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Germination biology of liverseedgrass (*Urochloa panicoides*) and its response to postemergence herbicides in Australian conditions

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Research Article

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Abstract

Liverseedgrass (*Urochloa panicoides* P. Beauv.) is one of the most important summer grass weed species in the eastern cropping system of Australia. Experiments were conducted to evaluate the effects of temperature, salt stress, water stress, burial depth, and sorghum crop residue load on germination and emergence of *U. panicoides* and the performance of postemergence herbicides on this weed species. The optimal germination temperature regimes for *U. panicoides* were 30/20 and 35/25 C (alternating day/night temperatures), but seeds also germinated at temperatures occurring in winter, spring, and autumn in Australia (15/5, 20/10, and 25/15 C). A concentration of 48 mM sodium chloride and −0.27 MPa osmotic potential inhibited germination of *U. panicoides* by 50%, indicating that this weed species is not salt and drought tolerant at germination. The maximum germination was obtained for the surface seeds; a burial depth of 1.9 cm inhibited emergence by 50%. No seedlings emerged from the 12-cm depth, but about 3% of seedlings emerged from the 8 cm depth. The addition of sorghum residue amounts up to 8,000 kg ha^{-1} to the soil surface stimulated *U. panicoides*' emergence compared with the no-residue treatment, suggesting that conservation agriculture will promote the emergence of *U. panicoides*. Several postemergence herbicides were found to be effective in controlling this weed species, especially when applied at an early stage. Information obtained from this study will help to develop effective and sustainable control measures for *U. panicoides* and other weed species with similar germination requirements.

Introduction

Weeds are an important biological constraint in Australian cropping systems. In the eastern region of Australia, summer weeds are of serious concern in different crops as well as chemical fallows. Liverseedgrass (*Urochloa panicoides* P. Beauv.) is among the most important summer weeds in this region. It is an annual grass, native to Asia and Africa, with a C_4 photosynthetic pathway (Hatch et al. 1988). Although *U. panicoides* is distributed throughout Australia, it is a problematic weed in grain-cropping systems, mainly in the eastern region (Adkins et al. 1998; AVH 2022). A summer fallow is very common in eastern Australia, and weeds, including *U. panicoides*, deplete soil moisture and nutrients from fallow fields (Adkins et al. 1998; Thomas et al. 1997; Webb et al. 1997). A field study conducted in this region reported that about 25 plants m^{-2} of *U. panicoides* caused a 50% yield reduction in mung bean [*Vigna radiata* (L.) R. Wilczek] (Gill et al. 2021). *Urochloa panicoides* is also a problematic weed in sorghum [*Sorghum bicolor* (L.) Moench] and cotton (*Gossypium hirsutum* L.) (Malan 2018; Manalil et al. 2017; Ustarroz et al. 2016; Walker et al. 2005). In a recent survey conducted in the cotton-growing regions of Australia, *U. panicoides* was found to infest about 6% of the surveyed fields, suggesting poor control of this weed in glyphosate-tolerant cotton crops (Manalil et al. 2017). The first glyphosate-resistant population of *U. panicoides* was reported in 2008 from the eastern grain region of Australia (Heap 2022), and there is a possibility that several populations of this weed have evolved resistance to glyphosate. Argentina is the only other country where *U. panicoides* has evolved resistance to glyphosate (Heap 2022). In Argentina, it is also a weed of soybean [*Glycine max* (L.) Merr.] and corn (*Zea mays* L.) (Ustarroz et al. 2016).

Urochloa panicoides is a prolific seed producer. In a recent study, this weed produced about 40,000 seeds m^{-2} at a density of 40 plants m^{-2} in competition with a mung bean crop (Gill et al. 2021). These observations suggest the potential seed production of *U. panicoides* is much higher in fallow situations in the absence of crop competition. Its seeds can remain viable for 2 yr in no-till farming systems and 3.5 yr in tilled farming systems (Chauhan and Manalil 2022). In some situations, *U. panicoides* is used as grazing pasture, but this weed has been reported to kill cattle because of nitrate poisoning (Hill and Blaney 1980). In well-fertilized pastures, this weed is more likely to accumulate toxic amounts of nitrate (Hill and Blaney 1980). The abovementioned studies suggest that *U. panicoides* is a serious weed in field crops, pastures, and fallows.

