

Germination ecology of hairy fleabane (*Conyza bonariensis*) and its implications for weed management

Research Article

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Abstract

Hairy fleabane [*Conyza bonariensis* (L.) Cronquist] is a problematic weed in Australian no-till cropping systems. Consequently, a study was conducted to examine the effect of temperature, light, salt stress, osmotic stress, burial depth, and sorghum crop residue on germination and emergence in two populations (C and W: collected from chick pea [*Cicer arietinum* L.] and wheat [*Triticum aestivum* L.] fields, respectively) of *C. bonariensis*. Both populations were able to germinate over a wide range of alternating day/night temperatures (15/5 to 35/25 °C); however, the C population had optimum (and similar) germination over the range of 20/10 and 30/20 °C, while the W population showed maximum germination at 25/15 °C. A negative relationship was observed between osmotic potential and germination, with 31% and 14% germination of the C and W populations at -0.6 MPa, respectively. These observations suggest that population C was more tolerant to higher osmotic potentials than population W. Seeds of both populations germinated when exposed to a wide range of sodium chloride levels (NaCl, 0 to 200 mM); however, beyond 200 mM NaCl, no germination was observed in either population. Maximum germination of the C (70%) and W (41%) populations was observed on the soil surface with no emergence from a burial depth of 1 cm. The application of sorghum residue at an amount of 6,000 kg ha⁻¹ reduced emergence of the C and W populations by 55% and 58%, respectively, compared with the no-residue treatment. Knowledge gained from this study suggests that the following strategies could be used for more efficacious management of *C. bonariensis*: (1) a shallow-tillage operation to bury weed seeds in conventional tillage systems, and (2) retention of sorghum residue on the soil surface in no-till systems.

Introduction

Hairy fleabane [*Conyza bonariensis* (L.) Cronquist] is a dicot annual broadleaf weed of the Asteraceae family. It originated in South America (Michael 1977) but is now widely distributed around the world. There are more than 150 species of *Conyza* (Roskov et al. 2016), and of these, eight species are found in Australia (Alpen et al. 2014). In Australia, *C. bonariensis* was first documented as a weed in the 1980s and is now recognized as a major weed in a number of different cropping systems. Globally, this species has been documented as a weed in more than 40 crops in more than 65 nations, indicating its high invasive potential (Holm et al. 1997). It possesses a high competitive potential in crops, being particularly aggressive in soybean [*Glycine max* (L.) Merr.], cotton (*Gossypium hirsutum* L.), and corn (*Zea mays* L.).

Several factors such as prolific seed production (more than 119,000 seeds per plant) (Wu et al. 2007), a low level of seed dormancy, a high emergence percentage, and the evolution of increasing resistance toward glyphosate have made *C. bonariensis* a particularly serious invasive weed (Wu et al. 2007). In addition, the seeds of *C. bonariensis* are lightweight and attached to a pappus, attributes that facilitate low wind velocity seed dispersal and consequent high invasiveness (Andersen 1992). It is recognized that *Conyza* species offer severe competition to crops for natural resources. In Australia, for example, uncontrolled *C. bonariensis* reduced grain sorghum [*Sorghum bicolor* (L.) Moench ssp. *bicolor*] yield by 65% to 98% (Wu et al. 2010). Elsewhere, compared with the weed-free treatment, significant yield reductions of up to 68% in soybean and 92% in cotton were documented due to competition with *Conyza* species (Byker et al. 2013; Silva et al. 2014). *Conyza bonariensis* at 3 plants m⁻² decreased the economic yield of soybean by 1%, 12%, and 36% when established at 0, 38, and 81 d before sowing of soybean, respectively (Trezzi et al. 2015).

