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Influence of Various Environmental Factors on Seed Germination and Seedling Emergence of a Noxious Environmental Weed: Green Galenia (*Galenia pubescens*)

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Green galenia is a South African woody prostrate perennial that was first recorded in Australia in the early 1900s and has since become a serious threat to indigenous temperate grasslands and surrounding agricultural areas. Laboratory and field based experiments were conducted to examine the effect of environmental factors on the germination and viability of green galenia seed. It was shown that green galenia was able to germinate over a broad range of temperatures, but short bursts (5 min) of high temperatures (80 C to 120 C replicating possible exposures to a fire) reduced seed germination. Seed germination was positively favored by light, declined rapidly in darkness, and decreased by $>$ 80% at a depth of only 0.5 cm in soil. Water stress greatly reduced seed germination (45% germination at osmotic potentials below –0.2 MPa). Germination was completely inhibited at water potentials of –0.4 to –1.0 MPa. This species is moderately tolerant to salinity, with over 50% of seeds germinating at low levels of salinity (60 mM NaCl), and moderate germination (49%) occurring at 120 mM NaCl, it can germinate well in both alkaline (pH 10 – 83%) and acidic (pH 4 – 80%) conditions. The results of this study have contributed to our understanding of the germination and emergence of green galenia, and this will assist in developing tools and strategies for the long term management of this noxious weed in Victoria and other parts of Australia.

Nomenclature: Green galenia, *Galenia pubescens* (Eckl. & Zeyh.) Druce.
Key words: Germination, osmotic potential, planting depth, smoke water, temperature.

Green galenia is a woody, prostrate perennial weed belonging to the Aizoaceae. This species is native to South Africa (Arnold and De Wet 1993), but has become established in other regions such as California (Ross 1994), southern Spain (García-de-Lomas et al. 2010), central Chile (Leuenberger and Eggli 2002), and various states and territories in Australia (Prescott and Venning 1984; Cook 2013). Green galenia was first identified in Victoria at Corio Bay near Geelong on the Victorian Basalt Plains in 1901 and has now spread widely throughout this ecosystem (Atlas of Living Australia). In Australia, green galenia is considered a serious threat to native vegetation, particularly dry coastal vegetation, lowland grassland, grassy woodland, dry sclerophyll forest, and rock outcrop vegetation (Carr et al. 1992). Green galenia is reportedly tolerant to fire and a wide range of climatic and salinity conditions (Kleinkopf et al. 1976).

Green galenia control programs have been unsuccessful in the past, primarily due to the extensive distribution of the species, and its capacity to produce abundant seeds, which persist in the soil for long periods of time (García-de-Lomas et al. 2010). The proliferation of this species in temperate native grasslands in Australia is likely to be related to aggressive seedling emergence and the difficulty associated with reducing seed bank. Understanding the factors that lead to a reduction of galenia seed viability is important for the development and implementation of effective control strategies.

A variety of environmental factors influence seed germination in weeds, including temperature, light, moisture, fire (temperature and smoke), salinity, soil acidity, and depth of seed burial. These factors can affect seed germination separately or jointly (Chauhan et al. 2006; Florentine et al. 2006; Koutsovoulou et al. 2014). Of these, temperature and light are the most important environmental signals regulating seed germination and subsequent survival and

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distribution of weed species (Florentine et al. 2006; Javaid and Tanveer 2014). Temperature plays a major role in determining the periodicity of seed germination and the distribution of species (Baskin and Baskin 1998), especially when factors such as moisture, salinity, and acidity are not limiting (Martinkova et al. 2006). Temperature also can affect the percentage and rate of germination through its effects on seed viability (deterioration, loss of dormancy) or by directly affecting the germination process (Kebreab and Murdoch 1999).

Light is also an important requirement for germination for some species. Some species are insensitive to changes in light levels while others are inhibited by any exposure to light during germination (Carta et al. 2014). The response of seeds to light also can control the timing of germination, and can be a crucial factor in the survival of resulting seedlings, and their growth and fitness in subsequent life stages (Pons 2000).

