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Germination Ecology of African Lovegrass (*Eragrostis curvula*) and Herbicide Options for Its Control

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Abstract: African lovegrass (*Eragrostis curvula*) is one of the invasive perennial grasses that continues to disturb natural ecosystems globally. Experiments were conducted in southeast Queensland, Australia, to evaluate the effects of temperature, salt stress, water stress, burial depth, and sorghum crop residue load on the emergence and efficacy of postemergence herbicides on two populations (Clifton and Crows Nest) of *E. curvula*. The optimal germination temperature regimes for *E. curvula* were 30/20 and 35/25 °C, but seeds did not germinate at temperatures commonly occurring in the Queensland winter (15/5 °C). Total darkness inhibited germination by 79%, indicating that the shade cover effect would reduce germination of *E. curvula*. The Clifton population tolerated a higher concentration of sodium chloride (160 mM) and osmotic potential (−0.8 MPa). Under both salt and water stress, germination was 31% and 20% greater in the Clifton population than in Crows Nest, respectively, suggesting that the Clifton population is more tolerant to salt and drought stress. The maximum germination was obtained for the surface seeds while emergence declined with increased burial depth up to 4 cm. No seedlings emerged from the 8 cm depth. The addition of sorghum residue amounts up to 8 Mg ha^{-1} to the soil surface inhibited emergence compared to the no-residue treatment, suggesting that retention of heavy cereal residue will further delay or restrict emergence. Several postemergence herbicides were found to be effective in controlling *E. curvula* at an early stage. Information from this study will further compliment earlier studies on the targeted management of *E. curvula* populations.

Keywords: water stress; salt stress; temperature; burial depth; crop residue; post emergence herbicide

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1. Introduction

Eragrostis curvula (African lovegrass) is an invasive C_4 perennial grass that has threatened natural ecosystems globally [1]. It originated in Africa and is quickly spreading into many countries where it disturbs pastures and agricultural landscapes [1]. Considering its ability to tolerate wide environmental conditions [1] its recent area of spread includes Chile, New Zealand, Australia, Europe, Asia, and the USA, according to EPPO International [2]. In temperate regions, germination of *E. curvula* is higher in warmer months (spring, summer, and autumn) with limited growth and germination at temperatures below 10 °C [1,3]. Its adaptive mechanisms include early emergence and establishment to avoid competition with co-habiting species [4], quick germination and seedling growth, early flowering [5], and production of thousands of small seeds [6]. In terms of reproduction, seeds can be propagated via sexual or asexual reproduction (apomixis) between mid-spring to late autumn every year, [7] and they flower and set seeds 3–4 months after emergence.

In terms of seed production, it was estimated that *E. curvula* can produce up to 600 kg ha^{-1} within a dense population [6,8]. The viability rate is high, and it reaches maturity quickly [7]. The seeds are very light and can quickly colonize new areas [6]. The

main means of dispersal are water, wind, and animals [9]. The viability of mature seeds often reduces with time. However, it was estimated to have a relatively long-term longevity of 26 years when stored under a controlled environment (5 °C and 8.5% moisture) [10]. Under field conditions, the seed longevity of *E. curvula* was found to increase with seed burial depths across a 14-month period [11].

Since the introduction of *E. curvula* in Australia [12], different populations of *E. curvula* have been identified in both agricultural and natural grasslands [3,12]. A recent study has proven that environmental stress could trigger genetic mutation in *E. curvula*, particularly from sexual to asexual propagation (apomixis) [13]. The role of environmental stresses on the germination of different populations needs to be well established [1]. Roberts et al. [11,14] studied the response of four different populations of *E. curvula* in Australia to drought stress, radiant heat stress, pH, temperature, burial depths, and salinity stress. The studies confirm that the germination of *E. curvula* is a function of environmental stresses, and that the results varied for different populations. They concluded that species-targeted management strategies may be necessary to control *E. curvula* from different populations in Australia. Hence, the implications of environmental stresses on specific populations of *E. curvula*, their management, or their potential spread to new areas need to be understood.

In addition, the use of glyphosate to control *E. curvula* has been a popular approach [15,16]. However, the continuous use of glyphosate to control *E. curvula* poses a higher risk of invasion and dominance of glyphosate-resistant species. Therefore, approaching the control of *E. curvula* with herbicides other than glyphosate has been recommended [1]. It is therefore necessary to identify which herbicide, or combination of herbicides, shows the best efficacy in the control of *E. curvula* other than glyphosate.

In this study, our objectives were to evaluate the effect of environmental factors on the germination biology of two populations of *E. curvula* seeds and its implications for their management. Our objectives were also to determine post-emergence herbicides that would be suitable for the control of both populations of *E. curvula*. The two hypotheses of this study were that (1) the two populations of *E. curvula* will have different germination responses to the environmental factors, and that (2) the two populations of *E. curvula* will respond differently to the post-emergence herbicides.