With the increased adoption of conservation agriculture systems in Australia, *C. bonariensis* has become a problematic weed in the northern region of Australia (northern New South Wales and southern Queensland) (Felton et al. 1994; Manalil et al. 2017). In these systems, it has become a competitive weed due to the low mechanical disturbance of the soil surface (Gibson et al. 2005; Shrestha et al. 2008). Reduced-till or no-till practices have resulted in the greater growth potential of a range of weed species (Chauhan et al. 2006). Currently, *C. bonariensis* ranks among the top 10 weeds in area of infestation and loss of grain yield across both the northern and southern regions of Australia (Llewellyn et al. 2016). Economically, an estimated revenue loss of AU\$ 1.1 million per annum in the northern grain region of Australia has been attributed to *C. bonariensis* (Llewellyn et al. 2016). Although both summer and winter season crops are impacted by *C. bonariensis*, the level of infestation is significantly greater in the wider row spacing of summer crops than in winter (Wu et al. 2010). Wide row spacing allows for the vigorous growth and proliferation of weeds. In Australia, wheat (*Triticum aestivum* L.) and chick pea (*Cicer arietinum* L.) crops are grown in winter. Wheat is the most significant grain crop and chick pea is the second most cultivated pulse crop.

Herbicides have become the main tool for *C. bonariensis* control in no-tillage agriculture systems. Due to the excessive use of herbicides with the same mode of action, several populations of this weed species have evolved resistance to herbicides. This is a significant practical issue, as farmers in Australia currently use glyphosate as a pre-sowing and fallow weed control herbicide. The first case of glyphosate-resistant *C. bonariensis* was reported in 2011 (Heap 2014). Glyphosate-resistant *C. bonariensis* populations have now been observed in Argentina, Australia, Brazil, Columbia, Greece, Israel, Portugal, South Africa, Spain, and the United States (Heap 2020). Because of this widespread herbicide resistance, integrated weed management (IWM) with nonchemical control approaches is highly needed.

The successful implementation of IWM practices for *C. bonariensis* is dependent upon a thorough understanding of the weed's biology (Chauhan and Johnson 2010). Germination is a vital component of weed establishment influenced by environmental factors such as temperature, light, moisture stress, salt concentration, burial depth, and crop residue cover (Chauhan and Johnson 2010). A previous study reported that seeds of *C. bonariensis* can germinate at different temperatures ranging from 10 to 25 C (Zinzolker et al. 1985), while a similar study documented 5, 20, and 35 C as the minimum, optimum, and maximum temperatures, respectively (Wu et al. 2007). In another study, highest germination of horseweed [*Conyza canadensis* (L.) Cronquist] was observed at 15 C (Ottavini et al. 2019). We note that these studies were conducted using constant temperature conditions, and the likelihood of constant temperature in nature is very rare. Fluctuating temperature conditions, which are more commonly found in the environment, may affect seed germination differently (Liu et al. 2013), but such information is not available for *C. bonariensis*.

In addition to variable temperature and light conditions, salt and water stress can also affect seed germination. Salinity is a major concern in the Australian cropping region, and about 60% of the total cropping region has sodic soils (Rengasamy 2010). However, information related to the effect of salt and water stress on *C. bonariensis* germination is currently unavailable. Similarly, there is very limited information available on the effect of crop residue amount and soil burial depth on seedling emergence of

C. bonariensis. Such information would be useful for the effective management of *C. bonariensis* in low- or no-till systems. Crop residue used as mulch creates a light barrier on the soil surface and can be a convenient and effective component for weed suppression in IWM programs. Before the adoption of no-till systems, crop residues were normally burned for ease of planting, but now, the widespread adoption of conservation agriculture systems in Australia has facilitated stubble retention (Walsh et al. 2019). Sorghum is the main summer grain crop grown in the northern region of Australia. After harvest, sorghum stubble is left in the field.

A thorough understanding of germination ecology of *C. bonariensis* will help growers to plan and implement proper management practices. Such studies would help in the prediction of potential areas of invasion by this weed and allow preemptive management strategies to be implemented. The current study was planned to evaluate the effects of fluctuating temperature and light conditions, osmotic stress, salt stress, soil burial depth, and sorghum residue cover on germination and emergence of two populations of *C. bonariensis*.

Materials and Methods

Seed Collection

Fully ripened seeds of two different populations of *C. bonariensis* were collected in November 2017. Seeds of one population were collected from the fence line of a chick pea field (the C population; 30.122°S, 149.919°E) and another from a wheat field (the W population; 29.75°S, 149.81°E in Gurley, NSW, Australia). These two locations were approximately 2 km apart, and the rotation at both sites was chick pea–fallow–wheat. Mature seeds were collected from 25 to 30 plants for each population, and there was no particular sampling pattern within the fields. After collection, seeds of each population from different plants were bulked, cleaned, and stored in airtight labeled plastic containers (separate for each population) in the laboratory until the commencement of experiments (January 2018).

