

# Germination ecology of wild mustard (*Sinapis arvensis*) and its implications for weed management

## Research Article

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### Abstract

Wild mustard (*Sinapis arvensis* L.) is a widespread weed of the southeastern cropping region of Australia. Seed germination ecology of *S. arvensis* populations selected from different climatic regions may differ due to adaptive traits. Experiments were conducted to evaluate the effects of temperature, light, radiant heat, soil moisture, salt concentration, and burial depth on seed germination and seedling emergence of two populations (Queensland [Qld] population: tropical region; and Victoria [Vic] population: temperate region) of *S. arvensis*. Both populations germinated over a wide range of day/night (12-h/12-h) temperatures (15/5 to 35/25 C), and had the highest germination at 30/20 C. Under complete darkness, the Qld population (61%) had higher germination than the Vic population (21%); however, under the light/dark regime, both populations had similar germination (78% to 86%). At 100 C pretreatment for 5 min, the Qld population (44%) had higher germination than the Vic population (13%). Germination of both populations was nil when given pretreatment at 150 and 200 C. The Vic population was found tolerant to high osmotic and salt stress compared with the Qld population. At an osmotic potential of  $-0.4$  MPa, germination of Qld and Vic populations was reduced by 85% and 42%, respectively, compared with their respective controls. At 40, 80, and 160 mM sodium chloride, germination was lower for the Qld population than the Vic population. Averaged over the populations, seedling emergence was highest (52%) from a burial depth of 1 cm and was nil from 8-cm depth. Differential germination behaviors of both populations to temperature, light, radiant heat, water stress, and salt stress suggest that populations of *S. arvensis* may have undergone differential adaptation. Knowledge gained from this study will assist in developing suitable control measures for this weed species to reduce the soil seedbank.

### Introduction

Wild mustard (*Sinapis arvensis* L.) is an annual broadleaf weed of the Brassicaceae family. It is believed to have originated in the Eurasia region, somewhere between the Mediterranean and western Asia (Warwick et al. 2009). Today, it is found in most parts of the world and is considered a problematic weed in Canada and many Mediterranean countries (Damanakis 1983; Wall and Townley-Smith 1996). *Sinapis arvensis* was first recorded in Australia in 1898 and is now well distributed in the southeastern region of the nation (Australasian Virtual Herbarium 1898). It causes considerable losses in quantity and quality of cereal, grain, and oilseed crops every year. *Sinapis arvensis* is the sixth most widely spread residual cropping weed in Australia, present on almost 1 million ha of agricultural land (Llewellyn et al. 2016). It causes an estimated loss of 19.9 million kg of grain yield annually, costing about AU\$4.9 million (Llewellyn et al. 2016).

*Sinapis arvensis* is considered a very competitive weed species (Preston 2019). It grows quickly over neighboring plants, attains great height, and develops side branches, thus depriving neighboring crop plants, such as spring wheat (*Triticum aestivum* L.), of sunlight and causes yield losses (Dezfooli 2000). It can cause a yield loss of more than 25% in triticale [*Triticosecale* (wheat [*Triticum aestivum* L.] × rye [*Secale cereale* L.])] and wheat (Dhima and Eleftherohorinos 2005). A study in Canada reported a grain yield loss of 44% in spring wheat due to *S. arvensis* infestation (Dezfooli 2000). A previous study showed that a density of 20 plants m<sup>-2</sup> of *S. arvensis* can reduce total seed weight in canola (*Brassica rapa* L.) by more

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than 35% and to almost half in chick pea (*Cicer arietinum* L.) at 40 plants  $m^{-2}$  (Preston 2019). Similarly, in Canada (Wellington), uncontrolled *S. arvensis* infestations caused yield reductions in wheat, oat (*Avena sativa* L.), and barley (*Hordeum vulgare* L.) by 53%, 63%, and 69%, respectively (Anderson 1956; Richardson 1980). Adding to this, yield losses due to *S. arvensis* infestation have been reported in several other crops, including flax (*Linum usitatissimum* L.), soybean [*Glycine max* (L.) Merr.], potato (*Solanum tuberosum* L.), corn (*Zea mays* L.), and kale (*Brassica oleracea* L.) (Warwick et al. 2000).

*Sinapis arvensis* is a prolific seed producer, producing 2,000 to 3,500 seeds per plant (Dezfooli 2000). Seeds are small in size (0.5 to 2 mm in diameter) and can disperse by wind, water, and human contact (Quartley and Wellington 1962). Almost three-quarters of freshly harvested *S. arvensis* seeds were dormant at maturity (Preston 2019). Further, seeds exhibit a dormancy period of ~2 yr and can remain viable for up to 60 yr (Mulligan and Bailey 1975). *Sinapis arvensis* only reproduces by seeds and does so by cross-pollination, as the flower is self-incompatible, suggesting its potential of invading faraway places through pollen movement. Seedlings of *S. arvensis* are difficult to distinguish from commercially grown members of the mustard family, including wild radish (*Raphanus raphanistrum* L.) (Preston 2019). In addition, several biotypes of *S. arvensis* have evolved resistance to the herbicides chlorsulfuron (Topuz et al. 2015) and ethametsulfuron-methyl (Dexter 2004). Around the world, resistance to acetolactate synthase inhibitors, photosystem II inhibitors, and synthetic auxins (disruptors of plant cell growth) has been reported (Preston 2019).

