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Seed Germination Ecology of Doveweed (*Murdannia nudiflora)* and Its Implication for Management in Dry-Seeded Rice

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This study was conducted in the laboratory and screenhouse to determine the effects of temperature, light, osmotic stress, salt stress, burial depth, use of crop residues as mulch, depth of flooding, and use of POST herbicides on the emergence, survival, and growth of doveweed. In the light/dark regime, germination was higher at alternating day/night temperatures of 35/25 C (95%) than at 30/20 C (72%), and no germination occurred at 25/15 C. Light strongly influenced germination (95%) and dark completely inhibited germination. No germination occurred at an osmotic potential of −0.8 MPa and a salt concentration of 150 mM and above. The highest germination (91%) was observed from the seeds sown on the soil surface and emergence decreased by 78, 86, and 92% when burial depths were increased to 0.5, 1, and 2 cm, respectively. No seedlings emerged from seeds buried at depths of more than 2 cm. The use of rice residues as mulch significantly reduced the emergence and growth of doveweed seedlings. The amount of residue required to suppress 50% of the maximum biomass was 2.5 t ha^{-1}. Flooding had a more pronounced effect on seedling biomass than seedling emergence. Biomass was reduced by 78, 92, and 96% when flooding depths increased from 0 to 2, 4, and 6 cm, respectively, for the seeds placed on the soil surface, whereas for the seeds buried at 0.5 cm, these values were 78, 100, and 100%. Bentazon (100 g ha^{-1}) and bispyribac-sodium (30 g ha^{-1}) provided 100% control of doveweed when applied at the three-leaf stage. Doveweed control was less than 31% with glyphosate rates up to 2,000 g ha^{-1}. The application of 2,4-D (500 g ha^{-1}) provided 100% control of doveweed even when applied at the seven-leaf stage. The information from this study could help in developing more sustainable and effective integrated weed management strategies for the control of this weed and weeds with similar response in dry-seeded rice systems.

Nomenclature: Bispyribac-sodium; bentazon; 2,4-D ester; glyphosate; doveweed, *Murdannia nudiflora* (L.) Brenan. MUDNU; rice, *Oryza sativa* L.

Key words: Depth, flooding, integrated weed management, light, POST, residue, stress, temperature.

Changes in the establishment method of transplanted rice to dry-seeded rice (DSR) in Asian countries have led to shifts in weed flora and resulted in more weed diversity (Ahmed et al. 2014; Chauhan and Johnson 2010; Singh et al. 2009; Tomita et al. 2003). This is true for doveweed, an invasive weed species that is considered a minor weed in transplanted rice systems but is becoming a more problematic weed in DSR (Chauhan and Abugho 2013b; Chauhan and Opeña 2012).

Doveweed has been considered the third worst weed of the Commelinaceae family since it reduces the economic yields of at least 16 crops (Holm et al. 1977; Wilson 1981), including cotton (*Gossypium hirsutum* L.), soybean [*Glycine max* (L.) Merr.], peanuts (*Arachis hypogaea L.*), tea [*Camellia sinensis* (L.) Kuntze], maize (*Zea mays* L.), banana (*Musa* sp.), citrus [*Citrus limon* (L.) Burm. f], sugarcane (*Saccharum spontaneum* L.), vegetables, rice, and coffee (*Coffea arabica* L.) (Baki and Khir 1983; Holm et al. 1977; Pancho and Obien 1995; Soerdarsan et al. 1974; Soerjani et al. 1987). In addition to reducing economic crop yields, doveweed is also a host of various crop pests and pathogens that have negative effects on crop growth and production. Among these pests are many phytophagous insects such as the plant hopper (*Nisia carolinensis*), which is common in rice fields, and the hairy caterpillar (*Diacrisia obliquais*), which feeds on the vegetative parts of crops (Satpathi 1999). Doveweed is also a host of the nematodes *Pratylenchus pratensis* and *Meloidogyne arenaria* (Valdez 1968), the fungi *Pythium arrhenomanes* (Sideris 1931) and *Rhizoctonia solani* (Galinato et al. 1999), and viruses such as the cucumber mosaic

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virus (Anonymous 1960), southern celery mosaic virus (King 1966), tomato mosaic virus, and clover yellow-vein virus (Baker and Zettler 1988).

It has been the practice of many farmers to use herbicides as the best economic and effective option to manage weeds in DSR systems (Mahajan and Chauhan 2013; Suria et al. 2011), especially in controlling the high weed infestation of doveweed. Usually, doveweed emerges later in the cropping season, thus escaping the efficacy of PRE herbicides (Wilson 1981). Therefore, POST herbicides are critical to control this weed species. Wilson (1981) also reported that bentazon applied as an early POST, either alone or in mixtures, was particularly effective in controlling doveweed, and triazines and 2,4-D were moderately effective when applied in mixtures. Bispyribac-sodium, bentazon, and 2,4-D are widely used POST herbicides in DSR systems since they control a range of grass, broadleaf, and sedge weeds. Glyphosate is commonly used in DSR systems as a preplant nonselective herbicide to control existing weeds in the field or after stale seedbed practice. The efficacy of herbicides in controlling weeds in DSR systems may also vary depending on the growth stage of the weed species, which influences the uptake and metabolism of the herbicides (Chauhan and Abugho 2012; Singh and Singh 2004). For example, the efficacy of bispyribac-sodium and fenoxaprop + ethoxysulfuron on barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], junglerice [*Echinochloa colona* (L.) Link], and southern crabgrass [*Digitaria ciliaris* (Retz.) Koel.] was reduced when these herbicides were applied at the eight-leaf stage compared with when applied at the four-leaf stage (Chauhan and Abugho 2012). Another example is the use of diclofop, which was more effective on green foxtail [*Setaria viridis* (L.) Beauv.] and wild oat (*Avena fatua* L.) when applied at an early growth stage (Friesen et al. 1976). Opeña et al. (2014) reported that bispyribac-sodium and penoxsulam + cyhalofop-butyl were effective on *Echinochloa glabrescens* L. at the four-leaf stage but not at the six- or eight-leaf stages; and fenoxaprop + ethoxysulfuron was effective at both the four- and six-leaf stages, but not at the eight-leaf stage.