General Seed Germination Test Protocol

All experiments were conducted in the weed science laboratory (27.601°S, 152.343°E) of the Queensland Alliance for Agriculture and Food Innovation (QAAFI) at the University of Queensland, Gatton, QLD, Australia. Germination experiments for *C. bonariensis* were executed by evenly placing 25 seeds of each population on the surface of 9-cm-diameter Petri dishes containing a double layer of Whatman No. 1 filters paper (Whatman® International, Maidstone, UK). Distilled water or a treatment solution (5 ml) was used to moisten the filter paper. This amount of solution was sufficient to saturate the filter paper. Petri dishes were placed inside transparent plastic ziplock bags and sealed to reduce evaporation before being placed in incubators (ICCBOD-300, Laboratory Equipment, Marrickville, NSW, Australia).

Experiments determining the effect of salt and water stress were carried out in an incubator configured at 25/15 C alternating day/night temperature, with a 12-h photoperiod that coincided with the higher temperature. These conditions were optimum for germination as found in the light and temperature experiment. In the incubator, the source of light was fluorescent lamps with a light intensity of 85 mol m⁻² s⁻¹. In a preliminary experiment, no seeds germinated after 21 d of incubation; therefore, seed germination data were recorded after 21 d of incubation. Seeds were

considered germinated when the radicle was >2 mm long. Seed viability was 97% for the C population, while it was 75% for the W population. Final germination data were converted to reflect percentage of seed viability. The remaining seeds (3% and 25% for the C and W populations, respectively) were found unfilled (i.e., nonviable) in an X-ray test (Faxitron MX-20 X-ray machine, Australia). The X-ray machine is a self-contained benchtop X-ray cabinet that produces digital images.

All experiments were conducted in a randomized complete block design, and each treatment was replicated three times. Each shelf in an incubator was considered a block. Petri dishes with different treatment solutions were randomized within a block. Each experiment was repeated once, and the second run was conducted immediately after the completion of the first run. The incubators were cleaned thoroughly before starting the second run.

Temperature and Light on Germination

To evaluate the optimum temperature and photoperiod for the germination of *C. bonariensis*, seeds of both populations were placed in different incubators set at five different alternating day/night temperatures (15/5, 20/10, 25/15, 30/20, and 35/25 C) in two different photoperiods: alternating light/dark (12 h/12 h) and complete dark (24 h). The five temperature regimes were chosen to reflect the temperature during different seasons in the northern grain regions of Australia. In general, the lowest temperature ranges are experienced in winter months (June to August) in this region, and the highest temperature ranges are experienced in summer months (December to February). Autumn (March to May) and spring (September to November) months experience the mid-range temperatures. In the complete-dark treatment, Petri dishes were wrapped in three layers of aluminum foil, which were opened to check for germination after 21 d of incubation.

Salt Stress on Germination

The effect of salinity on germination of *C. bonariensis* was evaluated by incubating seeds of both populations in 0 (control), 25, 50, 100, 150, 200, and 250 mM of sodium chloride (NaCl) concentrations (Sigma-Aldrich, NSW, Australia). This wide range of salinity was selected to represent high salinity levels occurring in different areas of Australia, including Queensland (Rengasamy 2002).

Osmotic Stress on Germination

The effect of osmotic stress on germination of *C. bonariensis* was evaluated by exposing seeds of both populations to seven different water stress treatments: 0 (control), -0.1, -0.2, -0.4, -0.6, -0.8, and -1 MPa. Solutions of desired osmotic potential concentrations were prepared by mixing polyethylene glycol 8000 (Sigma-Aldrich, St Louis, MO 63103, USA) in distilled water as described in an earlier study by Michel and Radcliffe (1995).

