Seaside Petunia Susceptibility to Herbicides Used in Dry Bulb Onion

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SUMMARY. Seaside petunia (*Calibrachoa parviflora*) is a mat-forming plant species that was recently reported in fall-seeded onion (*Allium cepa*) in the southwestern United States. To initiate development of herbicide recommendations for seaside petunia in onion, we conducted a study to determine seaside petunia susceptibility to commonly used herbicides for broadleaf weed control after onion emergence. Our study included herbicides applied at below-label rates, which provided insights on seaside petunia responses to reductions in the amount of herbicide available for plant absorption. For herbicides with preemergence activity, our growth chamber study indicated that soil applications of flumioxazin or oxyfluorfen (0.06 and 0.25 lb/acre, respectively) prevented seaside petunia seedling emergence when applied at 0.125×, 0.25×, 0.5×, and 1.0× the labeled rates for onion. Labeled rate treatments of dimethenamid-P (0.84 lb/acre) and S-metolachlor (0.64 lb/acre) inhibited seedling emergence similar to labeled rate treatments of flumioxazin and oxyfluorfen; however, below-label rate treatments of dimethenamid-P and S-metolachlor resulted in diminished control of seaside petunia compared with the labeled rate treatments. Following labeled rate applications of dimethyl tetrachloroterephthalate [DCPA (6 lb/acre)] and pendimethalin (0.71 lb/acre), more than 50% of seaside petunia seedlings emerged compared with the nontreated control. For herbicides with postemergence activity on weeds, our greenhouse study indicated that bromoxynil at 0.37 lb/acre, flumioxazin at 0.06 lb/acre, and oxyfluorfen at 0.25 lb/acre equally reduced growth of seaside petunia plants that were small at the time of spraying (stem length, 1–2 cm). Postemergence control of seaside petunia with oxyfluorfen and flumioxazin decreased as plant size at spraying increased; however, bromoxynil effects on seaside petunia remained high as stem length at spraying increased from 5 to 12 cm. Based on the results of this study, we conclude that promising herbicide programs for seaside petunia in onion include oxyfluorfen or flumioxazin for preemergence control and bromoxynil for postemergence control. These herbicides, alone and in combination, should be evaluated for seaside petunia control and onion phytotoxicity in future field trials.

onion produced during summer (U.S. Department of Agriculture, National Agricultural Statistics Service, 2021e). In New Mexico in 2020, ≈4.15 million cwt of onion were harvested from 6200 acres (U.S. Department of Agriculture, National Agricultural Statistics Service, 2021b, 2021c), which provided \$87.2 million in cash receipts to New Mexico farmers, and made the production value of onion in New Mexico fifth highest among onion-producing states in the country (U.S. Department of Agriculture, National Agricultural Statistics Service, 2021d). Across the United States in 2020, onion was planted on 134,700 acres, and onion production was worth about \$887 million (U.S. Department of Agriculture, National Agricultural Statistics Service, 2021a, 2021d).

Most of New Mexico's onion production is located in three contiguous counties in the southern region (Doña Ana, Luna, and Sierra Counties). This region features favorable soil (i.e., well-drained sandy-loam to clay-loam soil) and relatively mild winters that allow farmers to plant onion in fall and early spring, irrigate onion as needed, and harvest onion May through July. Onion leaf canopies absorb relatively little of the incoming photosynthetically active radiation (Tei et al., 1996), and thus onion is not competitive against weeds throughout much of the onion growing season (Menges and Tamez, 1981; Wicks et al., 1973; Williams et al., 2007). To reduce the impacts of weeds on onion, New Mexico farmers repeatedly use combinations of herbicides, tillage, and hand weeding to remove weeds from onion fields; however, weeds continue to persist. Weeds that have long been common in onion fields in southern New Mexico include, but are not limited to, sowthistle species (*Sonchus* sp.), london

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Dry bulb onion [*Allium cepa* (herein “onion”)] is a vegetable that is cultivated worldwide (Food and Agriculture Organization of the United Nations, 2021). In the United States, onion is grown primarily in nine states, with New Mexico responsible for about half the total nonstorage

Units			
To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
0.0454	cwt	Mg	22.0462
29.5735	fl oz	mL	0.0338
9.3540	gal/acre	L·ha ⁻¹	0.1069
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
0.4536	lb	kg	2.2046
1.1209	lb/acre	kg·ha ⁻¹	0.8922
0.1198	lb/gal	kg·L ⁻¹	8.3454
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

Fig. 1. Seaside petunia plant featuring a purplish, funnel-formed corolla (5–7 mm long) and linear to elliptical, nearly sessile leaves (8–18 mm long); 1 mm = 0.0394 inch.

rocket (*Sisymbrium irio*), flixweed (*Descurainia sophia*), palmer amaranth (*Amaranthus palmeri*), wright groundcherry (*Physalis acutifolia*), purple nutsedge (*Cyperus rotundus*), and yellow nutsedge (*Cyperus esculentus*).