2. Materials and Methods

2.1. Seed Collection

Seeds of two populations of *E. curvula* were collected for this study. One population was collected from a grass pasture field (Crows Nest, Queensland; S 27.148144; E 151.958119) on 2 April 2021, and the other was collected from a grass pasture fence line (Clifton, Queensland; S 27.9427031; E 151.9082524) on 3 April 2021. The two locations are about 100 km apart. Seeds from at least 100 mature plants were collected within a 5 ha area of land. Seeds were manually sieved in a tray prior to storage at the weed science lab of the University of Queensland, Gatton, QLD, Australia. In August 2021, plants of both populations were grown separately in the same environment at Gatton. Pots (24 cm in diameter) were filled with potting mix, and seeds were planted in these pots. There were about 25 pots for each population, and 4 plants per pot were maintained. Mature seeds from these plants were collected in mid-December 2021 and stored in plastic containers at room temperature (25 ± 2 °C) until the trials commenced in the first week of January 2022.

2.2. General Germination Protocol

To evaluate the influence of different environmental factors on seed germination, 25 seeds from each of *E. curvula* populations were counted and placed in a 9 cm diameter Petri dish in the lab. Before seed placement, two layers of filter paper (Whatman No. 1, Maidstone, UK) were placed in each Petri dish, and 5 mL of water or equivalent treatment solutions was added. To ensure no water loss due to evaporation, Petri dishes were kept in sealed plastic bags and carefully placed in an incubator set at 30/20 °C (12 h/12 h day/night) temperature unless otherwise specified. The incubator was lit by fluorescent

lamps (85 mol m^{-2} s^{-1} light intensity). Seed germination was assessed 21 d after incubation as no germination was observed after this period. Seed germination was assumed once radicles became visible up to 1 mm. Each treatment was replicated thrice. All experiments were repeated one month after completing the first run.

2.3. Experiment 1: Alternating Day/Night Temperatures

The effect of alternating day/night temperatures on the germination of *E. curvula* was determined by placing seeded Petri dishes in five incubators—set at five different temperature regimes (15/5, 20/10, 25/15, 30/20, and 35/25 °C). A 12 h/12 h (light/dark) photoperiod was maintained during the higher/lower temperature cycle, respectively. All chosen temperature regimes represent temperature conditions occurring year-round in the eastern cropping region of Australia.

2.4. Experiment 2: Effect of Light

The effect of light on seed germination of *E. curvula* was investigated by placing 25 seeds of each population in Petri dishes. Seeds were placed in either light/dark (12 h/12 h) condition or complete darkness (24 h). Under complete darkness, three layers of aluminium foil were wrapped around the dishes. All Petri dishes were kept in the incubating chamber set at 30/20 °C as this temperature regime was considered to be optimal for seed germination of *E. curvula* in the temperature experiment. Seed germination was evaluated at 21 d after incubation using the earlier described procedure.

2.5. Experiment 3: Sodium Chloride (NaCl) Concentration

The effect of NaCl concentrations on germination of *E. curvula* was determined by placing prepared Petri dishes holding seeds with different salt concentrations in the incubator set at the optimal day/night temperature 30/20 °C. Considering the soil salinity levels across different regions of Australia [17], concentrations of 0 (control), 20, 40, 80, 160, and 320 mM NaCl were chosen for this study.

2.6. Experiment 4: Osmotic Potential

To establish the influence of water stress on *E. curvula* germination, Petri dishes holding seeds and varying solutions of osmotic potentials were placed in the incubator set at the optimal day/night temperature 30/20 °C. Solutions of 0 (control), −0.1, −0.2, −0.4, −0.8, and −1.6 MPa osmotic potentials were chosen for this study. Solutions were prepared following the procedure of Michel and Radcliffe [18] by dissolving polyethylene glycol 8000 (Sigma-Aldrich, St. Louis, MO, USA) in distilled water.

2.7. Experiment 5: Seed Burial Depth

The effect of the seed burial depth on the emergence of *E. curvula* seeds was determined by placing 50 seeds each on the surface (0 cm) and at varying soil depths (0.5, 1, 2, 4, and 8 cm) in plastic pots (14 cm diameter with 16 cm depth). Soil depths were considered based on possible seed burial depths as a consequence of different tillage intensities (e.g., no-till or reduced-till) or planting operations practiced by farmers. A clay loam soil was used in this study. To eliminate any background seed bank in the soil prior to seeding, the soil was sieved through a 2 mm sieve and sterilized at 100 °C for 24 h. In addition, to ensure no background seeds of *E. curvula* in the soil, extra pots filled with the sieved soil were left unseeded to serve as a check. No *E. curvula* emergence was observed in the check pots. At the screenhouse of the University of Queensland, Gatton Farms, pots were placed within plastic trays on benches and sub-irrigated regularly to retain optimum soil moisture. Within the study period, the average maximum and minimum temperatures were 35.4 °C and 18.7 °C during the first run and 36.1 °C and 18.6 °C during the second run, respectively. The average light intensity in the screen house was 80% of the ambient light intensity. Seedling emergence was determined at 3 weeks after planting with visible coleoptiles on the soil surface. No further emergence was observed after this period.