Burial Depth on Seedling Emergence

The effect of burial depth on seedling emergence of *C. bonariensis* was studied in a screenhouse at the Gatton Research Farm of the University of Queensland, Australia. This experiment was conducted from October to December 2018. The range of average minimum and maximum temperature during the experiment was 9 to 17 and 22 to 42 C, respectively, and photoperiod ranged from 13.2 to 14.7 h. The light intensity (photosynthetic active radiation) in the screenhouse was 80% of the outdoor light intensity. Fifty

seeds of each population were planted on or in the soil within 10-cm-diameter plastic pots, which were filled with field soil. The soil texture was clay loam with a pH of 7.2 and organic matter of 2.7%. Seeds were placed on the soil surface (0 cm) or planted at depths of 1, 2, 3, and 4 cm. The soil was passed through a 2-mm sieve before use. To ensure that there was an absence of *C. bonariensis* seedbank in the soil, extra pots without *C. bonariensis* seeds were used as control measures. No *C. bonariensis* seedlings emerged in the control pots. Subirrigation was used to water all pots, and seedling emergence was counted at 4 wk after planting, and expressed as the percentage of total seeds used. This experiment was conducted in a randomized complete block design, and each treatment was replicated three times. The experiment was conducted twice, and the second run was conducted immediately after the completion of the first run.

Sorghum Residue Amount on Seedling Emergence

Sorghum ('MR-Buster') plants were placed in an oven at 70 C for 72 h. After this, leaves and stems of the oven-dried plants were chopped (2 to 3 cm) and used in the study. Fifty seeds of both the C and W populations of *C. bonariensis* were sown on the soil surface in 10-cm-diameter plastic pots. Crop residue was uniformly placed on the soil surface at amounts equivalent to 0, 1,000, 2,000, 4,000, and 6,000 kg ha⁻¹. These rates were chosen to reflect low- and high-output systems, depending on rainfall and availability of irrigation. This study was conducted in the same screenhouse as described in the seed burial experiment, and used the same type of pots and soil from the same source. Temperature and light conditions were also similar to those described for the seed burial experiment. Subirrigation was used to water all pots, and emerged seedlings were counted every week for 8 wk and expressed as the percentage of total seeds used in the experiment. This experiment was conducted in a randomized complete block design, and each treatment was replicated three times. The experiment was conducted twice, and the second run was conducted immediately after the completion of the first run.

Statistical Analyses

ANOVA was used to identify any significant treatment and interaction effects ($P \leq 0.05$). No interaction was observed between experimental runs and treatments in each experiment; therefore, the data from the two runs were pooled for ANOVA. Data variance was visually inspected by plotting residuals to confirm homogeneity of variance before analysis (GenStat, 18th ed.). Population was considered as one factor. Means were separated using Fisher's protected LSD test, except for the crop residue experiment, in which a functional three-sigmoid model was used (SigmaPlot v. 13.0). The model used for analysis was:

$$E(\%) = E_{\max} / [1 + (x/x_{50})^{E_{\text{rate}}}] \quad [1]$$

where E is the total emergence (%) at crop residue amount x , E_{\max} is the maximum emergence (%), x_{50} is time needed (in weeks) for 50% emergence, and E_{rate} indicates the slope.

Results and Discussion

Effects of Temperature and Light on Germination

A significant interaction ($P < 0.001$) between temperature regimes, light conditions, and populations was observed for the germination

Table 1. Effect of alternating day/night temperatures (15/5 to 35/25 C) and light regimes on the germination (%) of two populations (C and W) of *Conyza bonariensis*.^a

Alternating day/night temperature ^b	Germination ^c			
	C population		W population	
	Light/dark	Dark	Light/dark	Dark
—C—	%			
15/5	68.3	76.6	54.9	54.9
20/10	93.1	80.0	84.1	65.5
25/15	99.3	77.9	100.0	32.7
30/20	100.0	61.4	88.5	21.2
35/25	79.3	3.5	54.9	1.8
LSD	10.6			

^a C and W populations were collected from the fence line of a chick pea field and a wheat field, respectively, in Gurlley, NSW, Australia.

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

^c Germination (%) was adjusted to reflect seed viability (%) of each population.