The weedy characteristics of *S. arvensis*, combined with its ever-evolving herbicide resistance and a more favorable environment predicted to occur in Australia due to climate change, may make it a more troublesome weed for Australia in the near future. Development of an integrated weed management strategy for *S. arvensis* needs to be developed, given the surging issue of herbicide resistance. However, the development of such a strategy is only possible with detailed information on weed ecology and biology. A thorough understanding of seed germination ecology is vital for any weed control program, as it provides information on weed emergence, establishment, and seedbank dynamics (Chauhan and Johnson 2010). A greater ability to predict weed seed germination could help in better timing of cultural practices for effective control. Seed biology is an essential step toward the development of plant simulation models, which further help in developing an effective weed control program (Martinson et al. 2007; Schutte et al. 2008). Moreover, information on seed biology could also help to predict *S. arvensis* invasiveness beyond its current boundaries (Geng et al. 2016).

Seed germination and seedling emergence are influenced by various climatic parameters such as temperature, light, radiant heat, soil moisture, salt concentration, and burial depth. Temperature is one of the most important factors determining the germination of a seed. A study from Canada showed that *S. arvensis* seeds can germinate at temperatures in a range of 1.5 to 48 C (Huang et al. 2001). Another study reported 20 C as the most suitable temperature for radicle emergence (Lotfifar et al. 2014). All these studies used constant temperatures, which are rarely experienced under natural conditions. Seed germination and emergence behaviors are found to be different in alternating temperature regimes (Baskin et al. 2006); however, such information is not available for Australian populations of *S. arvensis*.

High radiant heat generated by fires can affect germination behavior in plant species (Bebawi and Campbell 2002). Fire can

also act as a thermal scarification agent and trigger germination in dormant seeds of some species (Gashaw and Michelsen 2002; Valbuena et al. 1992). In some subtropical grass species, such as kangaroo grass (*Themeda triandra* Forssk.), heat generated during a low-intensity fire greatly enhances the germination capabilities of the seeds (Ghebrehiwot et al. 2012). No such study on *S. arvensis* is currently available.

Soil moisture levels regulate water availability to the seed, which further influences cell elongation and seedling emergence (Bradford et al. 1995). According to a study from Iran, seed germination in *S. arvensis* was more than 70% at water potentials of 0 MPa and  $-0.2$  MPa and declined significantly at the water potential of  $-0.4$  MPa (Lotfifar et al. 2014). Probing further, soil salinity can also affect seed germination, as a high salt concentration does not allow imbibition of water into dry seeds. Almost 60% of 20 million ha of the total cropping land in Australia has sodic soils (Rengasamy 2010).

Light acts as an environmental indicator of soil depth, and dark inhibits germination in seeds (Cristaudo et al. 2007). The size of a seed can help determine its maximum emergence depth. In general, larger seeds tend to have larger food reserves and thus have a greater potential to emerge from deeper soil layers (Humphries et al. 2018). Generally, weed seeds are smaller in size compared with most winter cereals and thus have an advantage in no-till systems where most seeds stay close to the surface (Chauhan et al. 2006b). Information on the effect of burial depth on seedling emergence of *S. arvensis* is not available for Australian populations.

Weeds have higher plasticity than cultivated plants, which helps in their wider spread and their greater adaptability to local environments (Mahajan et al. 2015). While adapting to local conditions, different populations that develop in distinct ecosystems could behave differently when exposed to the same climatic parameters. Several researchers have reported considerable differences in the germination ecology of different populations of a species under the same conditions (Bajwa et al. 2018; McElroy et al. 2004). While some information on germination and emergence of *S. arvensis* is available for Canadian and Mediterranean populations (Lotfifar et al. 2014; Mennan and Ngouajio 2006), there is no recorded report on Australian populations. The objectives of this research were to evaluate the effect of the abiotic factors temperature, light, radiant heat, soil moisture, salt concentration, and burial depth on seed germination and emergence of *S. arvensis* and to compare the results of two populations of *S. arvensis* collected from two different states (Queensland and Victoria) of Australia.

## Materials and Methods

### Seed Description

Queensland (Qld) and Victoria (Vic) populations of *S. arvensis* were selected for seed collection. Queensland is marked by tropical climate and Victoria has temperate climatic conditions. The seed collection of the Vic population was done in November 2019 from a fallow wheat field in Kaniva, VIC, and the Qld population was collected from a sorghum field in Capella, QLD, in June 2020. Mature seeds were collected from at least 50 plants from each population by pressing the ripened pods. Seeds were cleaned after collection, dried in the shade, and kept in airtight containers in the laboratory until the commencement of experiments.