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Development and implementation of sustainable and effective weed management programs could help manage problematic weeds, including *U. panicoides*. However, to develop such programs, there is a need to better understand the biology of this weed. Knowledge of seed biology is the most important step to develop any weed control program (Chauhan and Johnson 2010). Seed germination is influenced by several factors, including temperature, soil salinity, soil moisture, and seed burial depth in the soil. Understanding the influence of environmental factors on seed germination could help predict a species' germination and invasiveness beyond its current boundaries (Guo and Al-Khatib 2003; Ustarroz et al. 2016). However, such information is not available on *U. panicoides* in Australian conditions. A previous study in Argentina evaluated the effect of constant temperatures of 9, 15, 25, and 34 C on seed germination of *U. panicoides* (Ustarroz et al. 2016). The authors reported the maximum germination at 34 C. Information on the influence of constant temperatures on germination could help in evaluating the base temperature for germination of a species; however, such conditions are rarely experienced in nature (Baskin et al. 2006). Therefore, there is a need to evaluate the effect of alternating day/night temperatures on seed germination of *U. panicoides*. A literature search revealed no information on the effect of salt and water stress, seed burial depth, and crop residue amount on the germination and emergence of *U. panicoides*. Salinity and drought conditions are common in Australian cropping systems (Mahajan et al. 2019; Rengasamy 2010), and the germination response of this weed to these abiotic stresses could provide insights into *U. panicoides*' invasiveness in new areas. Seed burial depth can also affect the germination and emergence of *U. panicoides* by influencing the microclimate surrounding the seeds (Chauhan and Johnson 2010). Similarly, the use of crop residue as mulch can affect the germination and emergence of a weed species. Knowledge generated from such studies could be used for the effective management of *U. panicoides* in no-till or reduced-tillage systems.

As *U. panicoides* is a prolific seed producer, its emergence is expected throughout the spring, summer, and autumn in Australia. Knowledge of the performance of different postemergence herbicides on this weed will strengthen the development of integrated weed management programs. Herbicide efficacy can also be affected by growth stage. In some situations (e.g., under environmental constraints), growers may not be able to spray at a young seedling stage (Chauhan et al. 2021). Therefore, there is a need to evaluate the performance of postemergence herbicides at different stages of *U. panicoides*. This study was conducted to determine the effects of alternating day/night temperatures, salt stress, water stress, seed burial depth, and crop residue amount on germination and emergence of *U. panicoides* and to evaluate the response of this weed at different stages to a range of postemergence herbicides in Australia.

Material and Methods

Seed Collection

Seeds of *U. panicoides* were collected in May 2019 from a sorghum field (26.845°S, 150.581°E) near Chinchilla, QLD, Australia. Seeds were collected in a tray by shaking at least 100 mature plants spread across an area of more than 5 ha. Seeds were brought to the weed science lab at the Queensland Alliance for Agriculture and Food Innovation, the University of Queensland, Gatton, QLD, Australia, cleaned, and stored in a plastic container at room temperature (25 ± 2 C). Seeds were highly dormant immediately after seed collection, as determined by using the procedure described in the "General Germination Protocol" section. In April 2021, seed germination reached >90% (data not shown), and experiments commenced in October 2021.

General Germination Protocol

The effect of different environmental factors on seed germination of *U. panicoides* was evaluated in the lab by placing 25 seeds in a 9-cm-diameter petri dish. A double layer of filter paper (Whatman No. 1, Maidstone, UK) was placed in each petri dish, and 5 ml of water or a treatment solution was added. In preliminary germination tests, seeds were found to be infested with a fungus; therefore, thiram fungicide at 2% was used in petri dishes. No fungus was observed after this treatment. Petri dishes were placed in sealed plastic bags, and the bags were placed in an incubator set at alternating day (12-h)/night (12-h) temperatures of 35/25 C, unless otherwise noted. Light in the incubator was provided with fluorescent lamps that had an intensity of 85 mol m^{-2} s^{-1}. Sealed plastic bags ensured that there was no water loss due to evaporation. Seed germination was determined at 28 d after the start of the experiment, as there was no further germination after this period in the temperature experiment (Experiment 1). Seeds were considered germinated when radicles of at least 1 mm were visible. There were three replications of each treatment, and each experiment was conducted twice. The second run commenced within a month after the completion of the first run.

Experiment 1. Alternating Day/Night Temperatures

To determine the effect of alternating day/night temperatures on germination of *U. panicoides*, petri dishes containing seeds and a water solution were placed in different incubators set at five different temperature regimes (15/5, 20/10, 25/15, 30/20, and 35/25 C). A 12-h photoperiod (using fluorescent lamps) was maintained during the higher-temperature cycle, and 12-h dark conditions were maintained during the lower-temperature cycle. The light intensity was similar in all incubators. These five temperature regimes were chosen to represent the temperature conditions occurring throughout the year in the eastern cropping region of Australia.

Experiment 2. Sodium Chloride (NaCl) Concentration

To determine the effect of NaCl concentrations on germination of *U. panicoides*, petri dishes containing seeds and different salt concentrations were placed in an incubator set at 35/25 C. Concentrations of 0 (control), 20, 40, 80, 160, and 320 mM NaCl were used in the experiment, as these salinity levels occur in different regions of Australia (Rengasamy 2002).

Experiment 3. Osmotic Potential

To determine the effect of water stress on germination of *U. panicoides*, petri dishes containing seeds and different osmotic potential solutions were placed in the incubator set at 35/25 C. Solutions of 0 (control), −0.1, −0.2, −0.4, −0.8, and −1.6 MPa osmotic potentials were used in the experiment. Solutions were prepared by dissolving polyethylene glycol 8000 (Sigma-Aldrich, St Louis, MO, USA) in distilled water following the procedure of Michel and Radcliffe (1995).

