metabolic activities (Bewley et al. 2013). Previous studies conducted elsewhere (Australia, Portuguese, and the United States) revealed that the germination of *Conyza* species may occur at a temperature range of 20 to 35 C, suggesting that *Conyza* spp. can germinate year-round or at a wider range of temperature conditions in Australia (Green 2010; Loura et al. 2020; Nandula et al. 2006; Vidal et al. 2007).

Light is not always required for the germination of some weeds. There are mixed opinions on light requirements for *Conyza* spp. germination. A study on *C. canadensis* revealed that light is not required for germination (Gorski 1975; Milberg et al. 2000; Nandula et al. 2006). Conversely, others reported that light is required for germination of *C. bonariensis* (Karlsson and Milberg 2007; Michael 1977; Wu et al. 2007). Within the agroecosystem, shading could be influenced by management practices, such as tillage, and this may influence seed germination/emergence. Under a conservation tillage system, crop residues can create a shaded microenvironment that can affect germination/emergence. Within conventional tillage, buried seeds in the soils face a dark environment that affects germination/emergence. It was opined that seed germination in C_3 species, such as *Conyza*, might be more influenced by shade than germination in C_4 species (Steckel et al. 2006).

Salt and water stress are a major concern to the Australian farming system, as 60% of the soils in the cropping regions are sodic soils (Regasamy 2010). Germination and emergence behavior of many weeds are altered in response to water and salt stress (Mahajan et al. 2018; Mutti et al. 2019). A recent study revealed that populations of erect horseweed [*Conyza stricta* (Willd.)] can tolerate salinity and germinate under 0 to 500 mM NaCl levels of salinity (Ali et al. 2020). In another study, it was found that *C. bonariensis* populations could germinate at an NaCl concentration of 200 mM, and germination was zero at 250 mM NaCl (Loura et al. 2020). The highest germination of *C. bonariensis* was found under no water-stress conditions; although there was ecotypic variation in response to water stress (Loura et al. 2020). These observations suggest that populations of *C. sumatrensis* may differ in their germination behavior in response to water and salt stress. Limited information is available on the seed germination ecology of *C. sumatrensis*. Knowledge gaps exist on the germination behavior of *C. sumatrensis* in response to environmental parameters such as temperature, light availability, salt, and water stress. Information is also scant regarding the emergence behavior of *C. sumatrensis* with respect to burial depth.

Previous studies suggested that seeds of *Conyza* are more likely to be photoblastic and emerge easily from the soil surface (Loura et al. 2020; Yanashita et al. 2016). The germination behavior of different populations of weeds may vary in response to environmental parameters. For example, in Australia, it was found that the germination behavior of herbicide-resistant and herbicide-susceptible populations of junglerice [*Echinochloa colona* (L.) Link] changed in response to environmental parameters, and it was found that 50% germination of the glyphosate-resistant and glyphosate-susceptible populations was inhibited at NaCl concentrations of 209 and 174 mM, respectively (Mutti et al. 2019). In another study on minor bluegrass (*Polypogon fugax* Nees ex Steud.), Tang et al. (2015) observed that optimum temperatures for the germination of an aryloxyphenoxy propanoate herbicide–susceptible population were 10 to 25 C, or alternating temperatures of 15/5 to 30/20 C, and light was not necessary. However, the maximum germination of the aryloxyphenoxy propanoate herbicide–resistant population occurred at 10 C or 15/5 C, and no germination occurred above 15 C or 25/15 C, suggesting that the herbicide-resistant population had a narrow range of temperatures for germination. This information suggests that the germination behavior of herbicide-resistant and herbicide-susceptible populations of *C. sumatrensis* may differ in response to environmental parameters. Differential germination behaviors of glyphosate-resistant populations could be an issue in Australia, as farmers in Australia currently use glyphosate for pre-sowing and fallow weed control. Recently, the first case of a paraquat-resistant and glyphosate-resistant *C. sumatrensis* population in Australia has been identified (Chauhan 2019). Therefore, a thorough understanding of the germination ecology of glyphosate-resistant and glyphosate-susceptible populations of *C. sumatrensis* is needed.