### General Seed Germination Test Protocol

All germination tests were conducted in 9-cm-diameter petri dishes containing two pieces of Whatman No. 1 filter paper (Whatman® International, Maidstone, UK). In each petri dish, 25 seeds were evenly placed followed by the addition of 5 ml of distilled water or treatment solution. All seeds used in this experiment were surface sterilized with sodium hypochlorite (1% v/v) for 2 min and then rinsed repeatedly with tap water to protect from any fungal infection. Petri dishes were placed inside a plastic zip-lock bag to avoid any water vapor loss. Then the bags were placed in temperature- and light intensity controlled incubators (ICCBOD-300, Laboratory Equipment, Marrickville, 2204 NSW, Australia). The fluorescent bulb inside the incubator emits white light with an intensity of  $85 \text{ mol m}^{-2} \text{ s}^{-1}$ . Light, radiant heat, water-stress, and salt-stress experiments were conducted in an incubator configured at 30/20 C and a photoperiod of 12 h coinciding with the higher temperature. This temperature regime was found to be optimal for seed germination in the temperature experiment (Figure 1). Germinated seeds were counted until 21 d after incubation. Seeds were considered germinated when the size of radicle was bigger than 1 mm.

### Effect of Temperature on Germination

To find the optimum alternating temperature conditions, petri dishes containing seeds of both populations of *S. arvensis* were placed in incubators calibrated at five different day/night temperatures, that is, 15/5, 20/10, 25/15, 30/20, and 35/25 C in the light (12-h)/dark (12-h) environment. These five treatments were selected to represent the temperature conditions occurring in the northern grain region of Australia during different seasons (BOM 2021).

### Effect of Light on Germination

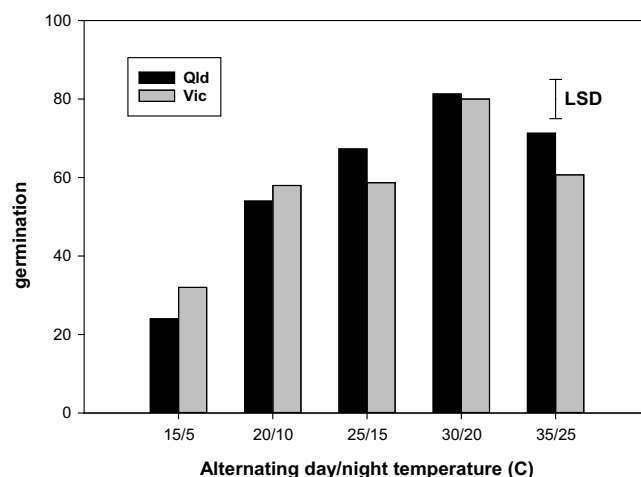
To check the response of light and dark environments on *S. arvensis* germination, seeds were exposed to two photoperiods of either an alternating light and dark period for 12 h each or 24 h of complete darkness. In the alternating light and dark treatment, the incubator was calibrated in such a way that the dark period corresponded with the low temperature (20 C) and the light period overlapped with the high temperature (30 C). Three layers of aluminum foil were wrapped around the petri dishes to create the complete-dark treatment and were removed after the 21 d incubation period.

### Effect of Radiant Heat on Germination

The effect of heat stress on germination was studied by exposing both populations of *S. arvensis* seeds to five different temperatures: 25 (control), 50, 100, 150, and 200 C for 5 min (Chadha et al. 2021). Seeds were placed in a netted mesh bags and kept inside a pre-heated oven on an aluminum tray. After 5 min, the treated seeds were removed from the oven and placed in the incubator at 30/20 C. Germination was evaluated as described previously.

### Effect of Osmotic Stress on Germination

The effect of water stress on seed germination of *S. arvensis* was assessed by incubating seeds of both populations in a broad range of water-deficit environments, that is, 0, -0.1, -0.2, -0.4, -0.8, and -1.6 MPa. These solutions were prepared using polyethylene



**Figure 1.** Effect of alternating day/night temperatures (15/5 to 35/25 C) on the germination of two populations (Qld and Vic) of *Sinapis arvensis*. Seeds were incubated for 21 d in light/dark (12-h photoperiod). LSD at a 5% level of significance.

glycol 8000 (PEG; Sigma-Aldrich, St Louis, MO 63103, USA) following the method of Michel and Radcliffe (1995).

### Effect of Salt Stress on Germination

To study the effect of salt stress on germination of both populations of *S. arvensis* seeds, sodium chloride (NaCl) at concentrations of 0, 20, 40, 80, 160, and 320 mM was used. These concentration levels were used to represent soil salinity levels occurring in different regions of Australia (Rengasamy 2002).

### Effect of Burial Depth on Germination

The effect of seed burial depth on seedling emergence of *S. arvensis* was conducted in a greenhouse at the University of Queensland, Gatton, QLD. The soil used was a clay loam in texture with organic matter composition of 2.7% and a pH of 7.2. In each 10-cm-diameter plastic pot, 40 seeds were sown at the surface or a depth of 1, 2, 4, or 8 cm. The soil used in the experiment was passed through a 2-mm sieve and sterilized to avoid any contamination. Control pots without any added *S. arvensis* seeds were used to ensure the absence of *S. arvensis* seeds in the soil. Seedling emergence was counted at 35 d after planting.