2.8. Experiment 6: Sorghum Residue Amount

To evaluate the influence of sorghum residue retention on the emergence of *E. curvula*, 50 seeds were placed on the soil surface in 14 cm diameter pots and mulched with varying rates (0, 1, 2, 4, and 8 Mg ha^{-1}) of sorghum residue (leaves and stems of 'Elite Sentinel IG'), with corresponding residue thickness of 0, 0.13, 0.25, 0.5, and 1.0 cm, respectively. Prior to placement in pots, residues were chopped into smaller sizes (approximately 2 cm) and dried in an oven set at a temperature of 70 °C for 72 h. All temperature, soil, and water conditions were similar to those described earlier in the seed burial depth experiment. Seedling emergence was determined at 3 weeks after planting with visible coleoptiles on the soil surface. No further emergence was observed after this period.

2.9. Experiment 7: Performance of Postemergence (POST) Herbicides

The efficacy of POST herbicides on *E. curvula* was determined by planting 15 seeds at a 0.5 cm depth within a 14 cm diameter pot filled with a commercial potting mix (Platinum® potting mix, Centenary Landscaping, Brisbane, QLD, Australia). Seedlings were thinned to 6 plants per pot shortly after emergence. Plants were placed on benches in the screenhouse and regularly irrigated with an automated sprinkler system. Plants were sprayed with different herbicides (Table 1) at the 5–6 leaf stage. These herbicide treatments were chosen because they are commonly used in crops and fallow conditions to control grass weeds. A research track sprayer was used to spray herbicides at a water volume of 108 L ha^{-1}. TeeJet® XR110015 (Sprayshop, Toowoomba, QLD, Australia), and flat-fan nozzles were used on the sprayer. Field-recommended rates of herbicides for most grasses were used for *E. curvula*. At 6 weeks after treatment, plant survival and biomass data were measured. *Eragrostis curvula* plants were assumed to have survived if a new leaf grew after spraying. Survived plants were cut at the soil surface, put in paper bags, and dried in the oven set at a temperature of 70 °C for 72 h. Dry weight was recorded.

Table 1. Herbicides, their trade names, site of action, doses, and adjuvants used in experiment 7.

Herbicide Treatments	Trade Names	Site of Action	Dose (g a.i./a.e. ha^{-1})	Adjuvant
Control	-	-	-	-
Amitrole + paraquat	Alliance®	Lycopene cyclase inhibitor + Photosystem I inhibitor	560	-
Butroxydim	Factor®	ACCase inhibitor	30	1% Uptake®
Clethodim	Havoc®	ACCase inhibitor	120	1% Supercharge®
Cyhalofop	Barnstorm	ACCase inhibitor	285	1% Uptake®
Glufosinate	Biffo®	Glutamine synthetase inhibitor	750	-
Glyphosate	Roundup Ultra®MAX	EPSP inhibitor	740	-
Haloxyfop	Verdict™	ACCase inhibitor	78	1% Hasten™
Imazamox + imazapyr	Intervix®	ALS inhibitor	36	1% Hasten™
Iodosulfuron	Hussar®	ALS inhibitor	10	-
Mesosulfuron	Atlantis®	ALS inhibitor	10	1% Hasten™
Paraquat	Gramoxone®	Photosystem I inhibitor	600	1% Hasten™
Pinoxaden	Axial®	ACCase inhibitor	10	0.5% Adigor®
Propaquizafop	Shogun®	ACCase inhibitor	30	1% Hasten™

Abbreviations: ACCase, acetyl-coenzyme A carboxylase; ALS, acetolactate sythase; EPSP, 5-enolpyruvylshikimate-3-phosphate; a.e., acid equivalent; a.i., active ingredient.

2.10. Statistical Analyses

All experiments were laid out as a randomized complete block design. In laboratory experiments, blocking was established by positioning Petri dishes with a replicate of all treatments on the same shelf within an incubator. Similarly, in the screenhouse experiments, pots of the same replicate were grouped on a bench. The POST herbicide trial was laid out as a factorial (leaf stage and herbicide treatment) randomized block design. All studies were repeated in time with three replicates for each sampling unit except for the herbicide trial, in which there were five replicates of each treatment in each run. Data were combined over the two runs as there was no interaction between treatments. All data were analysed with Genstat [19]. Significant interactions were observed between treatments and *E. curvula*

populations. Non-transformed data were used in the analysis as transformation did not improve the homogeneity of variance. Data from salt stress, water stress, seed burial depth, and residue experiment temperature, light, and herbicide trials were subjected to an ANOVA, and multiple comparisons were performed using Fisher's protected LSD test at a 5% level of significance.