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Experiment 4. Seed Burial Depth

To determine the effect of seed burial depths on emergence of *U. panicoides*, seeds were placed on the soil surface (0 cm), or buried at depths of 0.5, 1, 2, 4, 8, and 12 cm in plastic pots (14-cm diameter and 20-cm height). These soil depths were chosen to represent different tillage systems (e.g., no-till or reduced-till systems) or seed burial due to planting operations. The soil used in the experiment was a clay loam, which was sieved through a 2-mm sieve before being added to pots. Three extra pots without *U. panicoides* seeds were also used to ensure there was no background seedbank of this weed in the soil. No *U. panicoides* seedlings emerged in these extra pots. Pots were placed in trays without holes, and water was added to the trays to subirrigate pots. These trays containing pots were placed on benches in a screen house at the Gatton Farms of the University of Queensland. The screen house had a light intensity of approximately 80% of the outdoor light intensity, and the average maximum and minimum temperatures during the duration of the experiment were 35.8 and 18.1 C, respectively. Seedling emergence, with a criterion of visible coleoptiles on the soil surface, was counted at 4 wk after planting, and there was no further emergence after this period.

Experiment 5. Sorghum Residue Amount

To determine the effect of sorghum residue amounts on emergence of *U. panicoides*, seeds were placed on the soil surface in 14-cm-diameter pots and covered with sorghum residue (leaves and stems of 'Elite Sentinel IG') at rates equivalent to 0, 1,000, 2,000, 4,000, and 8,000 kg ha^{-1}. The residue thickness corresponding to these residue amounts was 0, 0.13, 0.25, 0.5, and 1.0 cm, respectively. Before being placed in pots, the residue was dried in an oven at 70 C for 72 h and chopped into small pieces (~2 cm). Soil, water, and temperature conditions in this experiment were as described previously for the seed burial depth experiment. Seedling emergence was counted at 4 wk after planting, and there was no further emergence after this period.

Experiment 6. Performance of Postemergence Herbicides

To determine the performance of postemergence herbicides on *U. panicoides*, 10 seeds were planted at 1-cm depth in 14-cm-diameter pots filled with a commercial potting mix (Platinum® potting mix, Centenary Landscaping, Brisbane, QLD, Australia). Immediately after emergence, plants were thinned to maintain 4 plants pot^{-1}. These plants were kept on benches in the screen house and regularly irrigated using an automated sprinkler system. Plants were sprayed with different herbicides (Table 1) at two growth stages: 6-leaf (small) and 18- to 20-leaf stages. Plant height at these two growth stages was 12 to15 cm and 22 to 25 cm, respectively. A research track sprayer was used to spray herbicides at a water volume of 108 L ha^{-1}. TeeJet® XR110015 (Sprayshop, Toowoomba, QLD, Australia) flat-fan nozzles were used in the sprayer. At 28 d after treatment, plant survival and biomass data were recorded. Plants were considered to survive if they had at least one new leaf. Surviving plants were harvested at the soil surface, placed in paper bags, and dried in an oven at 70 C for 72 h. Biomass was measured, and results were expressed as percent control.

Statistical Analysis

All experiments were conducted in a randomized complete block design. In the lab experiments, blocking was done by placing petri dishes of the same replicate on a single shelf within an incubator, whereas in the screen house experiments, pots of the same replicate were grouped. The postemergence herbicide trial was conducted in a factorial (leaf stage and herbicide treatment) randomized block design. All experiments were repeated over time, and there were three replicates for each run. Data were combined over the two runs, as there was no interaction between the runs and treatments, and the run was not significant (Genstat 2021). Data were validated to meet the assumption of normality and variance before analysis. Transformation did not improve the homogeneity of variance; therefore, original values were subjected to ANOVA.

Data from the temperature, sorghum residue, and herbicide trials were subjected to ANOVA, and multiple comparisons were done using Fisher's protected LSD test at a 5% level of significance. Nonlinear regression was used for the analysis of the salt, osmotic potential, and burial depth trials. The selected models were chosen because of biologically relevant interpretations of coefficients in the models. Germination data obtained in response to NaCl concentrations were modeled using a three-parameter log-logistic model:

$$G = a/\left[1 + (x/x_{50})^b\right] \quad [1]$$

In this model, G is germination percentage at NaCl concentration x, a is the maximum germination (%), x_{50} is the NaCl concentration required to inhibit germination by 50%, and b is the slope. A three-parameter sigmoid model was fit to germination data obtained in response to different osmotic potentials:

$$G = a/\left\{1 + \exp\left[-(x - x_{50})^b\right]\right\} \quad [2]$$

In this model, G is germination percentage at osmotic potential x, a is the maximum germination (%), x_{50} is the osmotic potential required for 50% inhibition of maximum germination, and b is the slope. Emergence data obtained in response to burial depths were modeled using an exponential decay model:

$$E = a \times e^{-bx} \quad [3]$$

In this model, E is emergence percentage at depth x, a is the maximum emergence, and b is the slope.