Since ≈2015, a weed species in the nightshade family (Solanaceae)—seaside petunia [*Calibrachoa parviflora* (synonym *Petunia parviflora*)]—has become increasingly abundant in New Mexico onion fields. Seaside petunia (Fig. 1) was historically found in sandy arroyos in the southwestern United States (Abrams, 1951; Wooten and Standley, 1915) and is now verified in 15 states, usually in geomorphic settings where soil is saturated or flooded at least seasonally (U.S. Department of Agriculture, Natural Resources Conservation Service, 2021). Seaside petunia stems are prostrate, diffusely branched, and 2 to 28 cm long (Beck and Wanstall, 2021). Along the stem, linear to elliptical (8- to 18-mm long) leaves are alternate, sessile, or have very short petioles. Seaside petunia leaves are fleshy and feature glandular hairs. Flowers on short pedicels are located in leaf axils and have a purplish, funnel-formed corolla that is 5 to 7 mm long. Seeds are spheroidal to angular and are 0.5 to 0.6 mm in diameter (Gunn and Gaffney, 1974). In New Mexico, seaside petunia has an annual lifecycle, and seedling emergence occurs from January to June.

Seaside petunia infestations that emerge during the middle phases of the growing season for fall-seeded onions can cause substantial losses in onion bulb yield (Schutte and Morris, 2019). This is generally consistent with previous studies that determined onion must be kept weed free for the first 8 to 12 weeks after onion emergence to prevent yield loss (Menges and Tamez, 1981; Wicks et al., 1973). In addition to reducing yields, seaside petunia infestations that emerge during middle phases of the onion growing season need to be controlled because they may interfere with onion harvest operations and possibly contribute to the weed seedbank, creating problems for future crops.

Farmers can potentially use herbicides to control midseason infestations of seaside petunia in onion. However, to our knowledge, there is no information on the abilities of herbicides registered for over-the-top applications in onion to control seaside petunia. Herbicides registered for over-the-top applications in New Mexico onion include the following soil-applied herbicides with activity on broadleaf and grass weeds: DCPA, dimethenamid-P, oxyfluorfen, pendimethalin, *S*-metolachlor, and trifluralin. Postemergence herbicides registered for over-the-top applications in New Mexico onion and

active on broadleaf weeds include bromoxynil and oxyfluorfen. Flumioxazin, which has pre- and postemergence activity on broadleaf and some grass weeds, can be applied to onion in some states, but is currently not registered for onion in New Mexico.

The overall objective of this study was to determine seaside petunia susceptibility to herbicides registered for over-the-top applications in onion. For herbicides with preemergence activity on weeds, this study compared preemergence herbicides for their ability to inhibit seedling establishment when applied at different rates. Treatments with rates less than labeled guidelines were not meant to serve as bases for recommendations. Rather, below-label rates were intended to identify preemergence herbicides to which seaside petunia is extremely susceptible. To assess seaside petunia susceptibility to herbicides with postemergence activity on weeds, this study compared postemergence herbicides for their capacity to control seaside petunia at different stages of growth.

Materials and methods

SEED AND SOIL MATERIALS. Seaside petunia seeds were obtained from plants growing in an onion field at the New Mexico State University (NMSU), Leyendecker Plant Science Research Center (lat. 32.19°N, long. 106.74°W) near Las Cruces during Spring 2017. Seed-bearing seaside petunia plants were hand-clipped at the soil surface and dried in the laboratory at room temperature (20 to 25 °C) for 28 d. Dried plants were then hand-threshed, and seeds were separated from chaff with sequential combinations of sieving and forced-air separation. Cleaned seeds were stored in an airtight container at 4 °C until needed. Before use in experiments, seed samples were subjected to 14-d germination assays conducted with petri dishes lined with moistened filter papers and placed in a growth chamber set to 27/17 °C day/night, 12-h photoperiods. These conditions were determined to be favorable for germination of seaside petunia (B. Schutte, unpublished data). At the conclusion of the germination assays, nongerminated seeds were tested for viability using the imbibed crush test (Borza et al., 2007). At the beginning of each experiment, at least 84% of viable seeds could be germinated.