The objectives of this study were to determine the optimal germination conditions for two populations of *C. sumatrensis* under a range of environments. Such information will help in designing better weed control measures to reduce the invasiveness of glyphosate-resistant populations in conservation farming.

Materials and Methods

Seed Collection

Seeds used in this study were originally collected from two locations Dalby, QLD, Australia, and Gatton, QLD, Australia. Seeds were collected from 50 to 60 random plants from each location. The GPS coordinates of the Dalby (R) and Gatton (S) populations were 27.4455°S, 151.5827°E and 27.5438°S, 152.3405°E, respectively. Previous studies conducted at the Gatton Research Farm of the University of Queensland, Gatton, QLD, Australia, confirmed that the Dalby population of *C. sumatrensis* was highly resistant to glyphosate (Chauhan 2019). Seeds used in this study were collected from freshly harvested plants, and the viability of the seed was 100%.

General Seed Germination Test Protocol

All germination/emergence experiments were conducted in the weed science laboratory (27.601°S, 51.343°E) of the Queensland Alliance for Agriculture and Food Innovation (QAAFI) at the University of Queensland, Gatton, QLD, Australia. Each experiment was repeated once immediately after the termination of the first experimental run. Germination experiments were conducted by placing 25 seeds of each population evenly on the surface of petri dishes (9-cm diameter) (Sarstedt, Mawson Lakes, SA, Australia) containing a double-layer of filter papers (Whatman® International, Maidstone, UK). Filter papers were moistened before placement of seeds using 5 ml ionized water/salt solution/polyethylene glycol (PEG) solution using a micropipette (BOECO, Hamburg, Germany). Seeds were placed in petri dishes using a pair of forceps and a desk magnifying lamp (White label, model QM3546, Jaycar Electronics, Underwood, QLD, Australia). Seeds with a dark creamy brown color were selected for experiments, and seeds that were damaged, diseased, or had irregularities in their shape were avoided. Before incubation, petri dishes were placed inside transparent plastic ziplock bags, and the bags were sealed to avoid evaporation losses. The bags containing the petri dishes were placed in incubators as per treatments. The light inside the incubators was provided by fluorescent lamps (Ultralamp ECO-T5, 28W, Cabramatta, NSW, Australia), with an 85 mol m^{-2} s^{-1} light intensity.

Effects of Temperature and Light on Germination

This experiment was conducted in a completely randomized design (three factors: alternating day/night temperature regimes [15/5, 20/10, 25/15, 30/20, 35/25, and 40/30 C with 12-h light/12-h dark photoperiod], light regimes [light/dark and dark], and population [R and S]) with three replicates. Bags containing petri dishes of both populations were placed inside six different incubators as per treatments. For the dark treatment, bags containing petri dishes of both populations were wrapped in two layers of aluminum foil before being placed in incubators. The purpose of wrapping the petri dishes inside plastic ziplock bags with double layers of aluminum foil was to provide a completely dark environment throughout the experiment. At 21 d after the experimental setup date, the petri dishes were removed from the incubator and opened to assess germination. Germinated seedlings were examined under a magnifying lamp (White label, model QM3546), and seeds with a radicle growth of more than 2 mm were considered germinated and recorded. The six temperature regimes were chosen in this study to simulate conditions of different seasons experienced in the cropping region of Australia. In Australia, the lowest temperature regimes (winter season) are experienced from June to August and the highest temperature regimes (summer season) are experienced from December to February. The autumn season is experienced from March to May, and the spring season is experienced from September to November.

Effects of Light Intensity on Germination

This experiment was conducted in a completely randomized design (two factors: light intensities [0%, 30%, 50%, 70%, and 100%] and population [R and S]) with three replicates. For seed incubation, the general seed germination protocol was followed, and seeds were incubated at 30/20 C. The temperature 30/20 C was selected for this study because it was the best temperature for germination, as evident by the results of the temperature regimes experiment. For this experiment, pieces of a shade cloth allowing varied light intensities (0%, 30%, 50%, 70%, and 100% light) were cut using a pair of scissors and sewn to create rectangular bags to allow placement of plastic bags containing petri dishes. The light intensity was measured with a quantum flux meter (model MQ-200, Instrument Choice, Dry Creek, SA, Australia). The petri dishes were placed inside shade bags as per treatments (light intensities of 0%, 30%, 50%, 70%, and 100%) and placed inside the incubator (Labec Laboratory, Marrickville, NSW, Australia) and left undisturbed for 21 d. After 21 days, the experimental units were removed from the incubator, and germinated seeds were counted.