Results and Discussion

Experiment 1. Alternating Day/Night Temperatures

Germination of *U. panicoides* was affected by alternating day/night temperature regimes (Figure 1). The maximum germination (97%) was obtained at 35/25 C; however, the germination value was similar to that obtained at 30/20 C. Germination decreased with a further decline in temperatures. About 30% of seeds germinated at 20/10 C, and some germination (4%) also occurred at 15/5 C.

The optimal germination temperature regimes (30/20 and 35/25 C) for *U. panicoides* in Australian conditions are similar to those reported (35 C) for this weed in Argentina; however, the previous study used only constant temperatures (Ustarroz et al. 2016). In tropical signal grass [*Urochloa subquadripara* (Trin.) R. D. Webster], germination was highest at 25 C and was reduced at temperatures above 25 C (Teuton et al. 2004). Germination responses of *U. panicoides* are similar to those of some other summer grass weed species (e.g., feather fingergrass [*Chloris virgata* Sw.] and windmillgrass [*Chloris truncata* R. Br.]), for which seeds germinated at temperatures ranging from 15/5 to 35/25 C (Chauhan et al. 2018; Desai and Chauhan 2021). In

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Table 1. Herbicides, their trade names, sites of action, and doses, and adjuvants used in Experiment 6.

Herbicide treatment	Trade names	Manufacturer	Sites of action[a]	Dose	Adjuvant
				g ae/ai ha^{-1}	
Control	—	–	—	—	—
Clethodim	Havoc®	Nufarm Australia Ltd, Laverton, VIC, www.nufarm.com.au	ACCase inhibitor	60	0.5% Cando™
Clethodim	Havoc®	Nufarm Australia Ltd, Laverton, VIC, www.nufarm.com.au	ACCase inhibitor	120	0.5% Cando™
Clodinafop	Topik®	Syngenta Australia Pty Ltd, Macquarie Park, NSW, www.syngenta.com.au	ACCase inhibitor	15.5	0.5% Hasten™
Clodinafop	Topik®	Syngenta Australia Pty Ltd, Macquarie Park, NSW, www.syngenta.com.au	ACCase inhibitor	31	0.5% Hasten™
Cyhalofop	Barnstorm®	Corteva Agriscience Australia Pty Ltd, Chatswood, NSW, www.corteva.com.au	ACCase inhibitor	214	1% Uptake®
Cyhalofop	Barnstorm®	Corteva Agriscience Australia Pty Ltd, Chatswood, NSW, www.corteva.com.au	ACCase inhibitor	428	1% Uptake®
Glufosinate	Biffo®	Nufarm Australia Ltd, Laverton North, VIC, www.nufarm.com.au	Glutamine synthetase inhibitor	750	—
Glufosinate	Biffo®	Nufarm Australia Ltd, Laverton North, VIC, www.nufarm.com.au	Glutamine synthetase inhibitor	1,500	—
Glyphosate	Roundup Ultra® MAX	Bayer Cropscience Pty Ltd, Hawthorn East, VIC, www.crop.bayer.com.au	EPSP inhibitor	370	—
Glyphosate	Roundup Ultra® MAX	Bayer Cropscience Pty Ltd, Hawthorn East, VIC, www.crop.bayer.com.au	EPSP inhibitor	740	—
Haloxyfop	Verdict™	Corteva Agriscience Australia Pty Ltd, Chatswood, NSW, www.corteva.com.au	ACCase inhibitor	52	1% Hasten™
Haloxyfop	Verdict™	Corteva Agriscience Australia Pty Ltd, Chatswood, NSW, www.corteva.com.au	ACCase inhibitor	104	1% Hasten™
Imazamox + imazapyr[b]	Intervix®	BASF Australia Ltd, Southbank, VIC, www.crop-solutions.basf.com.au	ALS inhibitor	36 (24.75 + 11.25)	1% Hasten™
Imazamox + imazapyr[b]	Intervix®	BASF Australia Ltd, Southbank, VIC, www.crop-solutions.basf.com.au	ALS inhibitor	72 (49.5 + 22.5)	1% Hasten™
Imazapic	Impose®	Adama Australia Pty Ltd, St Leonards, NSW, www.adama.com	ALS inhibitor	72	1% Hasten™
Imazapic	Impose®	Adama Australia Pty Ltd, St Leonards, NSW, www.adama.com	ALS inhibitor	144	1% Hasten™
Paraquat	Gramoxone®	Syngenta Australia Pty Ltd, Macquarie Park, NSW, www.syngenta.com.au	Photosystem I inhibitor	300	1% Hasten™
Paraquat	Gramoxone®	Syngenta Australia Pty Ltd, Macquarie Park, NSW, www.syngenta.com.au	Photosystem I inhibitor	600	1% Hasten™
Pinoxaden	Axial®	Syngenta Australia Pty Ltd, Macquarie Park, NSW, www.syngenta.com.au	ACCase inhibitor	15	0.5% Cando™
Pinoxaden	Axial®	Syngenta Australia Pty Ltd, Macquarie Park, NSW, www.syngenta.com.au	ACCase inhibitor	30	0.5% Cando™

[a]Abbreviations: ACCase, acetyl-coenzyme-A carboxylase; ALS, acetolactate synthase; EPSP, 5-enolpyruvylshikimate-3-phosphate.
[b]A commercial mixture.