Generally, herbicide efficacy is reduced when applied on older weeds because of faster herbicide degradation in bigger plants (Singh and Singh 2004). In this situation, herbicide rates may need to be increased to achieve the same level of control (Chauhan and Abugho 2012). Therefore, the timing of application and rates of herbicides are very important factors in effectively controlling weeds. However, although herbicide use may be an effective tool to manage weeds in DSR systems, high dependence on herbicides alone are not wise. Also, the intensive use of herbicides poses hazards to human health and to the environment and causes evolution of herbicide resistance in weed biotypes (Fischer et al. 2000). Thus, there is a need for an integrated approach for a sustainable weed management. Moreover, the development of effective integrated weed management strategies depends on a detailed knowledge of weed seed biology (Bhowmik 1997; Chauhan 2012).

Seed germination and seedling emergence of a weed species are usually influenced by many environmental factors such as temperature, light, soil moisture, soil salinity, seed burial depth in the soil through tillage, and the amount of crop residue in the field (Chauhan 2012). A better understanding of these factors inhibiting weed seed germination or encouraging germination can help to control them easily (Chauhan 2012). Temperature, for example, can affect germination by regulating the enzyme activities involved in germination and by promoting or inhibiting the synthesis of hormones that affect seed dormancy (Baskin and Baskin 1998). Seeds of weed species that require light for germination will germinate only when present on or near the soil surface (Kettenring et al. 2006). Information and knowledge on seedling emergence at various burial depths could help in deciding on an optimal tillage system to reduce the emergence of weed seedlings. Similarly, the use of crop residue in conservation agriculture systems may suppress the emergence of several weed species (Buhler et al. 1996; Teasdale et al. 1991). In many Asian countries, rice is commonly grown in salt-affected and drought-prone areas where weed flora is often different. Information on the effect of salt and water stress on weed germination could help predict the invasion potential of doveweed in such areas. Flooding is another important strategy that inhibits the emergence of many weed species in rice fields. Germination response to a range of environmental factors varies from species to species and such information on doveweed is limited in the literature.

Wilson et al. (2006) in the United States studied the effect of temperature and burial depth on doveweed germination. The effects of other factors on germination and emergence of doveweed, however, have not been studied. Furthermore, weed populations in different countries may respond differently to environmental factors. Therefore, the overall objective of our study was to determine the effects of temperature, light, salt and osmotic stress, burial depth, use of rice residues as mulch, depth of flooding, and application timing and rates of POST herbicides on the emergence and growth of doveweed.

Materials and Methods

Experiments were conducted at the laboratory and screenhouse facilities of the International Rice Research Institute (IRRI), Los Baños, Philippines from February to June 2014. Seeds of mature doveweed plants were collected in September 2013 from the upland rice fields at IRRI. Seeds were bulked, cleaned, and stored in an airtight container at room temperature (20–25 C) until used in the experiments. All experiments were arranged in a randomized complete block design with four replications. Each replication was arranged on different shelves in the incubators or different benches in the screenhouse and considered as blocks. Experiments were repeated over time, with the second run of experiments starting within a month after the termination of the first run.

Seed Germination Test. Seed germination of doveweed was determined by placing 25 seeds in 9-cm-diam petri dishes containing two layers of filter paper (Whatman No.1, Springfield Mill, James Whatman Way, Maidstone, Kent ME14, U.K.) and 5 ml of distilled water or a treatment solution. The petri dishes were sealed with parafilm to prevent water loss and then placed inside an incubator at fluctuating day/night temperatures of 35/25 C in light/dark conditions. These conditions were found optimum in another experiment. The incubator was set at a 12-h photoperiod to coincide with the high temperature interval. If necessary, distilled water was added to maintain adequate moisture during the experiment. The visible protrusion of the radicle was the criterion for germination. The number of germinated seeds was counted at 18 d after sowing (DAS) or until there was no further germination observed.

Effect of Temperature and Light on Germination. The effect of temperature and light on germination was determined by incubating 25 seeds of doveweed at three fluctuating day/night temperatures (35/25, 30/20, and 25/15 C) in both light/dark and dark regimes. The temperature regimes were selected to reflect the temperature variations in the Philippines (Chauhan and Johnson 2008a). In the dark treatment, the dishes were wrapped in three layers of aluminum foil to prevent any light penetration. The number of germinated seeds in the light/dark regime was counted at 3-d intervals for up to 18 d, whereas in the dark regime, the germination was counted only after 18 d. To be able to determine whether the dark conditions adversely affected seed germination, the seeds that did not germinate in the dark after 18 d were transferred to the light/dark conditions after adding 5 ml of distilled water to each dish. The number of germinated seeds was counted after 18 d.