Soil for the experiments was a loamy sand (87% sand, 6% silt, 7% clay, 0.3% organic matter; pH, 8.2) collected from a fallow field at the NMSU Agricultural Science Center at Los Lunas (lat. 34.77°N, long. 106.76°W). The field was not treated with herbicides for at least 2 years before soil was collected. Soil with high sand content was selected because coarse-textured soil is advantageous for onion production (Walker et al., 2009).

PREEMERGENCE HERBICIDE STUDY. The study was conducted in a growth chamber and included two experimental runs. Experimental run 1 occurred from 25 Oct. to 24 Nov. 2019. Experimental run 2 occurred from 20 Dec. 2019 to 21 Jan. 2020.

Experimental units were plastic pots (8 cm wide, 8 cm long, 8 cm deep) filled with the loamy sand soil described previously. Pot bottoms included drainage holes that were lined with nylon fabric mesh (<0.1-mm opening) that prevented soil loss during filling. Each pot contained 200 seaside petunia seeds distributed across the soil surface and buried at 0.5 cm.

Treatments were factorial combinations of herbicide and rate. Herbicides included DCPA [6 lb/gal, flowable formulation (Dacthal Flowable; Amvac Chemical Corp., Los Angeles, CA)], dimethenamid-P [6 lb/gal, emulsifiable concentrate (Outlook; BASF Corp., Research Triangle Park, NC)], flumioxazin [0.51 lb/lb, water-dispersible granule (Chateau SW; Valent U.S.A. Corp., Walnut Creek, CA)], oxyfluorfen [4 lb/gal, suspension concentrate (Goaltender; Corteva Agriscience, Indianapolis, IN)], pendimethalin [3.8 lb/gal, capsule suspension (Prowl H₂O, BASF Corp.)], and S-metolachlor [7.62 lb/gal, emulsifiable concentrate (Dual Magnum; Syngenta Crop Protection, Greensboro, NC)]. Herbicide rates were 0× (nontreated control), 0.125×, 0.25×, 0.5×, and 1.0× the labeled rates for onion on coarse soil. Labeled rates were as follows: DCPA at 6 lb/acre, dimethenamid-P at 0.84 lb/acre, flumioxazin at 0.06 lb/acre, oxyfluorfen at 0.25 lb/acre, pendimethalin at 0.71 lb/acre, and S-metolachlor at 0.64 lb/acre. Herbicides were applied using a moving-nozzle spray chamber (DeVries Manufacturing, Hollendale, MN) equipped with an even-flat nozzle tip (8002EVS; TeeJet Technologies, Wheaton, IL) and calibrated to deliver 20 gal/

acre. After application, herbicides were incorporated by applying 75 mL of water per pot over 5 min.

After the initial irrigation, pots were transferred to growth chambers set to 27/17°C day/night, 12-h photoperiods. Treatments were arranged on growth chamber shelves in a randomized complete block design with four replications. Once in growth chambers, pots were watered every 2 d by adding 30 mL water to the soil surface in each pot. This irrigation procedure did not cause water to exit through holes in the bottoms of pots. Seaside petunia seedlings were counted at 30 d after herbicide treatment (DAT).

POSTEMERGENCE HERBICIDE STUDY. A study was conducted in a greenhouse located at the NMSU Leyendecker Plant Science Research Center. The study consisted of two experimental runs. Experimental run 1 occurred from 13 May to 20 Aug. 2018. Experimental run 2 occurred from 3 Sept. to 18 Dec. 2018. Throughout the study, air temperature in the greenhouse ranged from 18 to 35°C. On days for which the duration of natural daylight was less than 12 h, natural light was supplemented with light from high-pressure sodium lamps (P.L. Light Systems, Beamsville, Ontario, Canada) from 6:00 to 8:00 AM and 5:00 to 8:00 PM.

Experimental units were square plastic pots that were 9 × 9 cm wide, and 9 cm deep. Pot bottoms included drainage holes that were lined with nylon fabric mesh (<0.1-mm opening) that prevented soil loss during filling. About 40 seaside petunia seeds were planted at a depth of 0.5 cm in each pot and later thinned to one plant per pot at 14 d after seedling emergence. Before thinning, pots were subirrigated by placement in basins with water. After seaside petunia populations were thinned, pots were surface irrigated with a sprinkler canister as required.