In Australia, surface fire has been used for many years as one of the options to control invasive species. In particular, prescribed fire events have been used widely to manage invasive weeds in Australian grassland ecosystems (Goergen et al. 2006; Morgan 1999, 2001; Russell-Smith et al. 2000). Thus, fire initially was thought to be an important management tool for containing green galenia and maintaining healthy grasslands on the Victorian Volcanic Plains (Morgan 1999). Fire increases the surface temperature of the soil matrix and produces significant levels of smoke, and these two components, either separately or together, may serve as germination cues or significantly affect the activity of weed seed banks (Clarke and French 2005; Gashaw and Michelsen 2002; Tieu et al. 2001; Wright and Clarke 2009). In this respect, smoke has been acknowledged widely as a key agent in the release of seed dormancy and may interact positively with heat to promote this release (Smith et al. 1999). De Lange and Boucher (1990) investigated plant-derived smoke as a germination cue and found that smoke products can stimulate germination in many South African species.

Depth and duration of burial also have an impact on germination, dormancy, and the viability of seeds (Bebawi et al. 2015; El-Keblawy 2014). Understanding the factors that relate to seed burial and survival is essential, because only the seeds close to the soil surface are generally able to germinate and emerge (Grundy et al. 2003).

Moisture stress and salinity also affect seed germination. Water is a basic requirement for germination, because it is essential for enzyme activation, breakdown, translocation, and use of reserve storage material (Beyranvand et al. 2013). Water limitation may delay, reduce, or prevent germination and later have an effect on the growth of the plant (Javaid and Tanveer 2014). Related to this, salinity stress affects seed germination either through dehydrating osmotic effects, by biologically preventing or delaying germination, or through ion toxicity, which can render the seeds unviable (Huang and Redmann 1995).

Seed germination also can be affected by soil pH. Whilst the response of plants to different pH values varies among species, many plants only can tolerate a pH range between 5 and 10. Beyond this range, high concentrations of ions can be directly toxic to plants. Recent work has shown, however, that there are some weeds that may germinate over a broad range of pH values. For example, seeds of sicklepod [*Senna obtusifolia* (L.) H.S. Irwin & Barneby] germinated at pH 3 to 10 (Norsworthy and Oliveira 2006), and seeds of eclipta [*Eclipta prostrata* L. (L.) and spiny emex [*Emex spinosa* (L.) Campd.] could germinate over a range of pH 4 to 10 (Chauhan and Johnson 2008a; Javaid and Tanveer 2014).

A deeper understanding of the effect of environmental factors on seed germination in green galenia is needed to help develop suitable and cost-effective weed control options (Koutsovoulou et al. 2014). Information about how these factors affect germination of this species may help to prevent its invasion into new areas. Results also may assist in the development of control strategies for other weed species with similar ecological characteristics. Therefore, the objectives of this study were: (1) to investigate the effects of temperature, light, heat, smoke, burial depth, water stress, salinity, and pH on germination and seedling emergence, and (2) to examine the seed viability of green galenia under field conditions.

Materials and Methods

Seed Collection and Processing. Mature seeds of green galenia were collected from over 300 mature plants in the Werribee region (37° 49′ 5.63″ S 144° 34′ 58.77″E) at an altitude of 66 m, near Ballan Road, southeast of the Werribee River, Victoria, Australia during October 2013. Seeds were considered matured when the capsule turned brown. Uncleaned seeds were placed in a labelled bag and taken to the Ballarat Campus of Federation University Australia, and stored at room temperature (16 to 27 C) and at a relative humidity from 30 to 50% until use.

Seeds of green galenia were surface-sterilized by rinsing in 1% w/v sodium hypochlorite for 1 min, and then washed clean with double-distilled water before the start of each germination trial. Germination tests were conducted by placing 25 seeds evenly in a 9-cm diameter Petri dish lined with Whatman® No. 10 filter papers, and moistened with 5 ml sterile distilled water or a treatment solution to ensure adequate moisture for the seeds. The Petri dishes containing the seeds were then placed in seed germination cabinets (Thermoline Scientific and Humidity Cabinet, TRISLH-495-1-SD, Vol. 240, Australia), which were equipped with cool-white fluorescent lamps that provided a photosynthetic photon flux of 40 μmol m^{-2} s^{-1} (cool white Philips 18 W/840 at 60 μmol m^{-2}) lighting. Daily observations were made under a green safe light for a period of 30 d from the date of sowing. Seeds were considered germinated when the radicle was approximately 2 mm long and cotyledons had emerged from the seed coat (Ferrari and Parera 2015). Nongerminated seeds were checked for viability using the 2,3,5-triphenyltetrazolium chloride (TTC) test (Saatkamp et al. 2011; Waes and Debergh 1986).