Effects of Osmotic Stress on Germination

An experiment to evaluate the effects of osmotic potential on germination was established in a completely randomized design (three factors: alternating day/night temperatures regimes [20/10 and 30/20 C], osmotic potential levels [0 = control, −0.1, −0.2, −0.4, −0.8, and −1.6 MPa], and population [R and S]) with three replications. For seed incubation, the general seed germination protocol was followed, but filter papers were moistened with 5 ml of PEG solution instead of water as per treatments. Solutions of desired osmotic potentials were prepared following the procedure of Michel and Radcliffe (1995) by dissolving PEG 8000 (Sigma-Aldrich, Castle Hill, NSW, Australia) in ionized water. The two temperature regimes were selected to reflect winter- and summer-season temperatures.

Effects of Salt Stress on Germination

An experiment to evaluate the effects of sodium chloride (NaCl) on germination was established in a completely randomized design (three factors: alternating day/night temperatures regimes [20/10 and 30/20 C], NaCl concentrations [0, 10, 20, 40, 80, 160 and 320 mM], and populations [R and S]). For seed incubation, the general seed germination protocol was followed, but filter papers were moistened with 5 ml of salt solution instead of water as per treatments. The required concentrations were prepared using NaCl (Sigma-Aldrich) and ionized water. A wide range of salt concentrations was used consistent with the salinity levels occurring in different regions of Australia (Rengasamy 2002). The two temperature regimes were selected to reflect winter- and summer-season temperatures.

Effects of Burial Depth on Seedling Emergence

Burial depth experiments were conducted in a completely randomized design (two factors: burial depth [0, 0.5, 1, 2, and 4 cm] and population [R and S]) with three replicates. The study was conducted using plastic pots (10-cm diameter) filled with field soil. A total of 50 seeds of both populations were either placed on the soil surface (0-cm depth) or placed at soil depths of 0.5, 1, 2, and 4 cm as per treatment in each pot. The pots were placed in nonporous plastic trays filled with water before being placed inside an incubator programmed at an alternating day/night temperature of 30/20 C. The soil for this experiment was collected from the Gatton Research Farm of the University of Queensland and sieved through a 2-mm plastic sieve. The soil had a pH of 7.1 and contained 33% sand, 46% silt, and 21% clay with 2.6% organic matter. Water was manually added into the plastic trays that were holding the pots every third day to ensure maintenance of adequate moisture levels

Table 1. Effect of alternating day/night temperatures (15/5 to 40/30 C) and light regimes on the germination (%) of glyphosate-resistant (R) and glyphosate-susceptible (S) *Conyza sumatrensis* populations.[a]

Alternating temperature regimes (day/night)	Germination[b]			
	Light/dark		Dark	
	R population	S population	R population	S population
—C—		—%—		
15/5	10b	20c	61d	57d
20/10	93f	78e	84e	75e
25/15	87ef	81e	77e	53d
30/20	87ef	82e	4ab	1a
35/25	82e	69d	0a	0a
40/30	0a	0a	0a	0a
LSD (0.05)		9.3		

[a] Seeds were incubated for 21 d under light/dark (12-h photoperiod) and complete dark (24-h photoperiod).

[b] Values followed by a common letter are not significantly different from each other.

in pots. Seedling emergence was counted 4 wk after the start of the experiment.