Effect of Osmotic and Salt Stress on Germination. The effect of osmotic stress was assessed by placing 25 doveweed seeds in solutions with osmotic potentials of 0, −0.1, −0.2, −0.4, −0.6, −0.8, and −1.0 MPa. The solution concentrations were prepared by dissolving 0, 99.4, 140.6, 198.8, 243.4, 281, and 314.2 g of polyethylene glycol 8000 (Sigma-Aldrich Co., 3050 Spruce St., St. Louis, MO 63103) in 1 L of distilled water. Meanwhile, the effect of salt stress on germination of doveweed was determined by placing 25 seeds in petri dishes containing 5-ml solutions of 0, 25, 50, 100, 150, 200, and 250 mM sodium chloride (Mallinckrodt Baker Inc., Phillipsburg, NJ). The solutions were prepared by dissolving 0, 1.5, 2.4, 5.8, 8.8, 11.7, and 14.6 g of NaCl per 1 L of distilled water (Michel 1983). These ranges of osmotic potentials and NaCl reflect the salinity and water-stress levels found in the tropical regions. The petri dishes were placed inside growth chambers under fluctuating day/night temperatures of 35/25 C to test germination. Seeds that did not germinate at the highest water-stress and salt concentrations were rinsed with running water for 5 min and placed in the incubator again after adding 5 ml of distilled water. The number of germinated seeds was counted after 18 d.

Effect of Burial Depth on Seedling Emergence. The effect of burial depth on seedling emergence was determined in a pot experiment conducted inside a screenhouse (a chamber framed with 2-mm iron mesh and covered overhead with a transparent plastic cover to prevent rain damage). The pots used in the experiment had a 15-cm diameter and a 15-cm height with holes at the bottom. To prevent soil from leaking out, a piece of paper was placed at the bottom of each pot. The soil used in this experiment was collected from upland rice fields and had a pH of 6.6, and consisted of 31% sand, 37% silt, and 32% clay. The soil was autoclaved and passed through a 3-mm sieve. Fifty seeds of doveweed were

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broadcast on the soil surface and then covered with the same soil to depths of 0, 0.5, 1, 2, 4, and 6 cm. The pots were irrigated with an overhead sprinkler initially and later subirrigated. The visibility of the coleoptiles on the soil surface indicated seedling emergence and the number of seedlings that emerged was recorded at 3-d intervals up to 24 DAS, after which no further emergence occurred.

Effect of Residue Amount on Seedling Emergence and Biomass. Fifty seeds of doveweed were broadcast on the soil surface inside plastic pots, and finely chopped rice straw (leaves and stems) was spread on the soil surface at rates equivalent to 0, 1, 2, 4, 6, and 8 t ha^{-1}. The pots and soil used in this experiment were the same as those described in the seed burial depth experiment. The number of germinated seeds was recorded at 3-d intervals until no further emergence was observed. At 24 DAS, shoots were cut from the base of the soil, cleaned, oven dried at 70 C for 72 h, and weighed.

Effect of Burial and Flooding Depths on Seedling Emergence and Biomass. Fifty seeds were broadcast on the soil surface in small plastic trays (8.0 cm by 8.0 cm by 5.5 cm) and covered with 0 or 0.5 cm of soil layer to achieve seed burial depths of 0 or 0.5 cm. The pots containing the seeds were placed inside larger plastic trays (30 cm by 20 cm by 12 cm) to retain and maintain flooding depths of 0, 2, 4, and 6 cm. After seeding, the pots were kept at saturated conditions for 6 h to let the seeds imbibe water to prevent them from floating. Flooding at the desired depths was introduced 6 h after seeding and pots were kept flooded at the aforementioned depths for 18 d. The number of seedlings that emerged was counted at 18 d after the start of flooding. The aboveground shoot was harvested and oven dried to constant weights at 70 C for 72 h to measure biomass.

Effect of POST Herbicides on Seedling Survival and Growth. Twenty-five seeds were broadcast on the soil surface in small plastic pots (15 cm in diameter and 15 cm in height) that were filled with the same soil as described above. Seedlings were thinned to 10 plants per pot at 8 DAS. POST Herbicides were sprayed at the three-, five-, and seven-leaf stages using a research track sprayer (DeVries Manufacturing, Hollandale, MN) that delivered 210 L ha^{-1} spray solution at a spray pressure of 140 kPa; flat-fan nozzles (Teejet 80015) were used in the sprayer. The POST herbicides used in the experiment were bispyribac-sodium at 15, 30, 45, and 60 g ai ha^{-1} (Bayer Crop Science, Canlubang City, Laguna, Philippines); bentazon at 50, 100, 150, and 200 g ai ha^{-1} (BASF, Philippines); 2,4-D ester at 250, 500, 750, and 1,000 g ai ha^{-1} (LEADS, Agricultural Products Corporation, Philippines); and glyphosate at 500, 1,000, 1,500, and 2,000 g ai ha^{-1} (Monsanto, Philippines Inc.). A nontreated control was included for comparison purposes. The number of seedlings (at least one green leaf on the plant) that survived any treatment was counted at 14 d after herbicide application. Shoots were harvested and oven dried at 70 C for 72 h and biomass was recorded.

Statistical Analyses. ANOVA was performed (Crop Stat 7.2; International Rice Research Institute, Los Baños, Philippines) on nontransformed and arcsine-transformed data; however, transformation did not improve the results. Therefore, the nontransformed values were used for the analyses. Because of the nonsignificant interaction between the runs, the data from the two experimental runs were combined for analysis (a total of eight replications).