Effects of Temperature and Photoperiod. The effects of temperature on seed germination were investigated by exposing the seeds to three alternating temperature regimes (17/7, 20/10, and 30/20 C) under two photoperiods of 12/12 h light/dark and 24 h of continuous darkness. Four replicates of 25 seeds of each treatment were used. These temperature regimes were selected to reflect temperature variations during the period of spring to winter in Victoria. The dark treatment was achieved by covering Petri dishes with a double layer of aluminium foil.

Effects of Heat and Smoke Water. To examine the effects of fire on seed germination, groups of seeds were exposed to four levels of heat-shock and two concentrations of smoke water. All seeds in this experiment were kept initially at the 17/7 C temperature regime and 12/12 h light/dark photoperiods. These were found to be the optimum conditions for germination of green galenia seeds in a previous trial. To apply heat shock, dry seeds were placed in a preheated convection oven for 5 min and then returned to the 17/7 C and 12/12 h temperature and photoperiod regimes. Seeds in the unheated control group were not placed into the oven. The following temperatures were used: (1) control treatment, no heat; (2) 40 C (simulating a hot day in summer), (3) 80 C (simulating a cool burn, such as a prescribed burning operation), and (4) 120 C (simulating heat from an intense wildfire).

Smoke treatments were conducted using commercially available aqueous smoke water, which is produced by Grayson Australia, a smoke-flavoring company in Australia, by burning eucalyptus wood and concentrating the smoke in aqueous solution (Read et al. 2000). A 10% solution of this smoke water was used (Tieu et al. 2001). After the heat treatment, half of the treated seeds were soaked in 25 ml of distilled water, and the other half were soaked in 25 ml of 10% smoke water solution for 2 min at room temperature. These seeds were then divided into four replicates of 25 seeds of each treatment and placed in Petri dishes. Each Petri dish received 10 ml respective solution and incubated at 17/7 C temperature under 12:12 h light and dark photoperiods. Seeds were checked daily for physical changes and the matrix moistened when necessary.

Effects of Seed Age and Field Burial on Seed Germination. To examine the seed viability of green galenia under field conditions, a 1-yr seed burial experiment was established at the ex-grassland reserve near southeast Werribee-River, Victoria, Australia during December 2013. This site was heavily infested with green galenia. A total of 24 stainless steel mesh envelopes (135 by 95 mm) were used to create conditions close to natural soil conditions (water and air diffusion and microorganisms). Each envelope contained 25 firm cleaned seeds of green galenia and was buried in the field and covered with 4 cm of surface soil. The site of each buried envelope was marked with a small metal marker and recorded with GPS for easy relocation. Four seed envelopes were exhumed approximately every 3 mo (from January 4, 2014, to January 4, 2015) for germination and viability testing. Control seeds were kept at room temperature until use. For this experiment, four replicates of 25 seeds were used.

Effects of Depth on Seedling Emergence. The impact of seed burial depth on seedling emergence was examined. Soil used for this trial was brought from the study site and sterilized to kill any viable seeds. Plastic pots (10 cm by 6 cm by 6 cm) were filled with sterilized sandy soil to a depth of 1 cm to allow soil moisture movement and aeration. This was then lined with paper towel and the pot was filled with the sterilized field collected soil. Fifty seeds of green galenia were placed at 0, 0.5, 1, 2, 3, 4, and 5 cm depths of the sterilized field collected soil, using three replicates for each depth in separate pots. Pots were placed into large trays (28 cm by 44 cm by 5.5 cm) to facilitate watering from below to ensure minimal disturbance of seed samples. The positions of pots within the growth chamber were changed every second week to reduce environmental bias. Trays were regularly placed in water so that soil was moist but not flooded. All the trays were placed in a growth chamber set at 17/7 C temperature under 12/12 light and dark photoperiods. A seedling was considered to have emerged when the cotyledons were visible at the soil surface (Amri 2010; Ren et al. 2002). Daily observations and counts were made of seedling emergence then removed, with the final counts being made after the last emergence of new seedlings.