Statistical Analyses

ANOVA was performed to identify the level of significance for each treatment and interactions between factors ($P \leq 0.05$). The experimental runs were modeled as random effects, and treatments were modeled as fixed effects. No interaction was observed between experimental runs and treatments in each experiment; therefore, the data were pooled across the two experimental runs for ANOVA. Data were subjected to ANOVA using the software CPCS1 (Punjab Agricultural University, Ludhiana, India). Data were subject to the homogeneity of variance before analysis. Means were separated using Fisher's protected LSD test. Graphs were made using SigmaPlot v. 14.0 Notebook (Systat Software, San Jose, CA, USA).

Results and Discussion

Effect of Light and Temperature

An interaction between temperature regimes, light/dark regimes, and populations was observed for germination of *C. sumatrensis* (Table 1). In alternating light/dark conditions, the R population had the highest germination (93%) at 20/10 C, which was reduced to 82% at 35/25 C. Under the same light conditions, the S population had the highest germination (82%) at 30/20 C, and its germination was reduced to 69% at 35/25 C. Both populations did not germinate at 40/30 C. In alternating light/dark conditions, the R population had higher germination than the S population when seeds were incubated at 20/10 C and 35/25 C. In these light conditions, the germination of both populations was lower at 15/5 C as compared with 20/10, 25/15, 30/20, and 35/25 C.

Under the complete darkness condition, both populations had the highest germination at 20/10 C, which was reduced to <5% at 30/20 C. In the dark, at 15/5 C and 20/10 C, both populations had similar germination; however, at 25/15 C, the R population had higher germination than the S population. At 15/5 C, both populations had higher germination under dark conditions compared with alternating light/dark conditions. In contrast, at 30/20 and 35/25 C, both populations had higher germination under light/dark conditions compared with dark conditions.

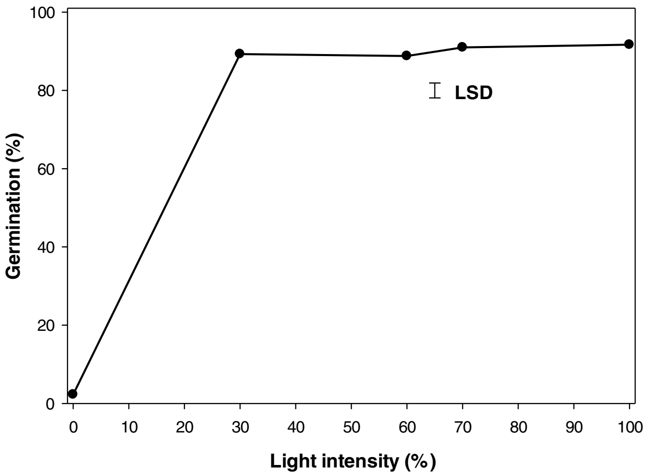

Figure 1. Effect of light intensity (%) on the germination of *Conyza sumatrensis* seeds (averaged over populations). Seeds were incubated for 21 d at an alternating day/night temperature of 30/20 C. LSD is the least significant difference at a 5% level of significance.

The results of this experiment demonstrate that both populations could germinate under a wide range of temperatures (15/5 to 35/25 C). Therefore, this weed has the potential to germinate year-round in eastern Australia. Higher germination of the R population compared with the S population at 20/10 C and 35/25 C in alternating light/dark conditions suggests that the R population may have higher germination over the summer and winter seasons. High germination of the R population at alternating day/night temperatures of 35/25 C could probably cause an increased spread of the R population in the wake of climate change. It has been observed that the daytime summer temperature in central Queensland ranged between 30 and 32 C for many years, and it is predicted to rise between 2 to 4.5 C by 2070 (ABM 2020). The results of this study are consistent with previous studies conducted in Australia on *C. bonariensis*, a closely related species, which suggest that it can germinate at a wide range of temperatures (15/5 to 35/25 C) and fluctuating light conditions, making its management difficult throughout the year (Loura et al. 2020).

The germination temperature range of *C. sumatrensis* (15/5 to 35/25 C) and the high soil moisture in conservation tillage systems could add to its success in eastern Australia. High germination in a dark environment at the lowest temperature (15/5 C) suggests that this weed tends to germinate in the winter season under conservation tillage systems. During the autumn and winter seasons in eastern Australia, a site under a high crop residue cover in a zero-till system could have reduced light intensity and temperature on the soil surface (Nyborg and Malhi 1989; Oryokot et al. 1997) and may increase the germination of *C. sumatrensis* in the winter season.