3. Results

3.1. Experiment 1: Temperature

There was a significant interaction between populations of *E. curvula* and temperature (Figure 1). Germination was highest at optimal (30/20 °C) and sub-optimal (35/25 °C) temperature regimes in both populations (91% and 80% for Crows Nest and 95% and 93% for Clifton at 30/20 °C and 35/25 °C, respectively). Germination was similar between 30/20 and 35/25 °C for the Clifton population but not for Crows Nest. At lower temperature regimes (25/15 and 20/10 °C), germination was reduced by 60% and 87% in the Crows Nest population and 51% and 85% in the Clifton population, respectively, compared to the highest germination at the optimal temperature (30/20 °C). No germination was observed in both populations at the lowest temperature regime (15/5 °C).

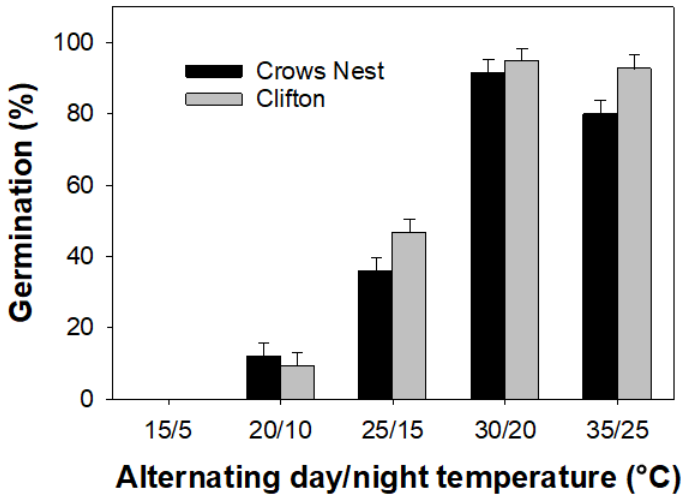

Figure 1. Effect of alternating day/night temperatures (°C) on seed germination of *Eragrostis curvula*. Error bars represent the least significant difference (LSD) at the 5% level of significance.

3.2. Experiment 2: Light

There was a significant interaction between light and populations of *E. curvula* (Figure 2). Generally, seed germination performed significantly higher (90% for Crows Nest and 92% for Clifton) under 12 h/12 h light and dark alteration compared to the total dark condition (20% for Crows Nest and 5% for Clifton). Germination between the two populations was similar under light and dark alteration (12 h/12 h), whereas, under dark conditions, germination differed between the populations. For example, germination in the Clifton population was reduced by 74% compared to germination of the Crows Nest populations under dark conditions.

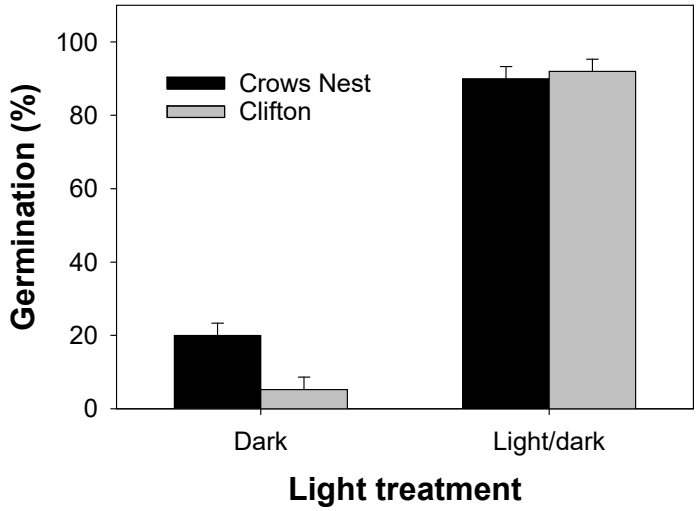

Figure 2. Effect of light on seed germination of *Eragrostis curvula*. Error bars represent the least significant difference (LSD) at the 5% level of significance.

3.3. Experiment 3: Salt Stress

The study shows a significant interaction between seed populations and salt concentration (Figure 3). Germination was greatest in the control (0 mM) for both populations (90% for Crows Nest and 94% for Clifton). No differences were observed between populations at low NaCl concentrations (0 and 20 mM). Germination for the Clifton population was similar from 0 to 40 mM NaCl concentrations while Crows Nest had lower germination at 40 mM NaCl than the control (0 mM). In the Clifton population, germination was more tolerant at 160 mM NaCl (75%) than in the Crows Nest (44%). Compared to their control, germination was reduced by 20% and 51% for both Clifton and Crows Nest populations, respectively, at 160 mM NaCl. Both populations did not germinate at the highest NaCl concentration observed (320 mM).