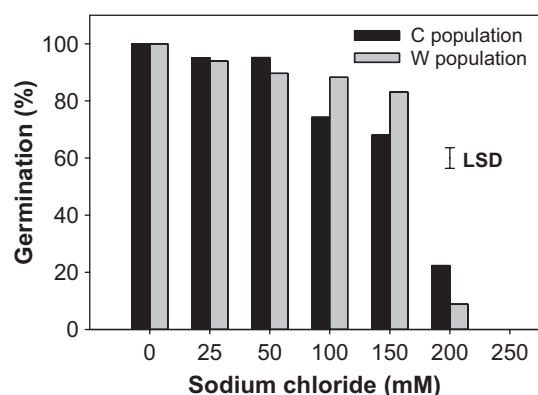


Figure 1. Effect of sodium chloride (NaCl) concentrations on the germination of C and W populations of *Conyza bonariensis* at alternating day/night temperatures of 25/15 C under a 12-h photoperiod. Germination (%) was adjusted to reflect seed viability (%) of each population. Seeds were incubated for 21 d. C and W populations were collected from the fence line of a chick pea field and a wheat field, respectively, in Gurlley, NSW, Australia.

of *C. bonariensis* (Table 1). Overall, the C population had a higher germination percentage (after the data were corrected for seed viability) than the W population across a majority of temperature and light conditions. Germination was greater in light/light than in complete darkness for both populations, except at 15/5 C day/night temperature. Under the light/dark condition at 20/10 C and 25/15 C, germination of the C population was similar to that of the W population, but not under other temperature regimes. Both populations were able to germinate over a wide range of alternating day/night temperatures (15/5 to 35/25 C); however, the C population had optimum (and similar) germination over the range of 20/10 and 30/20 C, while the W population showed the maximum germination at 25/15 C. These results suggest that the C population has the potential to become more problematic than the W population, as optimum germination for the C population occurred at a wider range of temperatures compared with the W population. Minimum germination for both populations was observed at 35/25 C under complete-dark conditions.

Germination across a wide range of temperatures means that *C. bonariensis* appears to have the potential to germinate over spring, summer, autumn, and mild winter seasons in Australia. These results are consistent with a previous study conducted in

Australia, which suggested that *C. bonariensis* can germinate at a wide range of temperatures (10 to 30 C) and fluctuating light conditions, making its management difficult throughout the year (Wu et al. 2007). In our study, the optimum temperature for seed germination was 25/15 C (average: 20 C) for both populations. Similar to our results, the previous study also reported 20 C as the optimum temperature (Wu et al. 2007). Another study reported that seeds of *C. bonariensis* germinated between 10 and 30 C, with optimal germination at 25 C (Green 2010). Overall, it is clear that both populations possess high germination potential over a broad range of temperature regimes, which may enable them to invade new regions that have more violent temperature fluctuations. Moreover, high germination percentages at the highest temperature range (35/25 C) also suggest increased spread and invasiveness of *C. bonariensis* due to increased temperature as a result of climate change.

Germination under fluctuating light and dark conditions was higher than in complete darkness. In the context of the light/dark regime, higher germination (>65% for the C population and >55% for the W population) was observed at all the tested temperatures. *Conyza bonariensis* seeds are photoblastic and thus had higher germination under conditions of light stimulation (Wu et al. 2007). Generally, seed germination would occur only on or in the upper layer of the soil surface under such requirements for light (Chauhan and Johnson 2010).

Effect of Salt Stress on Germination

A significant interaction ($P < 0.001$) was observed between population and NaCl concentration of the surrounding matrix (Figure 1). Germination was similar between the populations treated with 0 to 50 mM NaCl, but began to differ in the range from 100 to 200 mM NaCl. At 100 and 150 mM NaCl concentrations, greater germination was recorded for the W population, but at 200 mM NaCl, the C population had greater germination. These results suggest that at very high salinity levels, the C population has a greater chance to germinate and flourish compared with the W population. While both populations were able to germinate at the very high NaCl concentration of 200 mM, seed germination was completely inhibited for both populations at 250 mM NaCl.