Effect of Salinity Stress on Seed Germination. Sodium chloride (NaCl) treatments using 10-ml aliquots of the treatment solution were applied to 25 seeds on each Petri dish. NaCl solutions were applied at 0, 0.01, 0.05, 0.25, 1.25, 2.5, and 6.0% concentrations. All 10-ml aliquots were dripped directly onto the seeds. Petri dishes were incubated at 17/7 C alternating temperature and 12/12 h light/dark. Petri dishes were rotated within the cabinet every second day. This range of NaCl was selected to reflect the level of salinity occurring in typical Australian disturbed soils (Chauhan et al. 2006). Germination of green galenia seeds were determined for a period of 30 d.

Effect of Osmotic Stress on Seed Germination. To investigate the effect of drought stress on seed germination, green galenia seeds were tested for germination in 10-ml aqueous solutions of polyethylene glycol (PEG) with an average molecular weight of 8,000, prepared to obtain osmotic potentials of 0, −0.1, −0.2, −0.4, −0.6, −0.8, and −1.0 MPa by dissolving 0, 90, 126.8, 179.2., 219.6, 253.6, and 283.5 g, respectively, of polyethylene glycol 8000 (Sigma-Aldrich Co., 3050 Spruce St., Louis, MO 63103) in 1 L of distilled water (Michel 1983). Three replicates of 25 seeds of green galenia, at each level of PEG, were incubated at 17/7 C (day/night) under 12/12 h light and dark in Petri dishes as described above. Germination of seeds was determined for a period of 30 d.

Effect of pH on Seed Germination. The effect of pH on seed germination was examined by using buffer solutions with pH values 4, 5, and 6 (to simulate an acidic medium), 7 (neutral), and 8, 9, and 10 (to simulate an alkaline medium) with distilled water (pH 6.3) as a control. The solutions were prepared according to the method as described by Chauhan et al. (2006) using potassium hydrogen phthalate, and were adjusted to pH 4 with 1 N hydrogen chloride (HCl). A 2-mM solution of MES [2-(N-morpholino) ethanesulfonic acid] was adjusted to pH 5 and 6 with 1 N sodium hydroxide (NaOH). A 2-mM solution of HEPES [N- (2-hydroxymethyl) piperazine- N- (2-ethanesulfonic acid)] was adjusted to pH 7 and 8 with 1 N NaOH. The pH 9 and 10 buffers were prepared with 2-mM tricine [N-Tris (hydroxymethyl) methylglycine] and adjusted with 1 N NaOH. Petri dishes were incubated at 17/7 C (day/night) temperature cycles under 12/12 h light and dark photoperiods as described earlier. The pH treatments were applied using approximately 10-ml aliquots of the treatment solution directly to 25 seeds on each Petri dish. All aliquots were dripped directly onto the seeds. Petri dishes were incubated at 17/7 C alternating temperature and 12/12 h light/dark lighting. Petri dishes were rotated within the cabinet every second day. Germination of seeds were determined for a period of 30 d. All experiments were arranged in randomized complete block design. Each replication was arranged on different shelves in the cabinet and considered as block.

Statistical Analyses. At the end of these trials, the final germination percentage (FG %), viability adjusted germination (VAG %) were calculated:

$$\mathrm{FG\%} = \frac{\mathrm{SG}}{\mathrm{TS}} \times 100, \qquad [1]$$

where SG is the total number of seeds germinated and TS is the total number of seeds planted (Wang et al. 2009).

$$\mathrm{VAG} = \frac{\mathrm{FG\%}}{\mathrm{viability\%}} \times 100, \qquad [2]$$

where FG% is the final germination percentage and *viability %* is the percentage of alive seeds with (TTC) (Jefferson et al. 2008).

Germination (%) values at different concentrations of NaCl and osmotic potential were fitted to a three-parameter logistic model. The model fitted was

$$\mathrm{FG}(\%) = G_{\max}/[1 + (x/x_{50})g], \qquad [3]$$

where FG% is the final germination (%) at concentration x, $G_{\max}$ is the maximum germination

(%), x_{50} is the NaCl concentrations or osmotic potential for 50% inhibition of the maximum germination and g indicates the slope.