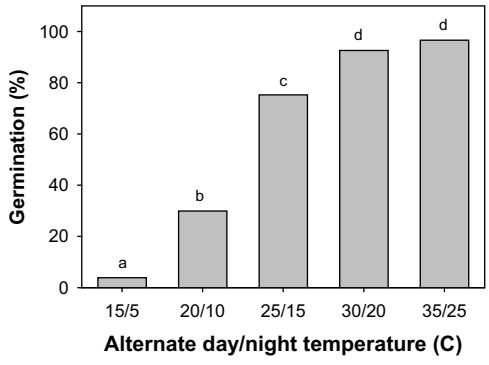

Figure 1. Effect of alternating day/night temperatures on seed germination of *Urochloa panicoides*. Bars with different letters are significant at the 5% level of significance.

junglerice [*Echinochloa colona* (L.) Link], another problematic summer grass species in eastern Australia, seeds germinated at temperature regimes ranging from 20/10 to 35/25 C but did not germinate at 15/5 C (Mutti et al. 2019). These results suggest that *U. panicoides* has a greater ability to germinate in winter months than *E. colona*. The results of the current study suggest that although the maximum germination of *U. panicoides* is expected in the spring and summer months in eastern Australia, this species has the ability to germinate throughout the year in this region. Recently, seasonal expansion has been observed in *C. virgata* in the eastern cropping system of Australia (P McIntosh, personal communication). Results suggest that growers must extend weed control in winter crops as well as winter fallows to avoid moisture and yield losses.

Experiment 2. NaCl Concentration

Maximum germination (96%) of *U. panicoides* was obtained in the control (no salt stress), and germination declined with increasing NaCl concentration (Figure 2). Seeds did not germinate at 160 and 320 mM NaCl, but about 25% of seeds germinated at 80 mM NaCl. The model predicted a concentration of 48 mM NaCl would inhibit germination by 50%.

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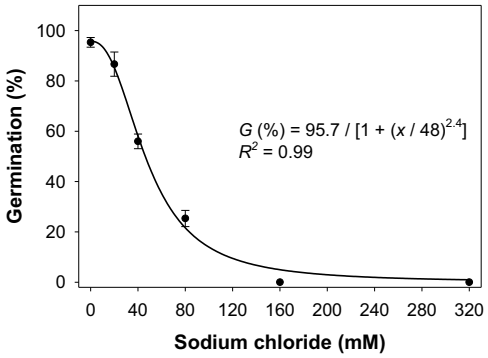

Figure 2. The effect of sodium chloride concentrations on seed germination of *Urochloa panicoides*. Germination data were modeled using a three-parameter log-logistic model {$G = a/[1 + (x/x_{50})^b]$}, in which G is germination percentage at different NaCl concentrations, a is the maximum germination (%), x_{50} is the NaCl concentration required to inhibit germination by 50%, and b is the slope.

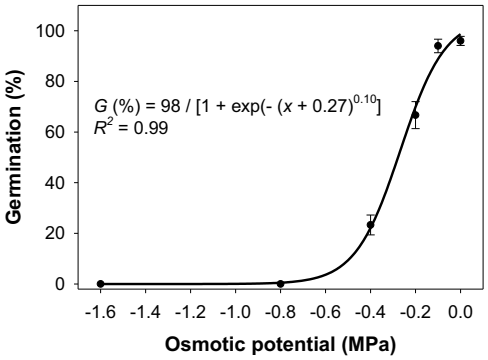

Figure 3. The effect of osmotic potential on seed germination of *Urochloa panicoides*. Germination data were modeled using a three-parameter sigmoid model {$G = a/\{1 + \exp[-(x - x_{50})^b]\}$}, in which G is germination percentage at different osmotic potentials, a is the maximum germination (%), x_{50} is the osmotic potential required for 50% inhibition of maximum germination, and b is the slope.