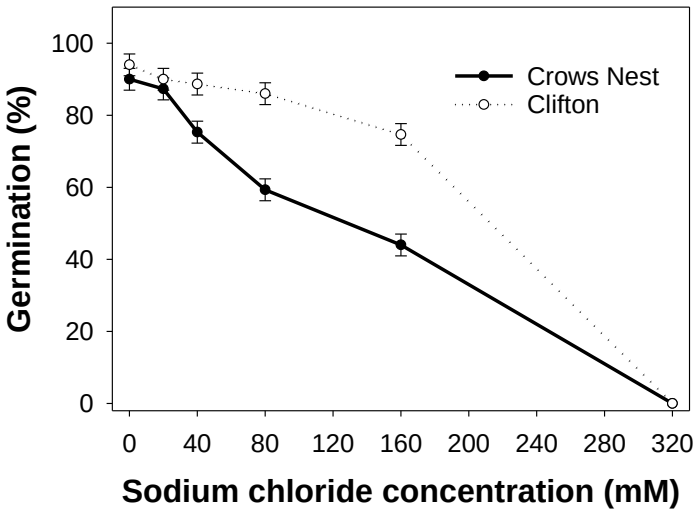

Figure 3. Effect of salinity stress on seed germination of *Eragrostis curvula* populations (Crows Nest and Clifton) using different concentrations of sodium chloride. Error bars represent the least significant difference (LSD) at the 5% level of significance.

3.4. Experiment 4: Water Stress

A significant interaction was observed for germination between seed populations of *E. curvula* and moisture stress (Figure 4). The highest germination was observed under the no stress condition (0 MPa) with similar germination rates for both populations (91% for

Crows Nest and 94% for Clifton). The germination rate declined gradually as moisture stress increased for both populations. However, the two populations differed in their response to increased stress. For instance, the Clifton population had significantly higher germination rates (77%, 75%, 67%, and 22%) under −0.1, −0.2, −0.4, and −0.8 MPa osmotic potential, respectively, compared to the germination rate of the CN population (57%, 51%, 47%, and 11%) under similar stress conditions. Both populations did not germinate at −1.6 MPa osmotic potential.

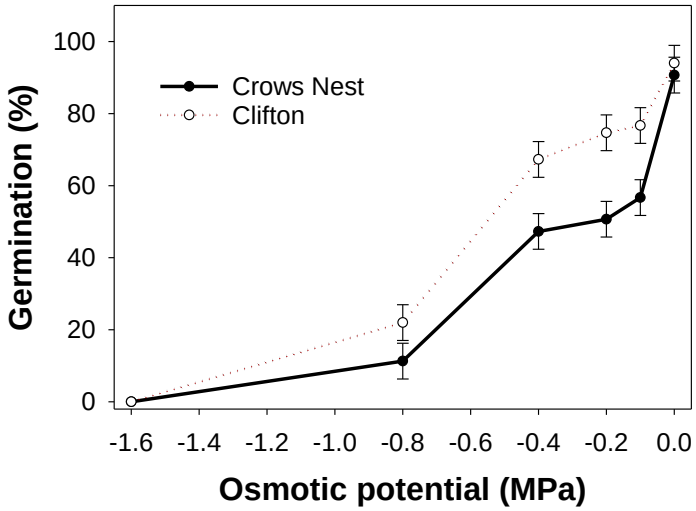

Figure 4. Effect of water stress on seed germination of *Eragrostis curvula* populations (Crows Nest and Clifton). Error bars represent the least significant difference (LSD) at the 5% level of significance.

3.5. Experiment 5: Burial Depth

A significant interaction was established for seedling emergence between populations of *E. curvula* and burial depth (Figure 5). The highest emergence was observed on the surface (0 cm) with a similar emergence recorded in both populations (71% for Crows Nest and 69% for Clifton). The emergence rate declined gradually with increasing burial depth for both populations, suggesting that seed burial can reduce emergence. Furthermore, emergence rates differed with populations within soil depths. For instance, the Crows Nest population had significantly higher emergence rates (26%, 19%, 15%, and 12%) under 0.5, 1, 2, and 4 cm soil depths, respectively, compared to the emergence rate of the Clifton population (15%, 5%, 4%, and 2%) under similar depths.

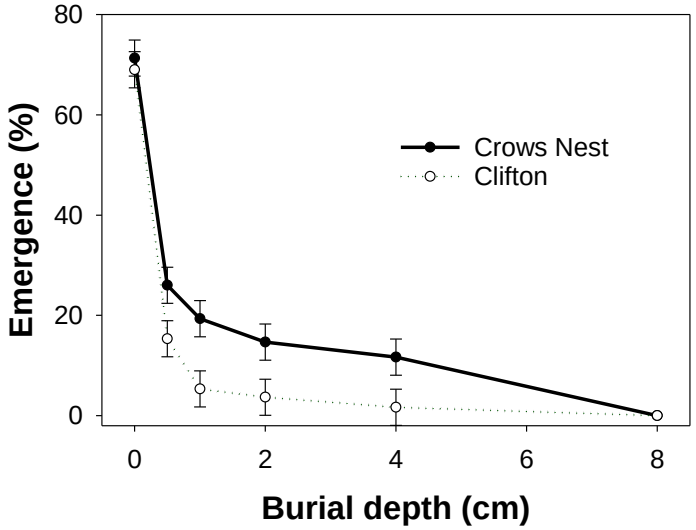

Figure 5. Effect of burial depth on seedling emergence of *Eragrostis curvula* populations (Crows Nest and Clifton). Error bars represent the least significant difference (LSD) at the 5% level of significance.