Literature is not available on the effect of salt stress on *C. bonariensis*; however, information on the effect of salt stress on *C. canadensis*, a closely related species, is available. A study from the United States reported that germination of *C. canadensis* was more than 20% at 20 mM NaCl and that the lowest germination (4%) was recorded at 160 mM NaCl (Nandula et al. 2006). In our study, the NaCl concentration required to inhibit seed germination by 50% was more than 150 mM, suggesting that *C. bonariensis* may have higher tolerance to salt than *C. canadensis*. It has been suggested that the inhibition in germination under salt stress may be due to a physiological disturbance in metabolic processes affected by ion toxicity (Farooq et al. 2015). Indeed, for some time, soil that has a NaCl concentration of 20 mM has been considered to be problematic, or salt affected (Abrol et al. 1988). Of relevance to this study is the concern that, due to increasing salinity problems in arid areas of Australia (Rengasamy 2002), *C. bonariensis* could become increasingly problematic in these regions in the future. Results of our study strongly suggest that *C. bonariensis* has the potential to germinate under high-salinity conditions and may become an increasingly aggressive competitor to field crops under such conditions.

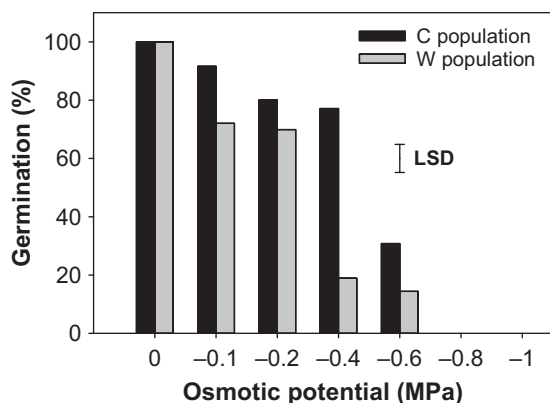


Figure 2. Effect of osmotic potential on the germination of C and W populations of *Conyza bonariensis* after 21 d of incubation at 25/15 C alternating day/night temperatures. Germination (%) was adjusted to reflect seed viability (%) of each population. C and W populations were collected from the fence line of a chick pea field and a wheat field, respectively, in Gurlay, NSW, Australia.

Effect of Osmotic Stress on Germination

The highest germination was observed in the no-stress condition (0 MPa) for both populations, and germination declined with an increase in water stress (Figure 2). In this experiment, a significant interaction ($P < 0.05$) was seen between population and osmotic potential. While germination was similar between the populations at 0 MPa osmotic potential, at -0.4 and -0.6 MPa, germination was greater for the C population compared with the W population, suggesting that W population was affected more by water stress. The concentration required to inhibit 50% germination was between -0.4 and -0.6 MPa for the C population and between -0.2 and -0.4 MPa for the W population. These results suggest that the C population has greater potential to germinate in high water stress conditions compared with the W population. No germination was observed for both populations at -0.8 and -1.0 MPa.

The results indicate that *C. bonariensis* has a significant potential to germinate at conditions with a higher level of water stress. Although relevant information on the effect of water stress on *C. bonariensis* is not available in the literature, information on *C. canadensis* is available. Germination of *C. canadensis* decreased from 25% to 2% as the applied osmotic potential concentration decreased from 0 to -0.8 MPa (Nandula et al. 2006). However, it is relevant to note that similar work related to tolerance to water stress conditions with other Asteraceae weed species has also been documented. For example, two Asteraceae weed species, Siamweed [*Chromolaena odorata* (L.) R.M. King & H. Rob.] and coatbuttons (*Tridax procumbens* L.), showed germination under -0.8 MPa and -0.6 MPa water stress conditions (Chauhan and Johnson 2008). This potential of *C. bonariensis* to germinate in medium to high water stress conditions could provide it with a competitive advantage over other species in restricted water environments and thus help to expand its invasion into more arid areas of Australia.

Effect of Seed Burial Depth on Emergence

Emergence percentage of *C. bonariensis* seedlings was significantly affected ($P < 0.01$) by seed burial depth. Germination for both populations was observed only in seeds placed on the soil surface (70% for the C population and 41% for the W population). No seedlings emerged from 1-cm or greater depths for either

population. In this study, lower germination was observed on the soil surface compared with germination recorded in Petri dishes in the light/dark environmental conditions. The possible reason for low germination on the soil surface during screenhouse trials could be poor soil–seed contact or low availability of moisture for seeds on the soil surface compared with the environment of the seeds on moist filter paper (Ghorbani et al. 1999).