A three-parameter logistic model:

$$E(\%) = E_{max}/[1 + (x/x_{50})e], \qquad [4]$$

was fitted to the seedling emergence (%) obtained at different burial depths, where E represents the seedling emergence (%) at burial depth x, E_{max} is the maximum seedling emergence, and e indicates the slope.

Two-way ANOVA was used to assess the effect of the various factors on FG%. FG% were tested for normality using the Shapiro-Wilk test (alpha = 0.05) prior to the ANOVA, while homogeneity of variance was assessed using the Brown-Forsythe test. Data were analyzed using SigmaPlot13 (Systat Software, Inc., Point Richmond, CA). All the experiments were repeated (except for the seed age and field burial experiment) and the data were combined from the two repeated experiments.

Results and Discussion

Effects of Temperature Regime and Photoperiod. A two-way ANOVA showed that light regime had a significant effect on the VAG ($F = 76.580$, $P < 0.01$), while no effect was detected for temperature ($F = 1.900$, $P = 0.350$) or any interaction between light and temperature ($F = 2.720$, $P = 0.091$). The data were subsequently pooled to perform a one-way ANOVA. Seeds of green galenia germinated in light at all temperatures tested with 86, 78, and 81% germination at 17/7, 20/10, and 30/20 C, respectively. Germination was 34, 51, and 30% at temperature regimes of 17/7, 20/10, and 30/20, respectively, in the 24-h dark cycle. Greater than 90% of seeds of green galenia were viable for all temperature regimes when the photoperiod was 12/12 h light/dark.

Germination under alternating light and dark cycles was greater than in continuous darkness. A similar effect has been reported for other invasive species (Amri 2010; Çirak et al. 2004; Florentine et al. 2006). The results of this study imply that the seeds of green galenia are light dependent. Greater germination of green galenia seeds in light suggests that its germination and subsequent emergence in the field will be favored by the presence of seeds at, or near, the soil surface. Our results are similar to those of Chauhan et al. (2006), who found that annual sowthistle (*Sonchus oleraceus* L.) had greater

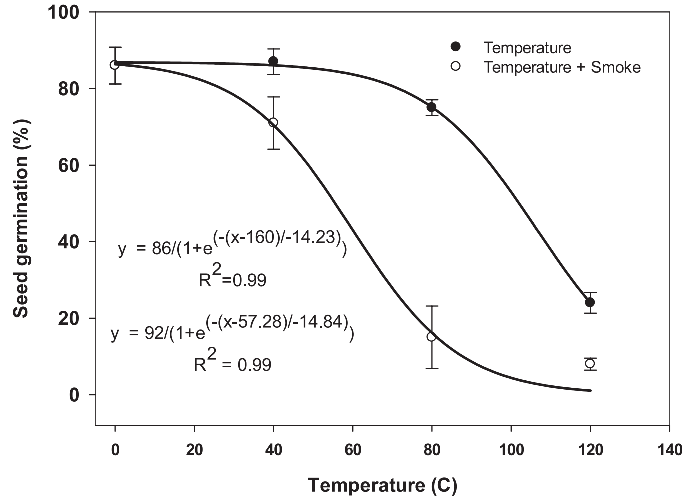

Figure 1. Effects of temperature and effects of temperature + smoke on seedling emergence of green galenia. The bold line represents Sigmoid, three-parameter model fitted to the data. Vertical bars represent ± standard error of the mean.

seedling emergence under a no-till system as compared with the system that buried seeds deeper in the soil.

Green galenia forms large circular prostrate mats under which seeds tend to accumulate. Once the branches die, seeds accumulated on the surface of the soil are exposed to light, and when conditions are suitable, many viable seeds germinate.

The ability of green galenia seeds to germinate at various temperature regimes ranging from 17/7 C to 30/20 C may explain why this species germinates successfully and subsequently becomes established in a wide range of environmental conditions in Australia and other parts of the world.

Effects of Heat and Smoke Water. Equation 3 was fitted to examine the final germination (%) when seeds were exposed to different temperature regimes (Figure 1). Green galenia seed germination declined from 86 to 24% when the temperature was increased to 120 C.