Effect of Light Intensity/Shade

No interaction was observed between light intensities and populations for germination of *C. sumatrensis*; therefore, data were pooled over populations (Table 1). Averaged over populations, seed germination of *C. sumatrensis* was highest (92%) under 100% light intensity, and seed germination was not reduced when seeds were exposed to 70% light intensity. However, when seeds were exposed to zero light intensity, seed germination was reduced to 2% (Figure 1).

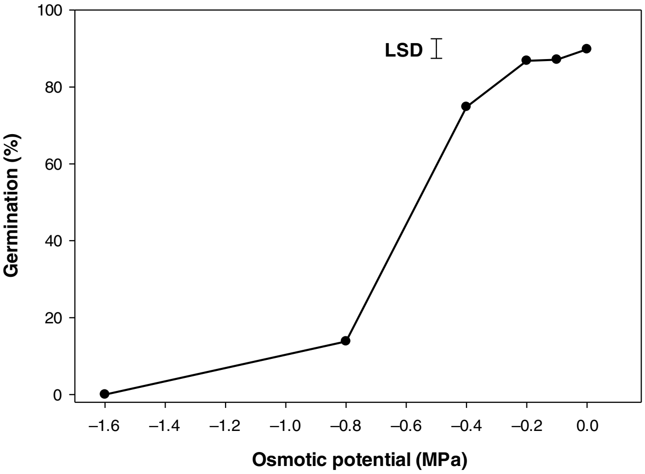

Figure 2. Effect of osmotic potential on the germination of *Conyza sumatrensis* seeds (averaged over temperature regimes and populations). Seeds were incubated for 21 d at alternating day/night temperatures of 20/10 and 30/20 C. LSD is the least significant difference at a 5% level of significance.

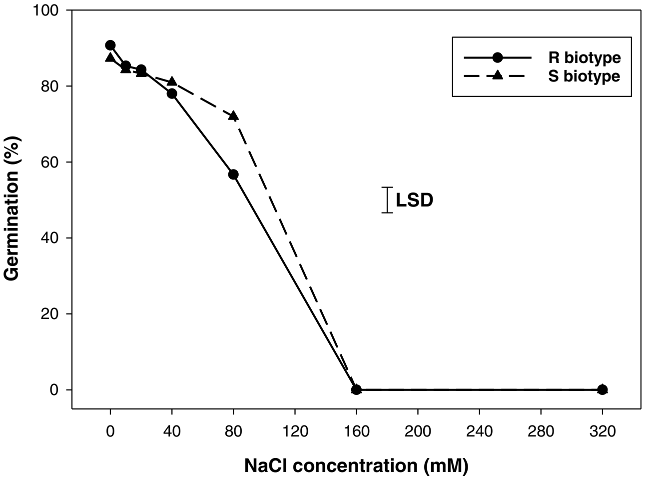

Figure 3. Effect of sodium chloride (NaCl) on the germination of glyphosate-resistant (R) and glyphosate-susceptible (S) populations of *Conyza sumatrensis* seeds (averaged over temperature regimes). Seeds were incubated for 21 d at alternating day/night temperatures of 20/10 and 30/20 C. LSD is the least significant difference at a 5% level of significance.

Sunlight has a red/far-red (R/FR) ratio of 1.2 and it helps in seed germination by influencing light intensity (Benech-Arnold et al. 2000). However, there is evidence that FR light (about 735 nm) can inhibit germination (Ballaré et al. 1992). Light is an important regulator for seed germination in small-seeded plants. Phytochromes, a class of photoreceptors, help in inducing seed germination by perceiving interactions of light and hormone signals (Seo et al. 2009). It has been reported that seed germination can be induced by a proportion of phytochrome in its FR light–absorbing form (Pfr/P) as low as 10^{-4} and is usually saturated by <0.03 Pfr/Pr (Benech-Arnold et al. 2000). These observations suggest that the quality and quantity of light received by seeds play an important role in seed germination.