Information is not available on *U. panicoides* to compare with the results of the current study. Studies on other summer weeds, such as *C. truncata* and *E. colona*, suggest that *U. panicoides* is less tolerant to salt stress. In *E. colona*, for example, germination was inhibited by 50% at about 200 mM NaCl solution (Mutti et al. 2019). Similarly, a solution of about 180 mM NaCl inhibited germination of *C. truncata* by 50% in the eastern region of Australia (Chauhan et al. 2018). In a *C. truncata* population from South Australia, however, about 70 mM NaCl inhibited germination by 50%, suggesting that populations from different regions may differ in their tolerance to salinity (Ngo et al. 2017). These observations suggest that it would be important to evaluate *U. panicoides* populations from across these regions in future studies. Soils with an NaCl concentration of 20 mM are considered as salt affected, and in Queensland alone, an area of more than 100,000 ha is saline (Trewin 2002), and the current study indicates that *U. panicoides* has the ability to colonize these areas. In such situations, in addition to salinity, *U. panicoides* may further impact crop production.

Experiment 3. Osmotic Potential

Germination of *U. panicoides* was highest (96%) in the control treatment (no stress) and germination declined with a decrease in osmotic potential (Figure 3). Seeds did not germinate at −0.8 and −1.6 MPa; however, about 23% of seeds germinated at −0.4 MPa. The model predicted that an osmotic potential of −0.27 MPa inhibited germination of *U. panicoides* by 50%.

Comparable studies are not available for *U. panicoides*; however, a study on *U. subquadripara* reported 5% or lower germination at −0.4 to −1.0 MPa (Teuton et al. 2004). Seeds of goosegrass [*Eleusine indica* (L.) Gaertn.] responded similarly to *U. panicoides* in a previous study conducted in Malaysia (Ismail et al. 2002). Germination of two populations of *E. indica* was completely inhibited by osmotic stress imposed by an osmotic potential of −0.8 MPa. The results of the current study are similar to a study conducted on crowfootgrass [*Dactyloctenium aegyptium* (L.) Willd.] in the United States (Burke et al. 2003). Seeds of *D. aegyptium* did not germinate at water potentials of −0.8 and −1.2 MPa. *Chloris truncata*, another summer grass species, responded similarly to osmotic potentials (Ngo et al. 2017). In that study, germination of *C. truncata* was inhibited by 50% at −0.27 MPa and completely at −0.8 MPa. In another summer grass species (*E. colona*) in eastern Australia, seeds did not germinate at −1.0 MPa. Observations also indicate that *U. panicoides* is not drought tolerant at germination, and seeds will only germinate when there is sufficient soil moisture. As reported for *U. subquadripara*, *U. panicoides* will not germinate in times of drought but will germinate after irrigation or significant rainfall events.

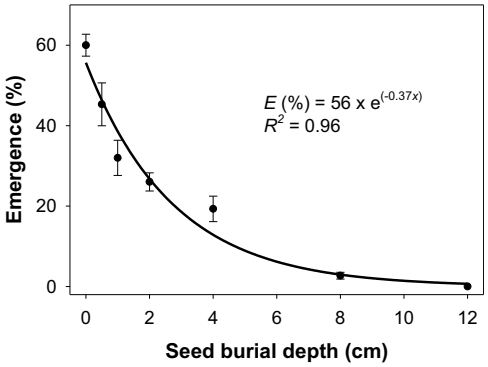

Figure 4. The effect of seed burial depth on seedling emergence of *Urochloa panicoides*. Germination data were modeled using an exponential decay model ($E = a \times e^{-bx}$), in which E is emergence percentage at different depths, a is the maximum emergence, and b is the slope.

Experiment 4. Seed Burial Depth

Seed burial depth greatly affected the seedling emergence of *U. panicoides*. Germination was maximum (56%) for the seeds placed on the soil surface, and seedling emergence declined exponentially with increased seed burial depth (Figure 4). No seedlings emerged from a burial depth of 12 cm, but some seedlings (3%) emerged from a depth of 8 cm. The model predicted that a burial depth of 1.9 cm inhibited emergence of *U. panicoides* by 50%.

Comparative studies are not available for *U. panicoides*; however, a study on a related species, *U. subquadripara*, also observed the highest germination from seeds placed on the soil surface (Teuton et al. 2004). Seedlings of *U. subquadripara* emerged from burial depths up to 7 cm but did not emerge from depths of 8 cm or greater. Similarly, seedling emergence of *D. aegyptium* was observed from burial depths of 0 to 6 cm (Burke et al. 2003). In eastern Australia, seedling emergence of *E. colona* was greatest on the soil surface, and no seedlings emerged from the 8-cm depth (Mutti et al. 2019). Some seedlings of *U. panicoides* emerged from a

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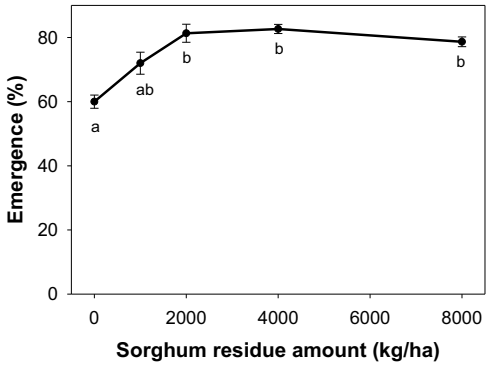