Regression analysis was done to determine relationships between germination or emergence and environmental factors (i.e., temperature regimes, osmotic and salt concentrations, burial depths, residue amounts, and flooding depths) using SigmaPlot 11.0 (Systat Software, Inc., Point Richmond, CA). Parameter estimates for each model were compared using their standard errors. The model fitted to germination at different temperature regimes was:

$$G = G_{max}/\{1 + e[-(T - T_{50})/G_{rate}]\} \qquad [1]$$

where G is the total germination (%) at time T, G_{max} is the maximum germination (%), T_{50} is the time required for 50% of maximum germination, and G_{rate} indicates the slope. The model fitted to germination at different osmotic and salt concentrations was:

$$G = G_{max}/\{1 + e[-(x - x_{50})/G_{rate}]\} \qquad [2]$$

where G is the total germination (%) at salt concentration or osmotic potential x, G_{max} is the maximum germination (%), x_{50} is the salt concentration or osmotic potential required for 50% inhibition of maximum germination, and G_{rate} indicates the slope. The model fitted to seedling emergence at different burial depth and amount of rice residue was:

$$E = E_{max} / \{1 + e[-(T - T_{50})/E_{rate}]\} \quad [3]$$

where E is the cumulative percentage emergence at time T, E_{max} is the maximum emergence (%), T_{50} is the time required for 50% of maximum emergence, and E_{rate} indicates the slope. The polynomial quadratic model fitted to emergence at different seed burial and flooding depths was:

$$E = E_{max} + ax + bx^2 \quad [4]$$

where E is the estimated emergence (%) as a function of flooding depth x, E_{max} is the maximum emergence (%), and a and b describe the slopes of the regression curves. An exponential decay curve was fitted to seedling biomass obtained at different depths of flooding:

$$M = M_{max} \times e(-M_{rate} \times x) \quad [5]$$

where M represents biomass (g) at flooding depth x, M_{max} is the maximum biomass, and M_{rate} indicates the slope.

Results and Discussion

Effect of Temperature and Light. This study found that germination of doveweed was affected by temperature and light ($P < 0.05$). Light strongly stimulated germination, whereas dark completely inhibited germination in all the tested temperature regimes. Also, when doveweed seeds were exposed to alternating temperatures in light/dark, the highest germination occurred at 35/25 C (95%), followed by 30/20 C (73%). No germination occurred at 25/15 C. Cumulative germination was higher (95%) in the temperature regime of 35/25 C, whereas the temperature regime of 30/20 C had 23% lower germination than 35/25 C (Figure 1).

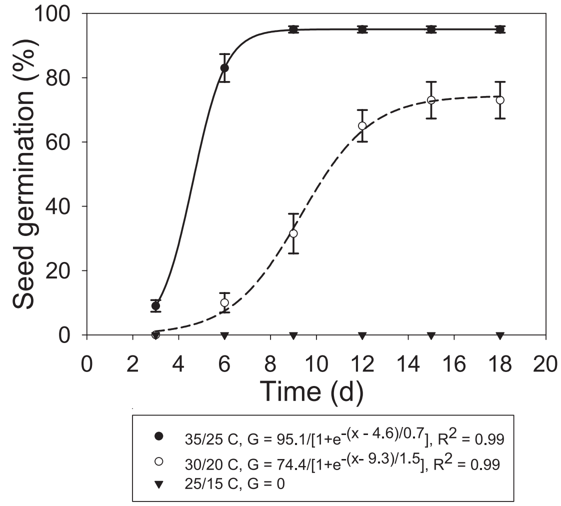

Figure 1. Seed germination of doveweed incubated at alternating day/night temperatures (25/15, 30/20, and 35/25 C) and light (light/dark) over a 12-h photoperiod for 18 d. Vertical bars represent standard errors.

The current study supports the findings of Burke et al. (2003) and Chauhan and Johnson (2008a) that temperature and light are important factors influencing weed seed germination. In our study, doveweed seeds did not germinate in the dark, which indicates that light is an absolute requirement for its germination. Seeds of some species can germinate only in conditions where there is light and others may germinate equally in light or dark conditions (Teuton et al. 2004). In a previous study, Chauhan and Johnson (2008a) found that Chinese spangletop [*Leptochloa chinensis* (L.) Nees] had an absolute light requirement for germination, whereas Opeña et al. (2014) reported that germination of *E. glabrescens* was reduced by 52–92% when exposed to dark. Weed species that show preference for germination in light have the potential to become problematic weeds in no-till or reduced-till systems (Cousens et al. 1993). The highest germination at 35/25 C indicates that higher temperatures favor the germination of doveweed seeds. These results are supported by a previous study in which the germination of doveweed was found to be greatest at 35/25 C (77%) and germination decreased as maximum and minimum temperatures were further increased or decreased, respectively. The absence of germination at 25/15 C suggests that doveweed might be a less problematic weed in cooler regions.

In our study, when nongerminated seeds from the dark treatment were transferred to light/dark conditions at 35/25 C, their germination reached 90–92% (data not shown). These results suggest that doveweed seeds were not adversely affected by the dark. In the field conditions, these seeds may remain dormant when buried deep and reinfest the area when brought back to or near the soil surface.