Crop residues in conservation tillage systems create a shaded environment, and this study indicates that a level of stubble providing 70% shade to the seed still permits high germination (70%) when moisture and temperature requirements are met. Seed germination was high in 70% shade, but only 2% germination in 100% shade suggests that a high level of residue cover or black mulch in the field could inhibit the germination of this weed. A high residue cover in the field may prevent germination of weed seeds by obstructing light penetration, decreasing soil moisture, and reducing oxygen availability (Acharya et al. 2005; Liebman and Gallandt 1997).

Effect of Osmotic Stress

No interaction was observed between temperature regimes (20/10 and 30/10 C), osmotic potential, and populations for germination of *C. sumatrensis*; therefore data were pooled for temperature regimes and populations. Averaged across temperature regimes and populations, seed germination of *C. sumatrensis* was affected by osmotic potential (Figure 2). Germination was highest (90%) in the control treatment and was reduced to 75% at an osmotic potential of −0.4 MPa. Low germination (14%) occurred at −0.8 MPa, and no seeds germinated at an osmotic potential of −1.6 MPa.

High germination in the no water-stress treatment suggests that uniform distribution of rains throughout the year in eastern Australia and irrigated cropping systems could favor the incidence of this weed (ABM 2020). The ability of *C. sumatrensis* to germinate under relatively dry conditions (−0.4 MPa) confirms that it can survive in dryland agriculture systems, although it would be favored by additional surface soil moisture in conservation tillage systems (Bond and Willis 1969; Nyborg and Malhi 1989; Oryokot et al. 1997; Singh et al. 1998). Relevant information on the effect of water stress on seed germination of *C. sumatrensis* is limited; however, information on closely related species such as *C. canadenesis* and *C. bonariensis* is available. Germination of *C. canadensis* decreased from 25% to 2% with a decreased osmotic potential concentration from 0 to −0.8 MPa (Nandula et al. 2006). Similarly, germination of *C. bonariensis* decreased from 100% to 50% with a decreased osmotic potential concentration from 0 to −0.4 MPa (Loura et al. 2020). Drier conditions anticipated under climate change would only increase the potential for germination of *Conyza* spp.

Effect of Salt Stress

An interaction between populations and salt concentrations was observed for the germination of *C. sumatrensis* (Figure 3). Both populations had the highest germination (~87%) in the control treatment, and germination was not inhibited at 40 mM NaCl. At 80 mM NaCl, the S population (73%) had greater germination than the R population (46%), suggesting that the S population is more tolerant to salt than the R population. Our results are in contrast to the previous study of Mutti et al. (2019), who confirmed that a glyphosate-susceptible population of *E. colona* had reduced germination under salt-stress conditions compared with a glyphosate-resistant population.

A previous study revealed that *C. bonariensis* had greater than 70% germination at 150 mM NaCl (Loura et al. 2020). However, *C. canadensis* had the lowest germination at 160 mM NaCl (Nandula et al. 2006). Inhibition of seed germination under salt stress might be due to the physiological disturbance of metabolic processes that are affected by ion toxicity (Farooq et al. 2015). The literature suggests that soil with an NaCl concentration of 20 mM is recognized as problematic or salt affected (Abrol et al. 1988). Due to increased salinity problems in the arid regions of

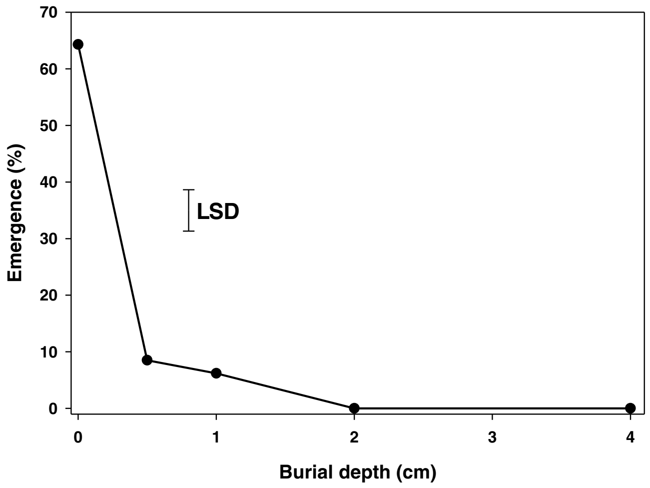

Figure 4. Effect of burial depth on the seedling emergence of *Conyza sumatrensis* (averaged over populations). Seeds were incubated for 21 d at alternating day/night temperatures of 30/20 C. LSD is the least significant difference at a 5% level of significance.