### Statistical Analyses

All experiments in this study were conducted in a completely randomized design (factorial). All experiments were repeated in time and space, and each treatment had three replications. There was no significant difference between the two experimental runs, so the data were pooled before analysis. Data were analyzed using ANOVA, and the graphs were plotted using SigmaPlot (v. 13.0, SyStat Software, Point Richmond, CA 94804, USA). Where appropriate, means of treatments were separated using Fisher's protected LSD test at  $P = 0.05$ . The fitness of the selected model was determined using  $R^2$  values. Weather data for both locations were obtained from the Bureau of Meteorology, Australia (BOM 2021).

A three-parameter sigmoid model was fit to germination (%) obtained in the radiant heat and osmotic potential experiments. The model was:

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

where  $G$  is germination percentage at different radiant heat or osmotic potentials,  $a$  is the maximum germination (%),  $x_{50}$  is the radiant heat or osmotic potential required for 50% inhibition of maximum germination, and  $b$  represents the slope.

A three-parameter exponential decay model was fit to germination (%) at different NaCl concentrations. The model was:

$$G = a + G_{\max} \exp(-b * x) \quad [2]$$

where  $G$  is germination percentage at NaCl concentration  $x$ ,  $a$  is baseline parameter,  $G_{\max}$  is the maximum germination (%), and  $b$  represents the slope.

A three-parameter Gaussian model was fit to the seedling emergence values resulting from the seed burial experiment. The model was:

$$E = a * e\{-0.5 * [(x - b)/c]^2\} \quad [3]$$

The graph of a Gaussian is a bell curve shape. In the model,  $E$  is seedling emergence percentage at burial depth  $x$ ;  $a$  is the peak of the curve (i.e., maximum emergence);  $b$  is the center of the peak required to achieve maximum seedling emergence; and  $c$  is the width of the “bell.”

## Results and Discussion

### Effect of Temperature on Germination

An interaction between populations and temperature regimes was observed for germination of *S. arvensis* (Figure 1). Both populations behaved similarly in the germination studies, except at the highest temperature (35/25 C). At the highest temperature (35/25 C), germination in the Qld population was 17% higher than in the Vic population. Both populations had the lowest germination at 15/5 C, and highest germination for both was at 30/20 C. Germination of Qld and Vic populations increased from 24% to 81% and 32% to 80%, respectively, with an increase in temperature from 15/5 C to 30/20 C. Germination of the Qld population remained similar at 30/20 C and 35/25 C. However, germination of the Vic population decreased by 15% with the increase in temperature from 30/20 C to 35/25 C.

This study suggests that seeds of *S. arvensis* can germinate under a wide range of temperature conditions. It has been suggested that this ability allows these weeds to invade a greater range of environments (Burke et al. 2003). A recent study on a closely related winter weed, African mustard (*Brassica tournefortii* Gouan), indicated that this weed could germinate under a wide range of temperatures (15/5 C to 35/25 C) and had the highest germination at 30/20 C (Singh et al. 2021). The ability of the Qld population to maintain higher germination at 35/25 C revealed that the Qld population is relatively tolerant to high-temperature conditions compared with the Vic population.

The long-term (average of 29 yr) monthly mean maximum and minimum temperatures between November to March of the region from where the Qld population was collected ranged from 32.8 to 34.6 C and 19.5 to 22.3 C, respectively (Figure 2). Similarly, long-term monthly mean maximum and minimum temperatures between November to March of the region from where the Vic population was collected ranged from 24.1 to

29.3 C and 9.1 to 12.3 C, respectively (Figure 2) (seasons; BOM 2021).

These long-term temperature conditions indicate that surface seeds of the Qld populations following maturity faced a warmer environment compared with the Vic population. This could be the reason that the Qld population might have adaptive traits for greater germination under a warmer environment (35/25 C) compared with the Vic population. However, it is also quite possible that Qld population germinates earlier and can germinate in higher temperatures, too.

Previous studies on *B. tournefortii* revealed that populations from South Australia and Queensland reported different germination behavior due to different climatic conditions (Chauhan et al. 2006a; Singh et al. 2021). A recent study in Iran suggested a constant temperature of 20 C to be the most suitable temperature for *S. arvensis* germination (Lotfifar et al. 2014). Relatively high germination of *S. arvensis* at 30/20 C in the present study suggests that this winter-season weed may be more adapted to the summer season in Australia and may increase its invasion in summer crops in the wake of climate change. Therefore, there is a particular need to study its growth and reproduction potential when this weed emerges in the summer or spring season. Previous studies suggested that winter annual weeds might germinate any time of the year under optimum moisture and temperature conditions (Baskin and Baskin 1998; Huang et al. 2001). Recently, rigid ryegrass (*Lolium rigidum* Gaudin), a winter annual weed in Australia, was reported to become a problematic weed in cotton (*Gossypium hirsutum* L.) (CRDC 2018).