3.6. Experiment 6: Sorghum Residue Cover

There was a significant interaction for seedling emergence between seed population and sorghum residue coverage (Figure 6). Between 0 and 1 Mg ha^{-1} coverage of sorghum residue, an average of 70% emergence was achieved with similarities between both populations. Increased residue coverage from 2 to 8 Mg ha^{-1} resulted in an increased restriction of seedling emergence in both populations. However, the emergence rate of the Clifton population (44% and 8%) was significantly lower than Crows Nest (51% and 23%) under 2 and 4 Mg ha^{-1} sorghum residue coverage, respectively. Notwithstanding, there was more or less no emergence for both populations at the highest coverage (8 Mg ha^{-1}). The above result suggests that a sorghum residue thickness of up to 1 cm (8 Mg ha^{-1}) may hinder the successful emergence of *E. curvula*, irrespective of the population.

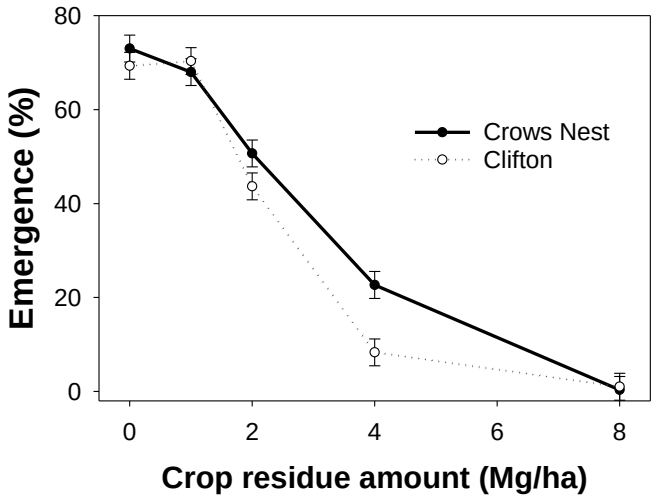

Figure 6. Effect of Sorghum residue cover on seedling emergence of *Eragrostis curvula* populations (Crows Nest and Clifton). Error bars represent the least significant difference (LSD) at the 5% level of significance.

3.7. Experiment 7: Post-Emergent Herbicides

In terms of survival, spike numbers per plant, and biomass production after postemergence herbicide application, there was no significant difference between *E. curvula* populations (Table 2). Therefore, results are combined over the two populations. Results revealed that amitrole + paraquat, glufosinate, cyhalofop, butroxydim, glyphosate, clethodim, paraquat, propaquizafop and, haloxyfop provided 100% control (i.e., no spike and 0% biomass production) of *E. curvula* when applied at the 5–6 leaf stage, while mesosulfuron, pinoxaden, imazamox + imazapyr, and iodosulfuron were not found to be effective (i.e., 100% survival) against *E. curvula* (Table 2). Mesosulfuron, pinoxaden and, iodosulfuron treatments resulted in an average of 3–4 spikes/plant. Mesosulfuron, pinoxaden, and iodosulfuron resulted in similar biomass (2–3 g pot^{-1}) accumulation compared to control while imazamox + imazapyr treatment resulted in 27% biomass accumulation (0.7 g pot^{-1}). This also confirms their non-efficacy on *E. curvula*.

Table 2. Effect of post-emergence herbicide application at the 5–6 leaf stage on *Eragrostis curvula* survival, biomass production, and spike numbers per pot.

Herbicides	Survival (%)	Spike (Number/Pot)	Biomass (g/pot)
Control	100	3.3	2.603
Amitrole + paraquat	0	0	0
Mesosulfuron	100	2.9	2.398
Pinoxaden	100	3.5	2.806
Glufosinate	0	0	0
Cyhalofop	0	0	0
Butroxydim	0	0	0
Glyphosate	0	0	0
Clethodim	0	0	0
Iodosulfuron	100	4.2	2.89
Imazamox + imazapyr	100	0	0.711
Paraquat	0	0	0
Propaquizafop	0	0	0
Haloxyfop	0	0	0
LSD	-	0.47	0.187