Australia (Rengasamy 2002), *C. sumatrensis* could be a problematic weed in these regions in the future. Our results strongly suggest that *C. sumatrensis* has the potential to germinate under high soil salinity conditions and could pose competition to crops in such environments by increasing its competitive ability against crops.

Effect of Seed Burial Depth on Seedling Emergence

Seedling emergence of *C. sumatrensis* was not affected by population. Seed germination was highest on the soil surface (64%), and seedling emergence decreased to 8% and 6% at burial depths of 0.5 and 1 cm, respectively (Figure 4). High germination of surface seeds suggests that no-till systems favor this weed. The possible reason for low germination on the soil surface compared with petri conditions could be poor soil–seed contact on the soil surface or limited soil moisture compared with the moist environment of the filter paper (Ghorbani et al. 1999).

Previous studies on closely related species revealed that *C. bonariensis* had higher germination on the soil surface compared with burial (Loura et al. 2020; Wu et al. 2007). *Conyza canadensis* also had the highest germination on the soil surface compared with burial depths of 0.5 cm or more (Nandula et al. 2006). *Conyza sumatrensis* seeds are known to be photoblastic, and the possible reason for high germination on the soil surface is light-stimulated germination, as made evident by the light/dark experiment. Soil gas exchange and light is limited at burial depths, which could explain low germination of buried seeds (Benvenuti and Macchia 1995).

Germination on the soil surface offers *C. sumatrensis* an ecological advantage under a no-till system, in which the majority of seeds remain on the soil surface due to lack of cultivation (Chauhan et al. 2006). Consequently, if the seedbank of this weed has been observed to build up on the soil surface, a shallow-tillage operation could bury the seeds below the depth of emergence. This also implies that *C. sumatrensis* seed longevity could be increased at greater burial depths if a tillage operation is allowed (Green 2010; Hayashi 1979). Therefore, strategic tillage depending upon the longevity of the seeds could be a useful strategy for the management of this weed. However, there is a need to verify the seed-dispersal movement of *C. sumatrensis* in relation to tillage operations. Tillage operations could also cause horizontal movement of weed seeds by wind displacement or as a result of soil displacement by agricultural machinery, for example, adhesion of soil matrix to the tires of movable machinery (Ghersa et al. 1993; Mayer et al. 1998).

In summary, *C. sumatrensis* seeds can germinate over a wide range of temperatures, suggesting that the weed has the potential to emerge year-round. The R population had greater germination than the S population at temperature regimes of 20/10 C and 35/25 C under light/dark conditions, suggesting that the R population could have a greater chance to invade agroecosystems in the winter and summer seasons. At a temperature range of 30/20 C and above, germination was inhibited under dark conditions, indicating that during the summer season, high residue cover or burial of seeds could restrict seed germination. Inhibition of germination under 100% shade (zero light intensity) also supports the advantage of high residue cover, black mulch, or seed burial for inhibiting germination. The ability of *C. sumatrensis* to germinate at osmotic potentials of −0.4 and −0.8 MPa and under high salt concentrations (up to 80 mM NaCl) suggests that this weed could invade dry regions and problematic soils of Australia. High germination on the soil surface suggests that a zero-till system may promote its germination.

The northern cropping region of Australia experiences hot summers, and reduced soil temperatures provided by some degree of crop residue cover in conservation tillage systems may promote the germination of *C. sumatrensis* in these systems (Blevins and Frye 1993; Nyborg and Malhi 1989; Oryokot et al. 1997). *Conyza sumatrensis* has a greater tolerance to shading/low light intensity for germination, which could explain the possible reason for its occurrence in the roadside environment/rangelands. However, a very high residue cover in the field may also inhibit its emergence if light is not available for seed germination.