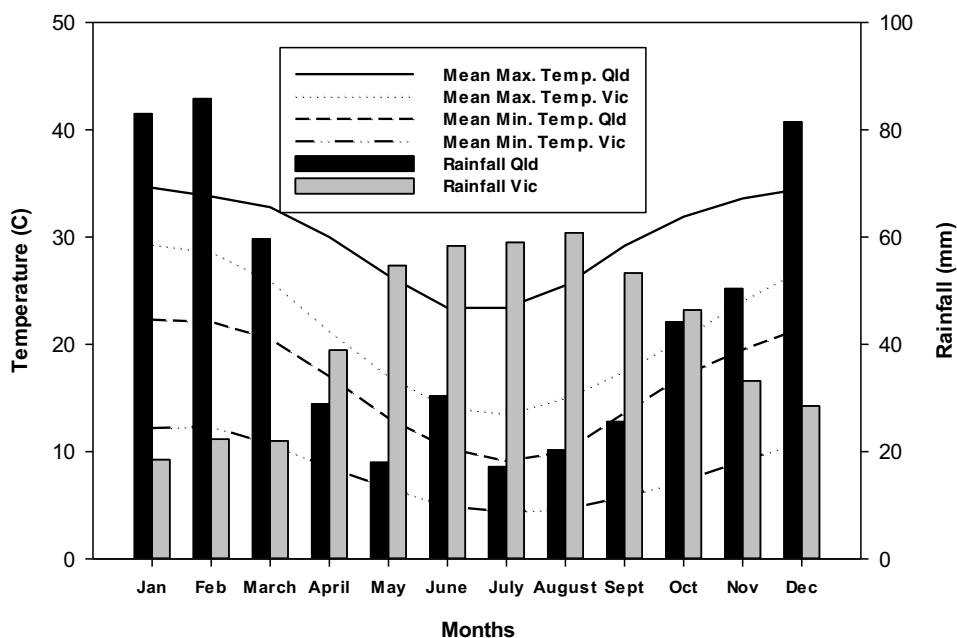
Reduced germination of *S. arvensis* at the lowest temperature regime (15/5 C) in the present study suggests that infestation of this weed can be reduced by adjusting the planting time of winter crops; however, implementation of this practice may depend upon the yield potential of the crop and competitive nature of the crop in the late planting season. Although weed infestation is low, it is likely that in late-season winter crops, due to the slow nature and weak competitive nature of the crop, weeds proliferate and produce a high number of seeds (P McIntosh, personal communication).

### Effect of Light on Germination

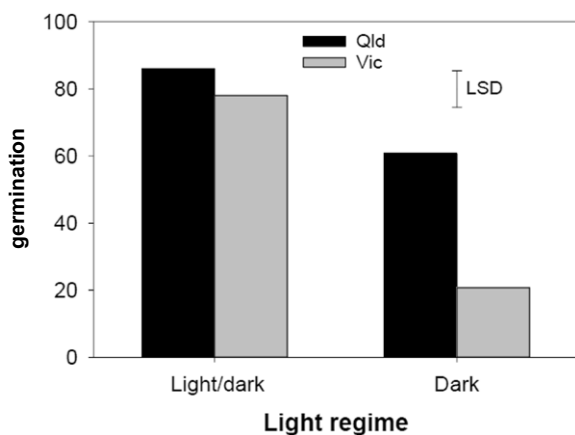
An interaction between populations and light/dark regimes was observed for germination of *S. arvensis* (Figure 3). Both populations had higher germination under light/dark regimes compared with complete darkness. Under light/dark regimes, both populations had similar germination. However, under the dark regime, the Qld population had higher germination than the Vic population. This suggests that Qld population germination in the field could occur even with the addition of crop residues in the field, unlike the Vic population. Differential germination responses of both populations under dark regimes could be due to genetic variants or adaptive traits among populations collected from various geographic or agroecological conditions. Some *Brassica* weeds, such as *B. tournefortii*, have a higher tendency to germinate under dark conditions compared with light/dark environments (Mahajan et al. 2018a; Singh et al. 2021).

### Effect of Radiant Heat on Germination

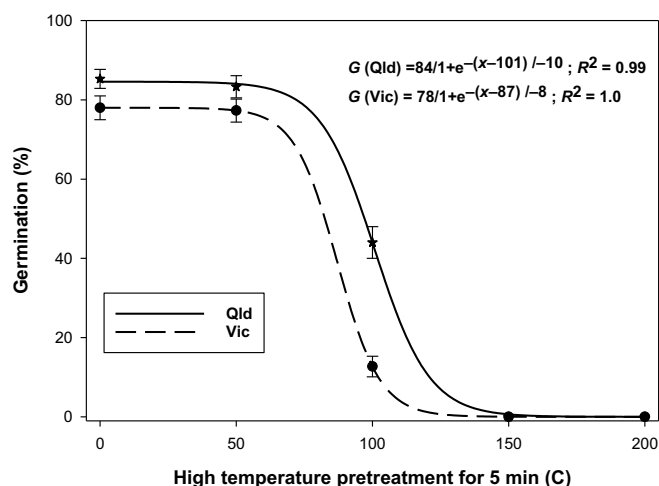
An interaction between population and radiant heat was observed for germination of *S. arvensis* (Figure 4). At pretreatment temperatures of 25 and 50 C, both populations behaved similarly for germination. However, at 100 C, the Qld population had higher



**Figure 2.** Mean monthly weather parameters of Capella, QLD, and Kaniva, VIC, locations where Qld and Vic populations were collected (average of 29 yr from 1992 to 2020).