Effect of Water Stress on Germination. Seed germination of doveweed was strongly influenced ($P < 0.05$) by water potential (Figure 2). Germination of seeds exposed to 0 (no-stress) and −0.1 MPa osmotic potentials was at 96 and 95%, respectively, and seed germination declined with further reduction in osmotic potential. Compared in no-stress conditions, seed germination was reduced by 10, 44, and 86% at osmotic potentials of −0.2, −0.4, and −0.6 MPa, respectively. No germination occurred at water potentials of −0.8

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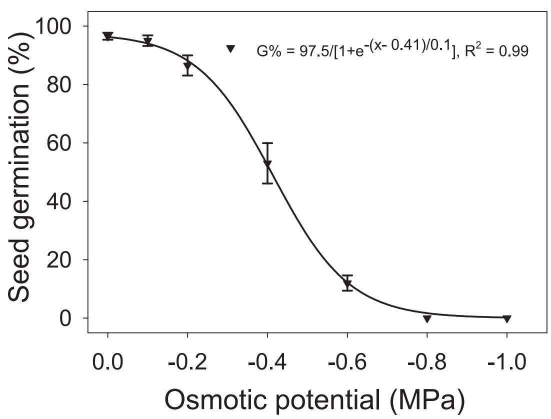

Figure 2. Seed germination of doveweed in response to osmotic potentials (MPa) when incubated in a growth chamber at 35/25 C day/night temperature over a 12-h photoperiod for 18 d. Vertical bars represent standard errors.

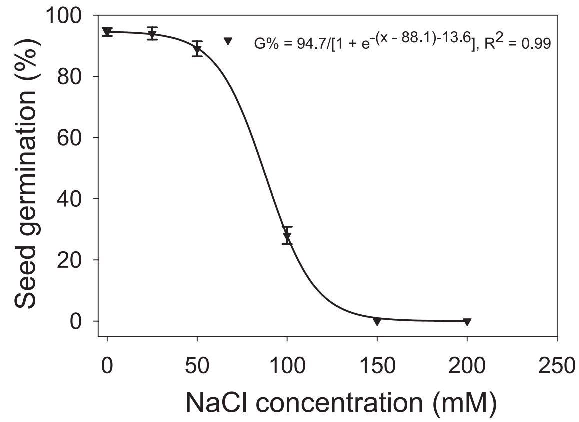

Figure 3. Seed germination of doveweed in response to sodium chloride concentrations when incubated in a growth chamber at 35/25 C day/night temperature over a 12-h photoperiod for 18 d. Vertical bars represent standard errors.

and −1.0 MPa. The osmotic potential required for 50% inhibition of maximum germination was −0.4 MPa. A previous study reported that the osmotic potentials required for 50% inhibition of the maximum germination of feather lovegrass [*Eragrostis tenella* (L.) ex Roemer & J. A. Schultes] was −0.7 MPa (Chauhan 2013). In our study, when nongerminated seeds from −1.0 MPa were rinsed and placed in distilled water, germination reached 80–90%. These results indicate that the seeds of doveweed were not adversely affected by exposure to low osmotic potentials for up to 18 d. These results also suggest that most of the seeds will germinate in moist conditions, whereas seeds in dry conditions may wait until moisture conditions are favorable before germination occurs.

Effect of Salt Stress on Germination. Doveweed germination decreased with increases in NaCl concentration (Figure 3). Maximum germination (94%) was observed in the seeds that were incubated at no-stress (0 mM) and 25 mM NaCl concentration. Germination at 50 and 100 mM NaCl was 89 and 28%, respectively, and thereafter, germination was completely inhibited at 150, 200, and 250 mM salt concentrations. These results suggest that this species might not be a problematic weed in high-saline soils. The results of our study are supported by a previous study on Chinese sprangletop, in which no seeds germinated at 150 mM or greater concentration of NaCl (Chauhan and Johnson 2008a). On the other hand, some weeds like *E. glabrescens* can germinate even at 250 mM NaCl (Opeña et al. 2014).The salt concentration required for 50% inhibition of maximum germination of doveweed was 88 mM NaCl. Similar results were reported for goosegrass [*Eleusine indica* (L.) Gaertn.], in which 78 mM NaCl inhibited 50% of the maximum germination (Chauhan and Johnson 2008b).

When nongerminated seeds after 18 d at the highest tested salt concentration (250 mM NaCl) were rinsed with distilled water and incubated again at 35/25 C, germination increased to 90–96%, indicating that the seeds were not adversely affected by saline conditions (data not shown). These results suggest that seeds in saline conditions may not germinate but may wait until favorable conditions prevail before germination occurs.

Effect of Seed Burial Depth on Seedling Emergence. Seedling emergence of doveweed was significantly affected by seed burial depth (Figure 4). Cumulative seedling emergence declined with increasing burial depths. The highest germination (91%) was observed at the soil surface, and no seedlings emerged at burial depths below 2 cm. Compared with surface seeding, seedling emergence decreased by 78% at the burial depth of 0.5 cm and by 86 and 92% at burial depths of 1 and 2 cm, respectively.

Reduced seedling emergence with increases in burial depth could be due to the absence of light at deeper depths. The response of seedling emergence to burial depth is also consistent with the response of germination to light as there was an absolute requirement of light for the germination of doveweed seeds. Seeds buried at a depth of more than 0.2 cm usually receive a very limited proportion of incident light, which is not enough to trigger germination (Egley 1986). Another possible reason for reduced emergence with increasing depth could be hypoxia and low rates of gaseous diffusion at

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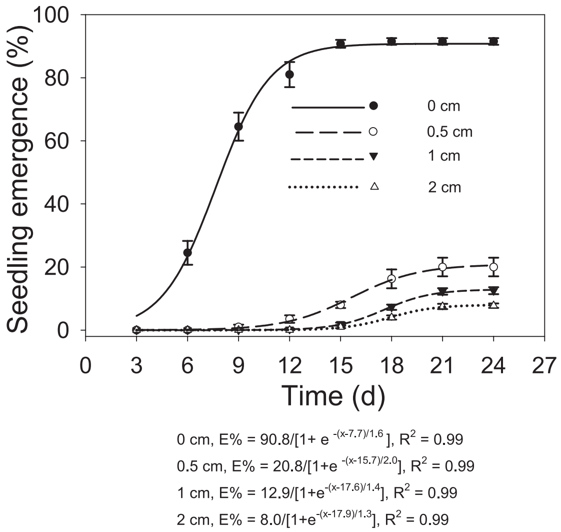

Figure 4. Seedling emergence of doveweed in response to burial depth (cm) when grown in screenhouse conditions for 24 d. Vertical bars represent standard errors.