4. Discussion

4.1. Experiment 1: Temperature

The highest germination (91% and 80% for Crows Nest and 95% and 93% for Clifton, respectively) observed at optimal (30/20 °C) and sub-optimal (35/25 °C) temperature regimes in both populations suggest that *E. curvula* germination is likely to be more successful at high-temperature regimes. The lack of germination observed in both populations at the lowest temperature regime (15/5 °C) implies that *E. curvula* seed germination could be restricted under a cold temperate climate. This further confirms earlier findings that *E. curvula* germination is common in warmer seasons (between spring, summer, and autumn) while growth and germination become slower at temperatures below 10 °C [1,3]. According to a previous study [11], 17/7 °C temperature reduced germination of *E. curvula* populations collected from mild-temperate and hot, dry, summer/cold winter climates in Australia. However, germination remained higher for seed populations from a warm temperate climate. The latter confirms possible reasons for the interaction of temperature with different *E. curvula* seed populations. Previous research showed that *E. curvula* suppression of native plants was possible where growth or germination was delayed for up to 3 weeks [20]. These results suggest that native plant species with relatively high germination potentials under low temperatures are likely to be able to suppress the emergence of *E. curvula*, where its germination is restricted under cold climate, especially where any of the native plant species co-exist with *E. curvula*.

4.2. Experiment 2: Light

The results of this study and Robert et al. [14] suggest that optimum germination of *E. curvula* is best achieved under alternating light conditions in seed populations of most climates observed, with the exception of warm climates. The latter confirms the reason for the possible interaction between the germination of *E. curvula* populations under different lighting conditions. According to Roberts et al. [14], *E. curvula* seeds from mild temperate and hot, dry, summer/cold winter climates in Australia had significantly reduced germination in complete darkness compared to alternating 12 h light and 12 h dark photoperiod, whereas germinations of seeds from warmer climates under complete darkness were higher compared to similar populations under alternating light conditions. Supporting evidence of the reduced germination under darkness may be a contributing factor to the low abundance of *E. curvula* populations reported by Firn et al. [16] in grassy woodlands with paddock trees as canopy cover. Therefore, sustainable management of *E. curvula* may further imply that permanent orchards are established in open-grazed areas where *E. curvula* germination has been majorly influenced by light.

4.3. Experiment 3: Salt Stress

The result shows that germination of *E. curvula* reduces with increasing salt stress. However, populations may vary in their tolerance to salt stress. For instance, a higher germination percentage was observed for the Clifton population at 160 mM NaCl, suggesting that the Clifton population may be more salt tolerant than the Crows Nest population. According to Roberts et al. [14], high NaCl concentrations between 100 to 250 mM significantly reduced the germination of *E. curvula* seeds from diverse climatic conditions, leading to a conclusion that seeds of *E. curvula* can only tolerate low salinity stress ($\leq$100 mM), irrespective of population. However, according to this study, the Clifton population copes with higher salinity stress and more than the Crows Nest population. The latter further suggests that *E. curvula* populations from different regions would differ in their tolerance to salinity stress. Therefore, the decision on proper management should entail adequate knowledge of soil salinity in a particular location.

High concentrations of sodium (Na+) and chlorine (Cl-) ions in plants often result in water loss and eventual stunting of the plants [21]. However, plants often show some mechanism of resistance to salinity stress. *Dinebra panicea* var. *brachiata* (Steud.) demonstrates a mild tolerance to salinity as 171–225 mM was required to obtain a 50% reduction in germination [22]. Giant chickweed [*Myosoton aquaticum* (L.) Moench] was equally reduced by 50% between 150 and 156 mM NaCl concentrations [23]. However, a report has defined soil with 20 mM NaCl concentration as saline soil [21]. Hence, increased tolerance of *E. curvula* and other weed species [22,23] beyond the optimal soil-salinity shows a high risk of their spread into saline soils.

4.4. Experiment 4: Water Stress

Irrespective of population, *E. curvula* shows the highest germination (91% for Crows Nest and 94% for Clifton) under no stress condition (0 MPa). The germination rate declined gradually as moisture stress increased for both populations, suggesting that increasing drought stress can reduce germination [11]. The above result implies that *E. curvula* populations may decline and be substituted by drought-tolerant native species under severe and permanent drought conditions. The high germination response of the Clifton population to increased moisture stress suggests that the Clifton population had a higher tolerance to moisture stress between -0.1 to -0.8 MPa when compared to Crows Nest. A previous study [11] shows that seed populations of *E. curvula* from warmer, mid-temperate, and hot dry/winter climates showed reduced germination at the osmotic potential of -0.6 MPa or higher while the two populations under consideration in this study (Crows Nest and Clifton) showed reduced germination as high as -0.1 MPa osmotic potential. The research outcome of *E. curvula* in response to increasing drought in this study is in contrast to the local experience of landholders on invasive grass in critically endangered grassy woodlands [16]. According to Firn et al. [16], most landholders in their study attributed drought as a major precursor to the increased invasion of *E. curvula*. Therefore, it becomes necessary that future research investigates the implication of post-drought stress on the germination of *E. curvula.*

4.5. Experiment 5: Burial Depth

The result from this study reveals that the highest emergence (71% for Crows Nest and 69% for Clifton) of *E. curvula* seeds were the ones deposited on the surface. A large deposit of *E. curvula* seeds on the bare ground [6,8], combined with low competition with other species and overgrazing, has increased the pasture susceptibility to *E. curvula* under low soil moisture content [16]. The emergence rate declined gradually with increasing burial depth for both populations, suggesting that seed burial can reduce emergence. However, emergence differed with populations within soil depths. For instance, the Crows Nest population had significantly higher emergence as soil depth increased, suggesting that the Crows Nest population has a higher tendency to emerge as soil depth increases when compared to Clifton. The emergence of the Clifton or Crows Nest populations could

be reduced by practicing tillage deeper than 8 cm as no emergence was observed from this depth.