A three-parameter sigmoid model was fitted to the germination values (%) observed when the seeds were exposed to similar heat and 10% v/v smoke water (Figure 1). The seed germination was reduced from 87 to 8% when exposed to both 120 C heat and smoke water.

Fire has been used as a control tool for managing weeds in Australia (Read et al. 2000; Russell-Smith et al. 2000; Tieu et al. 2001). Field observations also show that a large number of green galenia seeds are confined to the surface layers of the soil, but these seeds are generally covered with the thick foliage cover of the mature green galenia plants.

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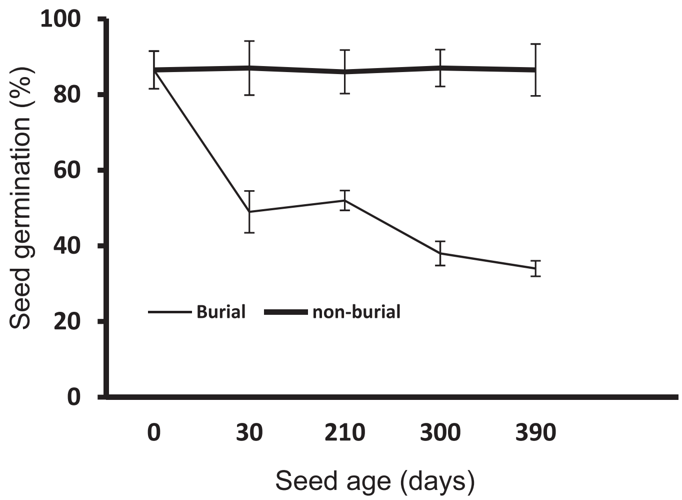

Figure 2. Effects of dry storage and field burial on germination of green galenia seeds. Vertical bars represent ± standard error of the mean. LSD for the nonburial and burial seed was 12.89 and 12.4, respectively.

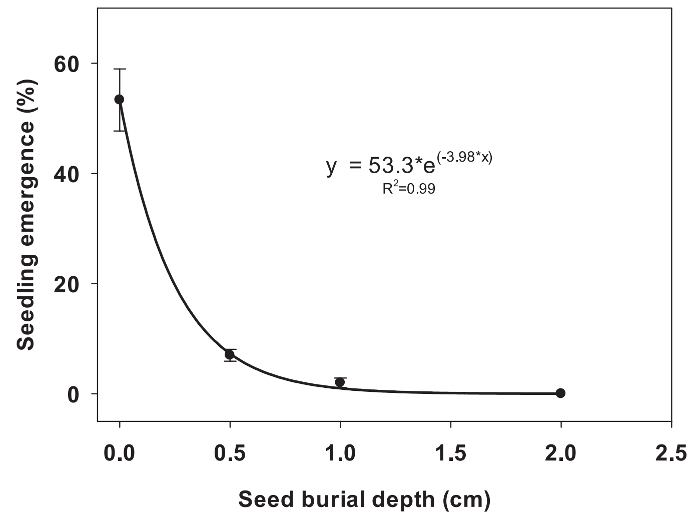

Figure 3. Effects of burial depth on seedling emergence of green galenia. The bold line represents an exponential decay, single, two-parameter model fitted to the data. Vertical bars represent ± standard error of the mean.

Based on the results, a combination of high temperature fire and smoke could be used to kill mature plants and reduce the viability of seeds stored in the surface soil. Other studies have shown that heat shock from fire negatively affects germination of weed seeds, either by desiccating the seed coat (Brits et al. 1993; Jeffery et al. 1988), or by directly damaging the embryo (Van de Venter and Esterhuizen 1988).

The findings of the present study show that although seeds located on the soil surface may be destroyed by high temperatures and combinations of high temperatures and smoke, any seeds located in deeper soil layers may escape the heat-shock, particularly in the case of a less severe fire (Todorović et al. 2010). Such seeds may remain viable until brought to the soil surface by various factors such as soil erosion. This implies that if fire is used as a tool to control green galenia, additional tactics to control green galenia would be essential. Establishment of rapidly growing native species should occur either by broadcasting seeds or planting seedlings to develop a rapidly closing canopy that can prevent the subsequent germination and reestablishment of green galenia.