**Figure 3.** Effect of light/dark regimes on the germination of two populations (Qld and Vic) of *Sinapis arvensis*. Seeds were incubated for 21 d at alternating day/night temperatures of 30/20 C. LSD at a 5% level of significance.



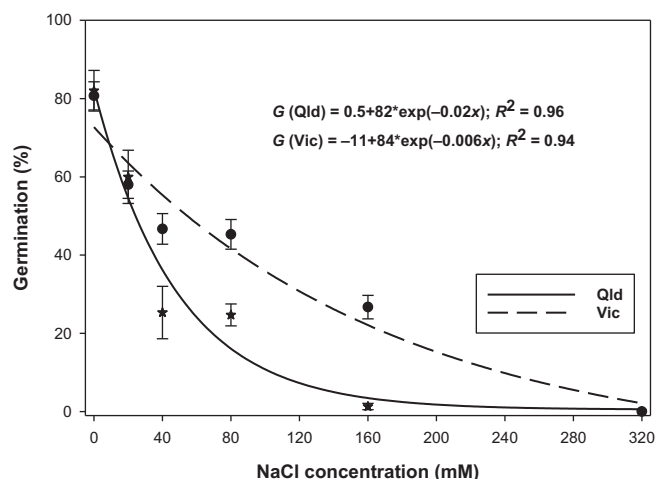
**Figure 4.** Effect of high-temperature pretreatment for 5 min (C) on the germination of two populations (Qld and Vic) of *Sinapis arvensis*. Lines represent a functional three-parameter sigmoid model. Error bars represent the standard errors of the means.

germination than the Vic population. Germination of both populations was nil at pretreatment temperatures of 150 and 200 C. The sigmoid relationship between germination and radiant heat treatments estimated that 50% of germination of the Qld and Vic populations was reduced at temperature (radiant heat) of 101 and 84 C, respectively (Figure 4). Higher germination of the Qld population compared with the Vic population at heat stress of 100 C suggests that the Qld population may be more tolerant to heat stress for short periods.

Germination of both populations was inhibited at 150 and 200 C, which suggests that burning may be a useful tool for managing *S. arvensis*, particularly when seeds are on the soil surface or at shallow depths (Willis et al. 2003). Exposure of seeds to fire could inhibit germination by desiccating the seed coat or by damaging the embryo (Baskin and Baskin 2014; Jeffery et al. 1988; Van de Venter and Esterhuizen 1988).

### Effect of Salt Stress on Germination

*Sinapis arvensis* seed germination was influenced by the interaction between population and salt concentration (Figure 5). In the control treatment and at a salt concentration of 20 mM NaCl, germination was similar between both populations. At 40, 80, and 160 mM NaCl, germination was lower for the Qld population than the Vic population. Germination of both populations was nil at 320 mM NaCl. At 160 mM NaCl, the Qld and Vic populations had 1% and 27% germination, respectively. At 80 mM NaCl, germination of Qld and Vic populations was reduced by 68% and 43%, respectively, compared with the control (Figure 5). The exponential decay model between seed germination and NaCl concentrations also predicted that germination of the Qld population with an increase in salt concentration was reduced to a greater extent compared with the Vic population (Figure 5). Soils are categorized



**Figure 5.** Effect of sodium chloride (NaCl) concentration on germination of two populations (Qld and Vic) of *Sinapis arvensis* at alternating day/night temperatures of 30/20 C under 12-h photoperiod. Seeds were incubated for 21 d. Lines represent a functional three-parameter exponential decay model. Error bars represent the standard errors of the means.

as salt affected if the total salt concentration in the soil exceeds 20 mM (Abrol et al. 1988). Therefore, both populations were found to be sensitive to the presence of salt. A previous study in South Australia revealed that germination of *B. tournefortii* was completely inhibited at 320 mM NaCl (Chauhan et al. 2006a).

These results suggest that both populations behaved differently with varying concentrations of NaCl. Higher germination of the Vic population between 40 to 160 mM NaCl concentrations in this study suggests that under saline soil conditions of Australia, the Vic population could thrive better and pose greater competition to crops compared with the Qld population. The differential germination response of populations at high salt concentrations might be due to genetic variation or adaption to localized climatic conditions (Dehnavi et al. 2020).