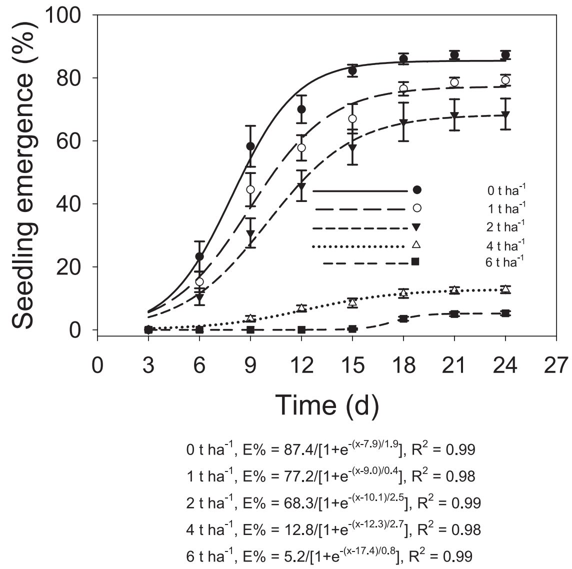

Figure 5. Seedling emergence of doveweed in response to rice residue (t ha^{-1}) grown in screenhouse conditions for 24 d. Vertical bars represent standard errors.

deeper depths (Benvenuti 2003). Seed size is another important factor that also influences the emergence of weed seeds from different burial depths. Larger seeds, for example, have greater carbohydrate reserves and can emerge from greater burial depths (Baskin and Baskin 1998), whereas small-seeded species such as Chinese sprangletop, rice flatsedge (*Cyperus iria* L.), smallflower umbrella sedge (*Cyperus difformis* L.), and globe fringerush [*Fimbristylis miliacea* (L.) Vahl] have insufficient reserves to support seedling emergence from deep depths (Chauhan and Johnson 2010). Although the burial depth response varied among species, it is very common that seeds of most weed species germinate when these are placed on the soil surface (Chauhan and Johnson 2010).

The stimulation of germination by light and the greater seedling emergence on the soil surface for doveweed suggest that zero-till or strip-till DSR systems may favor its emergence in the field. In no-till or conservation agriculture practices, most of the weed seeds remain on or near the soil surface after crop planting (Chauhan et al. 2012). Weed seeds present on the soil surface may be prone to faster desiccation and insect predation (Chauhan et al. 2010). The buildup of doveweed seed bank on the soil surface can be reduced by a deep tillage using a moldboard plow that would bury the seeds below 4 cm in the soil, thus discouraging their emergence. In addition, the stale seedbed technique can be practiced, in which a nonselective herbicide is applied when most of the weeds have emerged before the crop was planted.

Effect of Residue Amount on Seedling Emergence and Biomass. Seedling emergence and biomass of doveweed declined with the addition of residues (Figures 5 and 6). The highest seedling emergence (87%) occurred in the absence of residue, but decreased gradually with increases in rice residue amount (Figure 5). No seedling emergence was observed at 8 t ha^{-1} of residue. In addition, seedling emergence was also delayed when the amount of residue increased. Fifty percent of the seedling emergence under the no-residue condition was achieved at 7.9 d, whereas the amount of time to achieve 50% seedling emergence increased at 9, 10, 12, and 17 d at residue amounts of 1, 2, 4, and 6 t ha^{-1}, respectively. Similar to the response of seedling emergence, maximum seedling biomass (1.9 g pot^{-1}) was obtained in the absence of residue, and biomass declined sharply with increasing residue amounts (Figure 6). The amount of residue needed to suppress 50% of maximum biomass was 2.5 t ha^{-1}.

The results of our study suggest that the use of crop residue as mulches can suppress seedling emergence and biomass of doveweed. Our results are consistent with the results of a previous field study in the Philippines in which the emergence and growth of crowfootgrass [*Dactyloctenium aegyptium* (L.) Willd.], junglerice, eclipta [*Eclipta prostrata* (L.) L.], and Chinese sprangletop were suppressed with the use of 6 t ha^{-1} of rice residue in a zero-till DSR system (Chauhan and Abugho 2013a). Weed suppression by mulch occurs because of various factors such as reductions in light transmittance,

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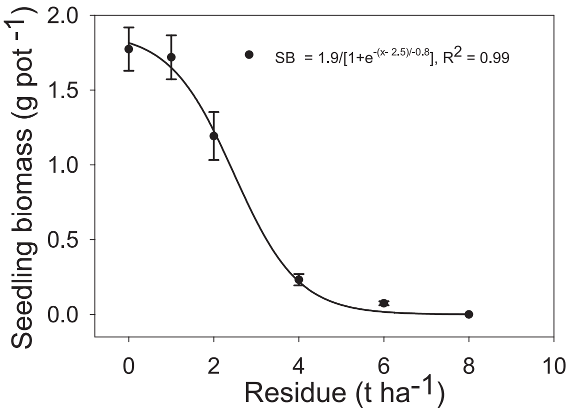

Figure 6. Seedling biomasses (g pot^{-1}) of doveweed in response to rice residue (t ha^{-1}) at 24 d. Vertical bars represent standard errors.