Effects of Duration of Field Burial on Seed Germination. The overall germination percentage of the seeds declined with duration of burial compared with (control) seeds that were not buried (Figure 2). The germination of fresh seeds before burial was over 90%. This declined to less than 50% in the first 30 d of burial (4 cm) and to 39% after 1 yr. In contrast, for seeds stored in dry conditions (not buried), the germination was 87% in the first 30 d and remained at the same percentage for up to 1 yr. The outcomes of this study indicate that, after 1 yr of burial, the median proportion of buried viable, nongerminated seeds ranged from 35 to 55%. Our results are similar to those of Bouwmeester and Karssen (1992) and Wijayratne and Pyke (2012) who demonstrated that buried seeds of ladysthumb (*Polygonum persicaria* L.) and big sagebrush (*Artemisia tridentata* Nutt.) lost viability with increasing duration of burial. This suggests that in undisturbed conditions, the problem of green galenia may be reduced in the long-term, if new seeds are not added to the seed bank. However, the relatively slow decrease in seed viability from 30 d to 1 yr suggests that it may have a very long-lived seed bank (Figure 2). This invasive weed is likely to remain problematic under field conditions due to the very large number of seeds it produces.

Effects of Depth on Seedling Emergence. Seedling emergence of green galenia decreased with increased planting depth (Figure 3). Seedling emergence was greatest (53%) for seeds placed on the soil surface and considerably decreased as planting depth increased from 0.5 to 1 cm. No seedlings emerged from seeds placed at the depths of 2 cm or greater.

Greater seedling emergence for seeds positioned on the soil surface is consistent with the positive effects of light on germination, and lower seedling emergence due to increasing depth of burial has been reported in several weeds (Chauhan and Johnson 2009; Tang et al. 2015). Light penetration is generally limited to the first few millimetres of the

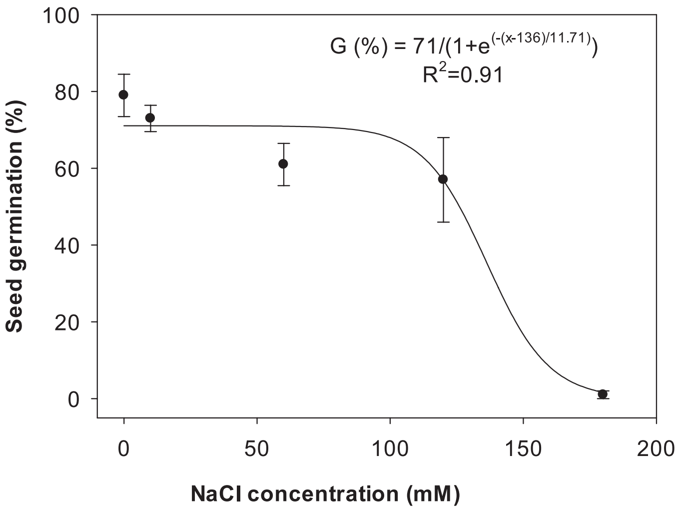

Figure 4. Effect of sodium chloride (NaCl) concentrations on seed germination of green galenia. The bold line represents a three-parameter logistic model fitted to the data. Vertical bars represent ± standard error of the mean.

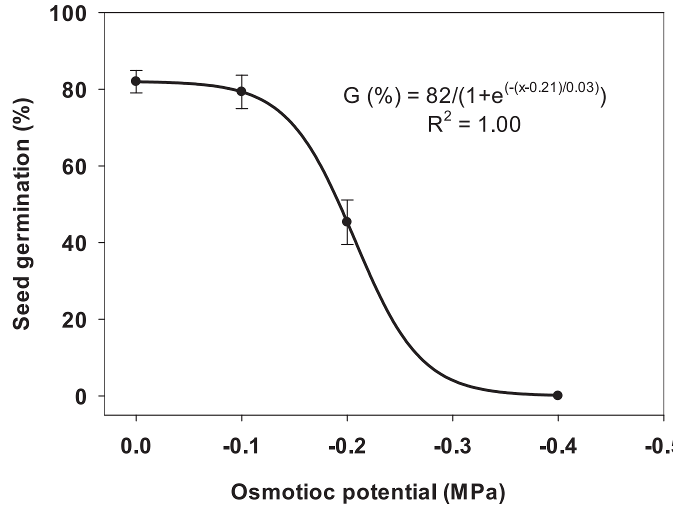

Figure 5. Effect of osmotic potential on seed germination of green galenia. The bold line represents a three-parameter logistic model fitted to the data. Vertical bars represent ± standard error of the mean.