Conyza sumatrensis is short-lived (i.e., annual or biennial), and therefore, for effective long-term management, seedbanks in the soil need to be targeted. This includes promoting practices that could reduce the seedbank and minimize future seedbank inputs or further reinfestation through seed rain. Practices for reducing the seedbank, such as harvest weed seed control (e.g., chaff lining, impact mill seed destructor system, burning of chaff in narrow windows) are promoted in zero-till systems where seeds remain on or near the soil surface (Walsh and Newman 2007; Walsh et al. 2018). Seedbank reduction by promoting seedling emergence is dependent on the effective control of seedlings leading to reduced weed density, competition, and further seedbank replenishment. The ability of *C. sumatrensis* to germinate/emerge year-round and under conditions of high salinity and water stress demands careful monitoring and control at an early stage through the use of both preemergence and postemergence herbicides. Seed inputs for seedbank enrichment are not just provided by plants grown in the fields. Seeds of *C. sumatrensis* outside the cropping region can also be blown in and infest the cropping region; therefore, the management of such plants outside the cropping region is also important.

In the case of large infestations or difficult to control populations in a zero-till system, cultivation could be useful, as it could inhibit germination by burying seeds. Rotating tillage practices can reduce selection pressures on *C. sumatrensis* and other weeds, which are favored by zero-till systems. The burial of *C. sumatrensis* seeds, however, could extend the period of seed viability, and information is required in this regard. Therefore, if tillage is to be used as the primary means of control, seed longevity in the soil should be taken into consideration, as the subsequent tillage operation could return those buried viable seeds to the surface in.

Effective long-term management of *C. sumatrensis* requires an integrated weed management strategy in which herbicide use is integrated with cultural and mechanical tactics (Mahajan et al. 2014; Sardana et al. 2017). These strategies may involve strategic tillage, crop competition, and harvest weed seed control. The use of herbicides, even when integrated with cultural options, needs to be practiced in such a way that it could minimize selection pressure for resistant weeds with repeated use of a single herbicide site of action. This can be achieved by rotating herbicides with different sites of action (Busi et al. 2020).

The zero-till system in Australia relies heavily on nonselective herbicides such as glyphosate. Glyphosate-resistant populations of *C. sumatrensis* are present worldwide (Heap 2021), and there are reports of glyphosate- and paraquat-resistant populations from a cropping region where these herbicides are intensively used in eastern Australia (Chauhan 2019). In these situations, strategies like the rotation of herbicides with different sites of action could provide long-term solutions by reducing selection pressure on weeds and by extending the useful life of currently used herbicides (Busi et al. 2020). For effective management of this weed, practices like farm hygiene must be promoted. Due to prolific seed production and the long-distance seed dispersal of *C. sumatrensis*, control measures need to be extended outside the cropping region to include areas such as roadsides, wasteland, vacant lots, and along railway lines.

Although there were some differences between populations for germination behavior, populations from different regions need to be tested for germination and emergence in further laboratory and field experiments to assess the greater risk of ecotypic variation that local habitat and management practices pose. For example, the emergence behavior differed between mouse barley (*Hordeum murinum* L.) populations growing in crops or along the roadside within a single field (Fleet and Gill 2012). The extent of genetic diversity within *C. sumatrensis* populations in Australia is not known. *Conyza* species have been reported to hybridize (Thebaud and Abbott 1995). Therefore, an understanding of the genetic diversity of different populations of *C. sumatrensis* that could explain the distribution of *C. sumatrensis* populations in different regions is needed. It is also necessary to focus on the emergence dynamics and fitness penalty of herbicide-resistant populations in the field by collecting large populations from different regions in Australia. There is also a need to study the phenology of different populations of *C. sumatrensis* under various planting dates and crop competition effects. This information could assist in better managing future risks, including the potential spread of herbicide-resistant populations, and could help in designing effective integrated weed management programs.

Acknowledgments. This research received no specific grant from any funding agency. No conflicts of interest have been declared.

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