Ion toxicity and osmotic stress under high salt conditions could influence seed germination (Bliss et al. 1986). Previous studies revealed that increased levels of  $\text{Na}^+$  and  $\text{Cl}^-$  concentration under high salt concentrations could disrupt the seed germination process by restricting cellular activity, energy production, and uptake of essential macronutrients (Gupta and Huang 2014; Maathuis et al. 2014). In addition to that, osmotic stress in response to an increased salt concentration could alter water and nutrient uptake and hormonal and enzymatic activity in seeds and may lead to poor germination (Thiam et al. 2013). Therefore, germination inhibition at the highest salt concentration in the present study might be due to ion toxicity or osmotic stress.

The region where the Qld population was collected has annual mean maximum and minimum temperatures of 29.9 and 16.3 C (average of 29 yr), respectively; whereas, the region where the Vic population was collected has annual mean maximum and minimum temperatures of 21.2 and 16.3 C (average of 29 yr), respectively. Relatively low annual rainfall in the Vic region (495 mm) compared with the Qld region (544 mm) may create a favorable environment for high salt concentrations in soils of the Vic region. Therefore, saline conditions might be less likely to develop in Queensland compared with Victoria, suggesting that *S. arvensis* plants adapted under different soil and climatic conditions produce seeds that can withstand different environmental constraints.

### Effect of Osmotic Stress on Germination

*Sinapis arvensis* seed germination was influenced by the interaction between population and osmotic potential (Figure 6). The germination of both populations was similar in the control treatment. Germination of both populations was inhibited even at  $-0.1$  MPa. None of the populations germinated at  $-0.8$  MPa. At an osmotic potential of  $-0.4$  MPa, germination of Qld and Vic populations was reduced by 85% and 42%, respectively, compared with the control. The sigmoid model between seed germination and osmotic potential concentrations estimated that germination of the Qld and Vic populations was reduced by 50% at osmotic potential concentrations of  $-0.07$  MPa and  $-0.3$  MPa, respectively (Figure 6). The osmotic potential study suggests that the Vic population can tolerate high osmotic stress ( $-0.4$  MPa) and therefore has the ability to adapt to water-stressed environments.

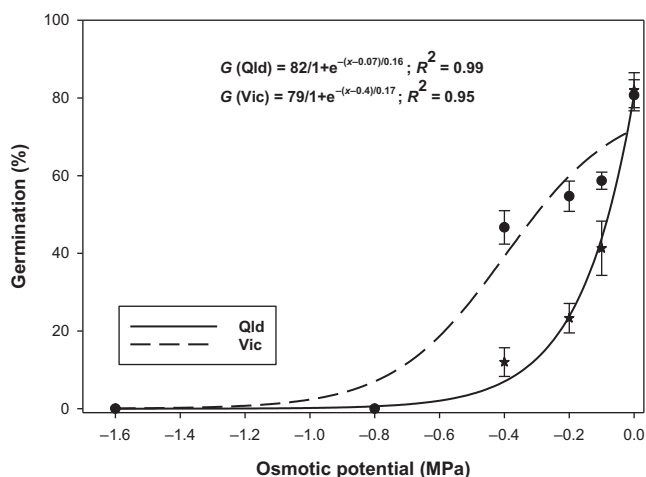
An increase in PEG concentrations might have harmed *S. arvensis* seed germination, as increased PEG concentrations could limit water availability, impose water stress, and inhibit the metabolic activity of the seeds. Previous studies suggested that seeds are unable to complete their metabolic activities for seed germination when they are unable to meet critical moisture threshold levels needed for imbibition (Bittencourt et al. 2017; Fenner and Thompson 2005).

These results indicate that good germination of *S. arvensis* may occur at relatively high levels of soil moisture conditions. Similarly, in a previous study, *S. arvensis* seeds were found to be sensitive to high water stress over  $-0.4$  MPa (Lotfifar et al. 2014). The Vic population was found to be relatively tolerant to water-stress conditions compared with the Qld population. Various authors have reported the sensitivity of some closely related weed species to osmotic stress for germination. For example, only 8% of *B. tournefortii* weed seeds germinated at an osmotic potential of  $-1.0$  MPa (Chauhan et al. 2006a). Similarly, 52% of seeds of London rocket (*Sisymbrium irio* L.) germinated at an osmotic potential of  $-1.2$  MPa (Ray et al. 2005). A recent study by Singh et al. (2021) revealed that populations of *B. tournefortii* also behaved differently with respect to germination in response to osmotic stress. Inhibition of germination under low water potential for the Vic population may enhance its survival mechanism by ensuring seed dormancy until favorable moisture conditions are available for successful germination (Fernando et al. 2016).