Our results are similar to a previous study conducted in Queensland, in which 23% of seeds germinated on the soil surface, and emergence decreased with increased burial depth; no seedlings emerged from seeds buried at 2- and 5-cm depths (Wu et al. 2007). Similar to *C. bonariensis*, *C. canadensis* seedling emergence was maximal on the soil surface, and no seedlings emerged from seeds buried at 0.5-cm or greater depths (Nandula et al. 2006). *Conyza bonariensis* seeds are known to be photoblastic, and a possible reason for higher germination on the soil surface may be due to light-stimulated germination. With increasing soil burial depth, there is limited soil gas exchange and absence of light, which could explain the low germination under greater soil depths (Benvenuti and Macchia, 1995). These factors could also explain the similar emergence response between the two populations for buried seeds. Consequently, if the seedbank of this weed has been observed to build up on the soil surface, a shallow-tillage operation would help to bury seeds below the depth for emergence. Seeds could persist longer after burial; therefore, tillage operations that could bring those seeds back on the soil surface should be avoided.

Effect of Sorghum Residue on Seedling Emergence

Seedling emergence of *C. bonariensis* was significantly influenced ($P < 0.01$) by the amount of sorghum residue placed on the soil surface (Figure 3; Table 2). Seedling emergence of both populations decreased with the increasing rate of sorghum residue from 0 to 6,000 kg ha⁻¹, but the populations responded differently to the residue amount. The C population had higher seedling emergence compared with the W population at all the tested residue rates. In the control treatment (no crop residue cover), seedling emergence was highest for both populations (67% for the C population and 38% for the W population). At 6,000 kg ha⁻¹ sorghum residue, final seedling emergence was reduced to 30% and 16% for the C and W populations, respectively. These reductions were similar (55% to 58% reductions in seedling emergence) between the two populations. For the C population, the time needed for 50% emergence was 0.8 and 5.1 wk for the 0 and 6,000 kg ha⁻¹ residue treatments. Similarly, the W population required 0.9 wk to reach 50% emergence in the no-residue treatment, and 4.9 wk in the 6,000 kg ha⁻¹ crop residue treatment.

It is thought that the application of sorghum residue on the soil surface might have created a shading effect that decreased the emergence of *C. bonariensis* seedlings (Dyer 1995; Teasdale 1996). From our light and temperature experiment, it was evident that the complete-dark condition reduced the germination of *C. bonariensis* seeds (Table 1), and thus this study suggests that a crop residue amount of 6,000 kg ha⁻¹ (commonly found on farmers' fields), which will create a significant shadow cover in the field, may help in decreasing germination. The residue created a physical barrier that seedlings could not penetrate. It has also been suggested that low seedling emergence could also be due to allelochemicals and other toxic microbial products of sorghum

Table 2. Parameter estimates of a three-parameter sigmoid model fit to the *Conyza bonariensis* seedling emergence in Figure 3.^a

Residue amount	Parameter estimates \pm SE ^b			
	E_{\max}	E_{rate}	x_{50}	R^2
—kg ha ⁻¹ —	C population			
0	67.0 \pm 1.1	0.22 \pm 0.10	0.84 \pm 0.08	0.99
1,000	63.6 \pm 2.3	0.51 \pm 0.15	1.06 \pm 0.16	0.95
2,000	65.6 \pm 1.8	0.79 \pm 0.12	1.83 \pm 0.13	0.99
4,000	54.4 \pm 2.3	1.05 \pm 0.14	3.74 \pm 0.17	0.99
6,000	30.2 \pm 2.3	1.25 \pm 0.17	5.10 \pm 0.28	0.99
	W population			
0	37.7 \pm 1.2	0.30 \pm 0.15	0.88 \pm 0.11	0.96
1,000	34.8 \pm 1.5	1.10 \pm 0.20	2.21 \pm 0.22	0.97
2,000	35.0 \pm 1.0	1.03 \pm 0.12	2.42 \pm 0.14	0.99
4,000	29.6 \pm 0.6	0.72 \pm 0.64	3.22 \pm 0.09	0.99
6,000	16.1 \pm 0.5	0.90 \pm 0.08	4.92 \pm 0.11	0.99

^a C and W populations were collected from the fence line of a chick pea field and a wheat field, respectively, in Gurley, NSW, Australia.