soil (Woolley and Stoller 1978) and because of this species' requirements for light, limited light penetration is considered to be the most likely reason for the observed low emergence of buried seeds. However, the fact that some seeds (4%) buried at 1 cm depth did emerge (Figure 3) suggests that additional factors might be responsible for the lack of emergence of deeply buried seeds. The presence of CO_2 deriving from soil biological activity also might be implicated (Benvenuti et al. 2001), and given that green galenia seeds are physically small (< 1 mm), a lack of energy to push through the soil layers (Milberg et al. 2000) may play a role in low emergence of seeds buried at greater depths.

Effect of Salinity Stress on Seed Germination. Equation 3 was fitted to the final germination values at different concentrations of NaCl (Figure 4). The highest germination (83%) occurred in the control treatment (no stress) and germination declined to 71 and 55% with increasing concentrations of NaCl from 10 mM to 60 mM. Germination was less than 50% at 120 mM NaCl and it was completely inhibited at 180 mM and higher concentrations of NaCl. The concentration of NaCl required for 50% inhibition of germination was 115 mM. Other invasive species such as the giant sensitive plant (*Mimosa diplotricha* C. Wright ex Sauville) had 50% inhibition of germination at 255 mM NaCl (Chauhan and Johnson 2008b). These outcomes suggest that even at high levels of soil salinity, green galenia seeds may germinate, and soils with such high levels are common in some parts of Australia (Chauhan et al. 2006). This weed trait allows green galenia to have a distinct advantage over other plants in high saline conditions.

Effects of Water Stress on Seed Germination. Equation 4 was fitted to the final germination at different osmotic potentials (Figure 5). Germination of green galenia decreased from 82 to 45% as osmotic potential decreased from 0 to –0.2 MPa, indicating that some seeds of green galenia can germinate under marginal water stress conditions. Germination was inhibited completely by osmotic potentials of –0.4 MPa or lower.

Effects of pH on Seed Germination. Green galenia seeds had greater than 70% germination over a pH range of 4 to 10. The highest percentages of final germination were 83% at pH 10 (alkaline medium) and 80% at pH 4 (acidic medium) (data not shown). This indicates that pH is not likely to be a limiting factor for germination of green galenia in most soil types in agricultural or nonagricultural areas of Australia. The ability to germinate over a wide range of pH values supports the view that green galenia is adapted to a wide range of soil conditions. This characteristic is common for many weed species such as nodeweed [*Synedrella nodiflora* (L.) Gaertn.] and spiny emex (Chauhan and Johnson 2009; Javaid and Tanveer 2014). Germination under a variety of soil conditions aids the ability of a weed to invade diverse habitats.

In summary, the results of this study indicated that seeds of green galenia can germinate under various environmental conditions. Germinating seeds of green galenia are not very tolerant to salinity and are sensitive to water stress. However, seeds germinated successfully over a broad pH range, which indicates that soil pH is not a limiting factor for germination of this species. Seed germination in green galenia was found to be stimulated by light, indicating that buried seeds are likely to remain in a dormant state until disturbed. Whilst seeds of green galenia were able to germinate over a broad range of temperatures, high temperatures, and high temperatures combined with smoke, reduced germination. This suggests that fire may be a useful tool in decreasing the seed germination of this invasive species, particularly for seeds stored in surface soil layers. This study identified a weakness in the life cycle of green galenia that land managers can exploit to effectively manage such exotic weeds. Commitment to follow-up control for the first few years following control of original infestations should be sufficient to diminish the seed bank to a negligible level. However, the elimination of localized infestations does not necessarily mean that the threat of green galenia is removed. There is a risk of reestablishment even if the local seed reserves are depleted and all mature plants are killed. A wide range of environmental conditions provide suitable environments for this species, which produces very large numbers of seeds that can quickly re-establish new populations over large areas.

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