Roberts et al. [11] conducted seed burial emergence variability of *E. curvula* across periods under field conditions in a warm climatic zone of Australia within burial depths of 0, 1, 3, 5, and 10 cm, and seeds were retrieved after 3, 6, 9, and 14 months. Results show that germination rates were lower at the surface across time periods, and that the seed longevity of *E. curvula* increased with depths. They attributed the results to a multi-play of environmental factors such as minimum/maximum temperature alterations observed across this period. They submitted that *E. curvula* seeds can lie dormant in the cooler months, followed by germination in the warmer months. Considering the potential of seed longevity of *E. curvula* in soils [11], it may be necessary to consistently adopt minimum tillage, together with a stale seedbed, to eliminate heavy deposits of active *E. curvula* seeds within 0–4 cm soil depths.

4.6. Experiment 6: Sorghum Residue Cover

The result from this study suggests that a sorghum residue thickness of up to 1 cm (8 Mg ha^{-1}) may hinder the successful emergence of *E. curvula*, irrespective of the population. There is no study to compare the impact of residue on *E. curvula*. However, studies are available for other weed species from Australia. For example, the emergence of awnless barnyard grass [*Echinochloa colona* (L.) Link] [24] and sweet summer grass [*Brachiaria eruciformis* (Sm.) Griseb.] [25] was 70% and 63%, respectively, without sorghum crop residue. Both species did not emerge with increased residue amounts up to 8 Mg ha^{-1}. Similarly, 7–15% emergence was reported in windmill grass (*Chloris truncata* R. Br) when covered with 4–6 Mg ha^{-1} [26]. The result from this study also confirms the non-emergence of *E. curvula* seedlings under sorghum residue cover up to 1 cm (8 Mg ha^{-1}). Hence, leaving about 1 cm sorghum residue as a mulch cover under no-till could help inhibit the emergence of *E. curvula.*

4.7. Experiment 7: Post-Emergent Herbicides

The result from this study suggests that applying recommended rates of amitrole + paraquat, glufosinate, cyhalofop, butroxydim, glyphosate, clethodim, paraquat, propaquizafop, and haloxyfop provided 100% control (i.e., 0% survival) of *E. curvula* when applied at the 5–6 leaf stage, and they all would be an alternative to glyphosate. However, the efficacy of these herbicides on larger plants remains uncertain. For instance, Chauhan [27] reported that treatment of liver seed grass [*Urochloa panicoides* L.] at the 6-leaf stage with clodinafop, glufosinate, and pinoxaden at the field rates resulted in 100% control while the same herbicide treatment at the 18–20 leaf stage resulted in 25% survival of *U. panicoides* seedlings compared to control. Hence, future studies may have to consider the effective doses of these selected herbicides on *E. curvula* at different growth stages.

5. Conclusions

In summary, *E. curvula* seeds germinated at temperatures ranging from 20/10 to 35/25 °C (day/night temperatures) with the highest germination at optimal (30/20 °C) and sub-optimal (35/25 °C) temperatures, whereas the seeds did not germinate at the lowest temperature (15/5 °C), suggesting that *E. curvula* may be substituted by co-habiting species that exhibit high germination in winter. Significant decline in the germination of *E. curvula* under dark conditions compared to light and dark alterations imply that the introduction of paddock trees as canopy cover in open grazed pastures/environment disturbed by *E. curvula* would help limit permanent exposure of surface seed to light, thus restricting or delaying germination. Generally, *E. curvula* germination declined as salt and water stress increased in both populations. Notwithstanding, germination of the Clifton population was consistently higher than the Crows Nest population, which further suggests that the Clifton population has a higher tolerance to high salt and drought conditions compared to Crows Nest. Although emergence was relatively higher in the Crows Nest population than

in Clifton as depth increased, seed emergence generally declined with increased soil depth in both populations, indicating that the routine practice of deep tillage (i.e., 8 cm or deeper) can bury heavy surface seed deposit of *E. curvula*. The addition of sorghum crop residue ranging from 2 to 8 Mg ha^{-1} restricted seedling emergence in both populations. The latter observation implies that no-till farming systems that often retain heavy cereal residue will suppress the emergence of *E. curvula* seeds near the surface. Several effective herbicides were found for the control of *E. curvula* at recommended rates. However, these herbicides are to be applied at an early stage of growth (5–6 leaves).

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