^b E (%) = $E_{\max}/[1 + (x/x_{50})^{E_{\text{rate}}}]$, where E_{\max} is the maximum emergence (%), x_{50} is time needed (in weeks) to 50% emergence, and E_{rate} indicates the slope.

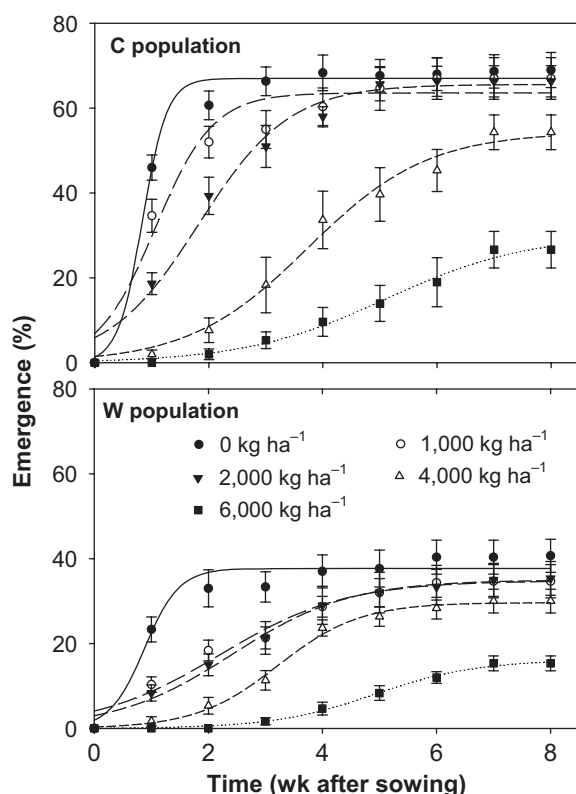


Figure 3. The effect of sorghum residue amount (kg ha⁻¹) on seedling emergence of C and W populations of *Conyza bonariensis*. Seedling emergence (%) was adjusted to reflect seed viability (%) of each population. The lines represent a three-parameter sigmoid model fit to the data. Vertical bars represent the standard error of the mean ($n = 6$). C and W populations were collected from the fence line of a chick pea field and a wheat field, respectively, in Gurley, NSW, Australia.

(Weston et al. 2013), but the effect of allelochemicals was not specifically evaluated in our study.

Depending on rainfall, sorghum residue amount may vary in the field in New South Wales and Queensland. In addition, the position and uniformity of sorghum residue could also affect the degree of *C. bonariensis* suppression. In the present study, loose

and chopped sorghum residue was spread evenly in pots. In the field, crop residue may be intact. It is important to note that the highest crop residue amount (6,000 kg ha⁻¹) did not provide complete suppression of *C. bonariensis*, suggesting that there is a need for IWM practices in which residue cover is employed in tandem with other control options (e.g., herbicide use) for effective management. Overall, our study suggests that crop residue retention or mulch as a component of conservation-tillage practices could help farmers in decreasing infestations of *C. bonariensis*.

In summary, *C. bonariensis* seeds can germinate over a wide range of temperature regimes, implying that the weed maintains its potential to spread throughout the year in the warm climates of New South Wales and Queensland. Seed germination was stimulated by light and seeds also demonstrated significant potential to germinate at high levels of osmotic stress. It is also clear that *C. bonariensis* tolerates a wide range of NaCl concentrations, thus it may be able to spread and adapt to saline soils in the future. Germination was recorded to be higher from the soil surface, and it was found that seedlings did not emerge from a burial depth of 1 cm or below.

These findings support the theory of this weed species' survival being favored in no-till agriculture systems. In no-till systems, the weed seedbank builds up on the soil surface, but this seed profile could be reduced by using a strategic tillage operation. The use of strategic tillage would bury most weed seeds below their maximum depth of emergence, reducing the common occurrence of seedbank build-up at the soil surface in no-till systems. Alternatively, the retention of crop residue on the soil surface in conservation agriculture systems could provide management of *C. bonariensis*.

Although there were some differences in germination and emergence between the two populations, inferences from the results of this study should be carefully related to populations, as the study had a single representative of each population type. Also, this study was conducted in the laboratory and greenhouse, where conditions are different from the field. Therefore, there is a need to conduct field trials to confirm results obtained in the controlled-environment trials.

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