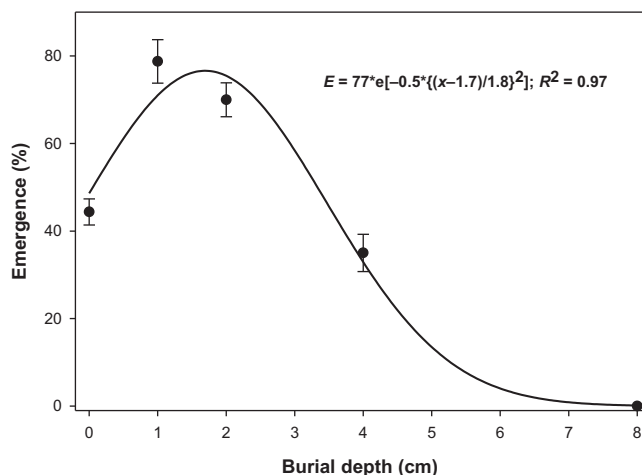
### Effect of Seed Burial Depth on Emergence

Both populations behaved similarly for emergence when sown at different seed burial depths. Emergence in pots was lower than seed germination in petri dishes, which could be due to the better contact of seeds with water in the petri dishes. Averaged over populations, emergence was highest (52%) at a burial depth of 1 cm (Figure 7). Emergence was 29%, 46%, and 23% on the surface and at 2- and 4-cm depths, respectively. No emergence of *S. arvensis* was recorded from the 8-cm depth. The gaussian relationship between seedling emergence and seed burial depths estimated that the maximum (peak) seedling emergence of *S. arvensis* was 77% and the center of the peak was at a burial depth of 1.8 cm (Figure 7).

In this experiment, seedling emergence was found to be highest at 1 cm. Contrary to this, in an earlier study from Turkey, the highest germination of *S. arvensis* seeds was recorded on the soil surface, and emergence was reduced at 5 cm and deeper (Mennan and Ngouajio 2006). The differential results in both studies are far more likely related to experimental conditions or due to genetic variation or adaption to localized climatic conditions (Dehnavi et al. 2020).



**Figure 6.** Effect of osmotic potential on germination of two populations (Qld and Vic) of *Sinapis arvensis* at alternating day/night temperatures of 30/20 C under 12-h photoperiod. Seeds were incubated for 21 d. Lines represent a functional three-parameter sigmoid model. Error bars represent the standard errors of the means.



**Figure 7.** Effect of seed burial depth on seedling emergence of *Sinapis arvensis*. Data were pooled over the two populations (Qld and Vic). Lines represent a functional three-parameter Gaussian model. Error bars represent the standard errors of the means.

Our results are in line with the earlier study of Chauhan et al. (2006a) on a closely related weed, *B. tournefortii*, that revealed no emergence from 5 cm or deeper soil depths. The results of the burial study revealed that shallow burial of seeds or mulching in the conservation agriculture system could increase the emergence of *S. arvensis*. This could be due to better soil moisture–seed contact. With increased soil depth, seedling emergence of many small-seeded weeds was reported to be decreased (Mahajan et al. 2018b; Manalil et al. 2018; Singh et al. 2021), as carbohydrate reserves are unable to support the emergence of the seedlings of small-seeded species from greater depths (Teasdale et al. 1991). Our results indicated that *S. arvensis* could be a problematic weed in no-till or under shallow-tillage situations.

Deep tillage (>4 cm) could reduce emergence; therefore, inversion tillage and preventing seed production of new plants could be a weed management strategy under high infestation conditions. It has been reported that the emergence of small-seeded weeds is reduced with increased burial depth, as soil–gas exchange is limited

and light is unable to reach the deeper layers of soil (Benvenuti 2003). However, it is important to consider other parameters, like weed seed longevity, when planning to use tillage as a management tool. As *S. arvensis* has been reported to remain viable for up to 60 yr (Mulligan and Bailey 1975), tillage operations can bring buried seeds back to the soil surface and potentially increase infestation by increasing seed germination near the surface.

In summary, *S. arvensis* seeds germinate over a wide range of environmental conditions; and the Qld population was more tolerant to high-temperature and heat conditions compared with the Vic population. The Qld population had higher germination in the dark environment compared with the Vic population. Seed germination of *S. arvensis* was affected by osmotic stress, suggesting that the conservation agriculture system may stimulate the emergence of this weed by conserving soil moisture. The Vic population was found to be relatively tolerant of water- and salt-stress conditions. Therefore, the Vic population of *S. arvensis* may compete better than the Qld population with the crops in problematic soils and under water-stress situations. The emergence of *S. arvensis* was greatest from the shallow depth (1 cm), and seedlings did not emerge from >4-cm soil depths. If a large weed seedbank accumulates on the soil surface under no-till systems, inversion tillage could bury most seeds below the maximum depth of emergence. However, knowledge of seed longevity of populations under different climatic conditions is required for strategic tillage, as inversion tillage operations could return viable seeds to the soil surface.

Differential germination behaviors of both populations for temperature, light, radiant heat, water stress, and salt stress suggest that populations of *S. arvensis* may have undergone differential adaptation. However, this is not clear, as the differences could be due to climatic conditions or genetic diversity, because this species cross-pollinates. Various models for predicting future climate change in Australia have revealed that frequent droughts with rising temperatures are predicted for the arid regions of eastern Australia (Nguyen et al. 2017). Therefore, it is expected that populations of *S. arvensis* that have tolerance for abiotic stress (e.g., the Vic population) may invade and spread to larger areas in Australia in the wake of climate change.

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