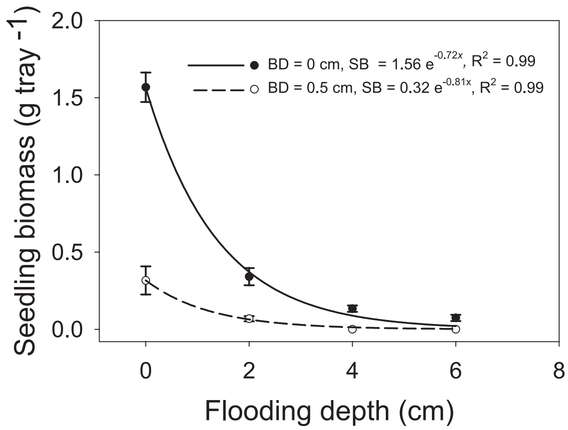

Figure 8. Seedling biomass of doveweed in response to seed burial depth (BD) and flooding depth when grown in screenhouse conditions at 18 d. Vertical bars represent standard errors.

temperature fluctuations, and physical obstructions provided by the mulch itself (Crutchfield et al. 1985). Our results suggest that the use of residue as mulch can be integrated with other weed management strategies to achieve effective weed control of doveweed. This approach would be helpful in reducing herbicide use in DSR systems.

Effect of Seed Burial and Flooding Depths on Seedling Emergence and Biomass. Seedling emergence was reduced with increases in the depths of burial and flooding (Figure 7). For the seeds placed on the soil surface, seedling emergence was reduced by 7, 9, and 19% at flooding depths of 2, 4, and 6 cm, respectively. However, for the seeds buried at 0.5 cm, these reductions were at 63, 100, and 100%, respectively. Flooding had a more pronounced effect on seedling biomass than on seedling emergence (Figure 8). Biomass of the surface-sown seeds reduced by 78, 92, and 96% when flooding depths increased from 0 cm to 2, 4, and 6 cm,

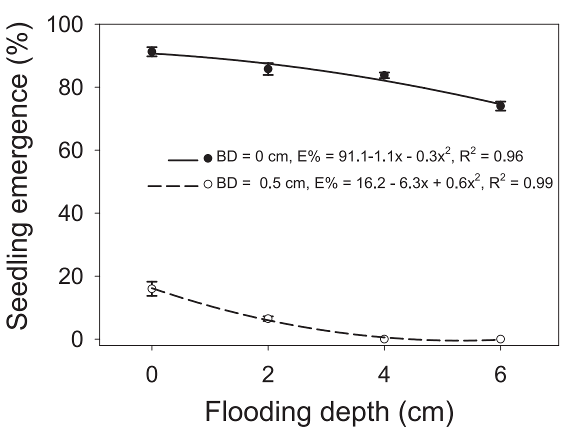

Figure 7. Seedling emergence of doveweed in response to seed burial (BD) and flooding depth grown in screenhouse conditions at 18 d. Vertical bars represent standard errors.

respectively. These reductions were at 78, 100, and 100%, respectively, for the seeds sown at 0.5-cm depth.

Flooding is an important strategy in controlling weeds; however, the response of weeds to flooding varies from species to species. Some weed species such as rice flatsedge, junglerice, and forked fringerush can be controlled by flooding (Civico and Moody 1979; Smith and Fox 1973), but weeds such as monochoria [*Monochoria vaginalis* (Burm. f.) Kunth] (Pons 1982) and gooseweed (*Sphenoclea zeylanica* Gaertn.) (Kent and Johnson 2001) prefer flooding for robust growth. The suppression of the emergence and growth of some weeds due to flooding might be because of reductions in the O_2 level, CO_2 accumulation, toxic gases produced from anaerobic decomposition, and the presence of reduced forms of chemical radicals and gases such as methane, nitrogen, nitrogen oxides, and sulfides (Smith and Fox 1973). In addition, the depth-sensing mechanisms of weed seeds might be related to the amplitude of temperature fluctuations (Pons 1982). Deeper water levels could have smaller temperature fluctuations, which might result in lower germination.

In our study, flooding did not reduce the emergence of doveweed when seeds were placed on the soil surface; however, flooding greatly reduced seedling biomass. These results are consistent with the findings of Chauhan and Johnson (2008a) who demonstrated that the growth of Chinese sprangletop decreased greatly when flooding depths increased from 0 to 2, 6, 8, or 10 cm. Our results indicate that shallow flooding can be used to suppress the growth of doveweed. Flooding after POST herbicide application or hand weeding

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Table 1. Effect of POST herbicides on survival (%) and shoot biomass (g pot^{-1}) of doveweed sprayed at three-, five-, and six-leaf stages of the weed.