Figure 5. The effect of sorghum residue load on seedling emergence of *Urochloa panicoides*. Means with different letters are significant at the 5% level of significance.

depth of 8 cm in the current study, which could be due to the larger seed size of *U. panicoides* compared with *E. colona*. In both studies, germination on the soil surface was less than in the petri dish experiment. As suggested in the Mutti et al. (2019) study, the soil condition, soil–seed contact, and temperature fluctuations in the screen house might have affected germination on the soil surface. Similar to the current study, the maximum germination of *E. indica* was observed for the surface seeds, about 10% of seedlings emerged from a depth of 7 cm, and no seedlings emerged from a depth of 10 cm (Ismail et al. 2002).

Decreased seedling emergence in response to increasing burial depth is common in weed species, which could be due to small seed size, limited seed reserves, limited soil-gas diffusion, and soil compaction (Benvenuti and Macchia 1995, 1998; Teuton et al. 2004). The high germination of surface seeds indicates that conservation agriculture systems may promote greater emergence of *U. panicoides*, as these systems retain most seeds on the soil surface after crop planting. In the hot summer months, surface seeds are likely to desiccate faster after a rainfall event than seeds buried at shallow depths, for example, at 1 or 2 cm (Ngo et al. 2017). These speculations are supported by a recent study in which surface seeds of *U. panicoides* depleted within 24 mo, whereas it took 42 mo to completely exhaust the seedbank when seeds were buried at 2 or 10 cm (Chauhan and Manalil 2022). In cases in which the seedbank of *U. panicoides* is concentrated on the soil surface, growers may consider a deep-tillage operation to bury seeds below the maximum depth of emergence (Chauhan and Johnson 2010; Mutti et al. 2019; Teuton et al. 2004). However, future tillage operations should be avoided, as they can bring the buried seeds on or close to the soil surface.

Experiment 5. Sorghum Residue Amount

Seedling emergence of *U. panicoides* was affected by the addition of sorghum residue on the soil surface. Without crop residue, *U. panicoides* emergence was 60%, and the addition of sorghum residue stimulated its emergence (Figure 5). Seedling emergence was similar between the 0 and 1,000 kg ha^{-1} treatments, but further addition of crop residue resulted in greater emergence of *U. panicoides* compared with the no-residue treatment. Seedling emergence was similar at 1,000 to 8,000 kg ha^{-1} residue amounts.

Comparative studies are not available for *U. panicoides*, but similar information is available for other summer weed species in the eastern region of Australia. In *E. colona*, for example, emergence was about 70% without sorghum crop residue and decreased with increasing residue amounts up to 8,000 kg ha^{-1} (Mutti et al. 2019). Similar results were reported for sweet summergrass [*Brachiaria eruciformis* (Sm.) Griseb.] (Mobli et al. 2020) and *C. truncata* (Chauhan et al. 2018). The results of the current study are different from those reported in the previous studies, as the emergence of *U. panicoides* did not decrease with the addition of sorghum residue up to 8,000 kg ha^{-1}. The thickness of the 8,000 kg ha^{-1} residue amount was 1 cm. A burial depth of 1 cm reduced *U. panicoides* emergence by 30% (Figure 4), suggesting that a sorghum residue amount of 8,000 kg ha^{-1} (i.e., 1-cm depth of mulch) may not be able to provide a sufficient physical barrier to impede *U. panicoides* seedling emergence. Increased emergence after the addition of a high amount sorghum residue could be due to high moisture conservation that supported increased germination and emergence. These results suggest that no-till farming systems that retain high residue cover on the soil surface could promote greater emergence of *U. panicoides*. Although sorghum is known to have an allelopathic effect on weed seed germination (Weston et al. 2013), such effects were not observed in the current study.

Table 2. The interaction effect of growth stage (small: 6-leaf and 12–5 cm in height; and large: 18- to 20-leaf and 22–25 cm in height) and herbicide on the survival and aboveground biomass of *Urochloa panicoides*.

	Survival		Biomass	
	Growth stage[a]			
Herbicide treatment	Small	Large	Small	Large
	%		g pot^{-1}	
Control	100 a	100 a	12.13 a	12.16 a
Clethodim 60	0 e	0 e	0 e	0 e
Clethodim 120	0 e	0 e	0 e	0 e
Clodinafop 15.5	0 e	33.3 c	0 e	2.02 d
Clodinafop 31	0 e	0 e	0 e	0 e
Cyhalofop 214	0 e	0 e	0 e	0 e
Cyhalofop 428	0 e	0 e	0 e	0 e
Glufosinate 750	0 e	25.0 cd	0 e	0.52 e
Glufosinate 1500	0 e	0 e	0 e	0 e
Glyphosate 370	100 a	100 a	4.99 c	6.50 b
Glyphosate 740	70.8 b	87.5 a	1.26d e	5.10 c
Haloxyfop 52	0 e	0 e	0 e	0 e
Haloxyfop 104	0 e	0 e	0 e	0 e
Imazamox + imazapyr 36	4.2 e	16.7 d	0.04 e	0.60 e
Imazamox + imazapyr 72	0 e	0 e	0 e	0 e
Imazapic 72	0 e	0 e	0 e	0 e
Imazapic 144	0 e	0 e	0 e	0 e
Paraquat 300	8.3 e	37.5 c	0.32 e	1.81 d
Paraquat 600	0 e	12.5 de	0 e	0.55 e
Pinoxaden 15	0 e	25.0 cd	0 e	1.90 d
Pinoxaden 30	0 e	8.3 e	0 e	0.23 e