Weed control treatments	Growth stage					
	Three-leaf		Five-leaf		Seven-leaf	
	Survival	Shoot biomass	Survival	Shoot biomass	Survival	Shoot biomass
	%	g pot^{-1}	%	g pot^{-1}	%	g pot^{-1}
Nontreated control	100	1.94	100	2.81	100	5.43
Bentazon 50 g ha^{-1}	56	0.34	98	1.18	100	1.73
Bentazon 100 g ha^{-1}	0	0.00	51	0.68	64	1.41
Bentazon 150 g ha^{-1}	0	0.00	0	0.00	38	0.51
Bentazon 200 g ha^{-1}	0	0.00	0	0.00	21	0.15
Bispyribac-sodium 15 g ha^{-1}	0	0.00	20	0.20	69	1.25
Bispyribac-sodium 30 g ha^{-1}	0	0.00	15	0.16	31	0.53
Bispyribac-sodium 45 g ha^{-1}	0	0.00	0	0.00	25	0.44
Bispyribac-sodium 60 g ha^{-1}	0	0.00	0	0.00	11	0.10
2,4-D ester 250 g ha^{-1}	16	0.06	28	0.70	56	1.30
2,4-D ester 500 g ha^{-1}	0	0.00	0	0.00	0	0.00
2,4-D ester 750 g ha^{-1}	0	0.00	0	0.00	0	0.00
2,4-D ester 1,000 g ha^{-1}	0	0.00	0	0.00	0	0.00
Glyphosate 500 g ha^{-1}	100	0.68	100	1.71	100	2.82
Glyphosate 1,000 g ha^{-1}	100	0.56	100	1.47	100	2.29
Glyphosate 1,500 g ha^{-1}	74	0.41	76	1.33	100	1.81
Glyphosate 2,000 g ha^{-1}	69	0.36	74	0.86	76	1.44
$LSD_{0.05}$	13.29	0.18	18.92	0.85	22.47	0.94

could be an option to prevent the subsequent growth of this weed in DSR systems.

Effect of POST Herbicides on Seedling Survival and Growth. This study found that application of all the POST herbicides except glyphosate effectively controlled doveweed; however, the response varied depending on herbicide rate and weed growth stage (Table 1). The efficacy of POST herbicides, except glyphosate, was greater when applied at the three- and five-leaf stages and 2,4-D ester was effective even when applied at the seven-leaf stage. The increased rates of herbicides were more effective when applied to doveweed that was more aged (seven-leaf stage). Bispyribac-sodium, regardless of the rate, was able to completely control doveweed at the three-leaf stage. Bentazon and 2,4-D ester were similarly effective (100% control) at this stage, except when applied at the lowest rate. At the three-leaf stage, the application of bentazon and 2,4-D ester at the lowest rate had 56 and 16% seedling survival, respectively. The application of glyphosate at the same leaf stage did not control this weed when applied at 500 and 1,000 g ha^{-1}; however, at 1,500 and 2,000 g ha^{-1}, glyphosate provided 26 and 31% kill, respectively. Although glyphosate was unable to kill doveweed seedlings at the three-leaf stage, it reduced biomass significantly compared with the nontreated control. At the five-leaf stage, 2,4-D ester provided 100% control of doveweed when applied at 500 g ha^{-1} or at higher rates; however, 28% of the weed seedlings survived when applied at 250 g ha^{-1}. Similarly, bispyribac-sodium at 45 and 60 g ha^{-1} and bentazon at 150 and 200 g ha^{-1} provided 100% control, but at lower rates these herbicides did not kill all seedlings. At the five-leaf stage, plant survival and shoot biomass in the glyphosate treatment had a similar trend as that found at the three-leaf stage.

At the seven-leaf stage, 2,4-D ester applied at 500 g ha^{-1} and at higher rates provided 100% control of doveweed. At this stage, glyphosate controlled only 24% of the weeds when applied at 2,000 g ha^{-1}, and rates lower than this did not kill any seedling. Other herbicides did not provide 100% control, although they reduced biomass significantly, with the reductions more prominent when herbicide rates were increased.

The results of our study suggest that glyphosate cannot control doveweed. Other POST herbicides were very much effective; however, application timing and rate were critical in achieving maximum efficacy. Herbicide application, even at lower rates, at early stages (three- and five-leaf stages) provided effective control of doveweed. At the seven-leaf stage, 2,4-D ester at 500 g ha^{-1} effectively controlled doveweed, but rates needed to be increased for bispyribac-sodium and bentazon to effectively control this weed.

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Previous studies reported that POST herbicides applied at an early growth stage are more effective than when applied at later stages. Chauhan and Abugho (2012), for example, reported that the application of bispyribac-sodium, fenoxaprop-p-ethyl + ethoxysulfuron, and penoxsulam + cyhalofop at the four-leaf stage provided greater than 97% control of barnyardgrass, junglerice, and southern crabgrass. In a recent study, POST herbicides provided reductions of 85–100% in seedling survivals, 41–81% in shoot biomass, and 75–100% in root biomass of *Echinochloa glabrescens* when applied at the four-leaf stage (Opeña et al. 2014). In our study, we found that 2,4-D ester was equally effective at all the leaf stages when applied at 500 g ha^{-1} or at higher rates. The results of our study indicate that glyphosate would not provide effective weed control if doveweed emerged after the practice of the stale seedbed, which is a common practice for planting rice under zero-till conditions. However, other POST herbicides that are more effective in controlling doveweed may be used, thus giving farmers different herbicide options from which to choose to manage this weed in DSR systems.

In summary, doveweed germination was strongly stimulated by light and may not be a problematic weed in salt- and drought-affected areas. The highest germination was observed from seeds placed on the soil surface and seedling emergence was greatly reduced with increases in burial depths. The use of rice residue as mulch suppressed seedling emergence and biomass. Flooding significantly reduced the emergence and biomass of doveweed. Bispyribac-sodium, bentazon, and 2,4-D provided excellent control of this weed when applied at the three- and five-leaf stages.

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