[a]Means (survival or biomass) within a column or a row with the same letters are similar at the 5% level of significance.

Experiment 6. Performance of Postemergence Herbicides

Seedling survival and biomass of *U. panicoides* were affected by the interaction between growth stages and herbicide treatments (Table 2). Irrespective of growth stages and herbicide rates, *U. panicoides* plants did not survive the application of clethodim, cyhalofop, haloxyfop, and imazapic. Clodinafop, glufosinate, and pinoxaden at low rates resulted in 100% mortality when applied at the 6-leaf stage, but these herbicide treatments resulted in at least 25% survival of *U. panicoides* seedlings when applied at the 18- to 20-leaf stage. The surviving seedlings, however, produced only 4% to 17% of the biomass produced by the nontreated control plants. The recommended doses of clodinafop and glufosinate did not

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provide complete mortality of the large plants. Paraquat at both rates provided 100% mortality when applied on small plants, but about 13% of seedlings survived when paraquat was applied at the high rate on large plants. The dose of the commercial mixture of imazamox and imazapyr had to increase above the field rate to achieve 100% mortality of *U. panicoides* at both growth stages. Glyphosate, regardless of growth stages and herbicide rates, was not effective on *U. panicoides*. The glyphosate-resistance status of the population used in this study is not known; however, glyphosate-resistant *U. panicoides* has been reported in the eastern region of Australia (Heap 2022). These observations suggest evaluating the glyphosate-resistance status in the current population by comparing it with other populations.

The present study identified clethodim, cyhalofop, haloxyfop, and imazapic as the most effective herbicide treatments to control *U. panicoides* at 6-leaf and 18- to 20-leaf stages. Clethodim and haloxyfop have also been found to be very effective in controlling large *C. virgata* plants in southeastern Australian conditions (Chauhan et al. 2021). In *E. colona*, however, clethodim at 60 and 90 g ai ha^{-1} and haloxyfop at 52 and 78 g ai ha^{-1} provided poor control when applied at the 8-leaf stage rather than at the 4-leaf stage (Ndirangu Wangari et al. 2022). These four herbicides are acetyl-coenzyme A carboxylase (ACCase) or acetolactate synthase (ALS) inhibitors, which are highly prone to causing resistance. Therefore, farmers should rotate these herbicides with other herbicide sites of action. In Australia, cyhalofop is registered for use in rice (*Oryza sativa* L.) only, and *U. panicoides* is not listed on the label of imazapic products. The current study suggests that cyhalofop can provide effective control of *U. panicoides* in addition to the *Echinochloa* species listed on its label.

The efficacy of some herbicides, particularly clodinafop, glufosinate, imazamox + imazapyr, and pinoxaden, was reduced when their applications were delayed from 6-leaf to 18- to 20-leaf stages. The growth stage can significantly affect uptake and metabolism of herbicides, especially the contact herbicides glufosinate and paraquat (Singh and Singh 2004). Although farmers delay herbicide applications due to weather and other constraints, the results of the current study suggest that they may achieve poor control of *U. panicoides* with these herbicides if applications are delayed. Therefore, farmers need to apply herbicides at an early stage to achieve effective control of *U. panicoides*.

In summary, *U. panicoides* seeds germinated at temperatures ranging from 15/5 to 35/25 C (day/night temperatures), suggesting that this species can germinate throughout the year in eastern Australian cropping systems, and growers may need to extend weed control measures to winter crops in addition to summer crops. Compared with other summer grass weed species, *U. panicoides* is not salt and drought tolerant at germination. The maximum germination of *U. panicoides* was obtained at the soil surface, and the addition of sorghum crop residue on the soil surface stimulated seedling emergence of *U. panicoides*. These observations indicate that no-till farming systems that retain low (e.g., legumes) or high (e.g., cereals) residue amounts will promote greater emergence of this weed species. In these cases in which the *U. panicoides* seedbank is concentrated in the topsoil profile in a continuous no-till system, a deep tillage operation would help bury the seeds below the maximum depth of emergence (i.e., 12 cm or deeper). Several effective herbicides were found for the control of *U. panicoides* in summer crops and fallows; however, these herbicides need to be applied at an early stage and used in rotation.

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