Treatments were factorial combinations of postemergence herbicide and seaside petunia plant size at spraying. Herbicide treatments were 1) bromoxynil at 0.37 lb/acre [2 lb/gal, emulsifiable concentrate (Moxey 2E; Winfield Solutions, St. Paul, MN)], 2) flumioxazin at 0.06 lb/acre (Chateau SW), 3) oxyfluorfen at 0.25 lb/acre (Goaltender) with 0.25% v/v nonionic surfactant (Induce; Helena Chemical Co., Collierville, TN), and 4) no herbicide (nontreated control

for comparison). Herbicide rates were maximum labeled rates for single applications in onion in New Mexico. Herbicides were applied using a moving-nozzle spray chamber (DeVries Manufacturing) equipped with an even-flat nozzle tip (8002EVS, TeeJet Technologies). Spray application rates were the equivalent of 20 gal/acre for flumioxazin and oxyfluorfen, and 50 gal/acre for bromoxynil. Spray application rates were minimum spray volumes for emerged onion according to labeled guidelines (Dow AgroScience, 2014; Valent U.S.A., 2019; Winfield Solutions, 2016). To ensure herbicide absorption by seaside petunia plants, pots were not watered for 48 h after herbicide application.

At the time of spray, seaside petunia plants had one primary stem. The length of the primary stem was the basis for plant size treatments. Seaside petunia size treatments were 1) stem length 1 to 2 cm, 2) stem length 5 to 7 cm, 3) stem length 8 to 12 cm, and 4) stem length 13 to 16 cm. Seaside petunia size treatments were obtained by initiating new experimental units every 16 d for 64 d. Specifically, plants with stems 13 to 16 cm were sown 64 d before spraying, plants with stems 8 to 12 cm were sown 48 d before spraying, plants with stems 5 to 7 cm were sown 32 d before spraying, and plants with stems 1 to 2 cm were sown 16 d before spraying. This sowing schedule allowed all seaside petunia plants to be treated with herbicides on the same day.

Immediately after spraying, pots were arranged on the greenhouse bench in a randomized complete block design with four replications. At 14 DAT, seaside petunia plants were evaluated for visual estimates of herbicide injury using a rating scale, with 0.5 intervals, ranging from 0 to 10, with 0 indicating no visual difference from nontreated control and 10 indicating complete shoot death. At 14 DAT, seaside petunia plants were harvested and weighed immediately to determine aboveground fresh biomass.

DATA ANALYSIS. Statistical analyses were performed using the open source statistical software program R (version 3.6.2; R Foundation for Statistical Computing, Vienna, Austria). Levene's test for homogeneity of variances (Zar, 1999) indicated equal variances between experimental runs, and

preliminary analyses indicated that response variables were unaffected by experimental run or interactions between treatments and runs ($P > 0.05$). Therefore, data for the two experimental runs were combined.

For the preemergence herbicide study, seaside petunia seedling density data were expressed as percentages of the nontreated control and were analyzed with a two-step process. First, seaside petunia percent density responses to preemergence herbicides at the $1.0\times$ labeled rates were assessed with a linear mixed-effect model developed with the R library *nlme*. The fixed effects were herbicide and run, and the random effect was replicate within run. During model development, visual inspections of residuals plotted against fitted values indicated that the arcsine transformation of the response variable improved model fit. Thus, percentage data for seaside petunia density were subjected to arcsine transformations before final statistical modeling. For presentation in this article, arcsine-transformed data were back-transformed after statistical analyses.

Preemergence herbicides with equally low numbers of seaside petunia seedlings were assessed further with the second step for analyzing seaside petunia seedling density data. In the second step, mean densities for a specific herbicide were expressed as percentages of nontreated controls and plotted as functions of application rate. Then, the R library *drc* was used to select the best-fit, nonlinear regression model from the following four candidates: 1) three-parameter log-logistic model, 2) three-parameter exponential decay model, 3) three-parameter Weibull type I model, and 4) three-parameter Weibull type II model (Ritz et al., 2015). To account for inherent constraints on the relationship between percent seedling density and herbicide application rate, upper asymptotes were restricted to values less than or equal to 100, and lower asymptotes were restricted to values greater than or equal to zero. Model fits were evaluated with information criteria provided by the *drc* function *mselect*, with best-fit models featuring minimum values for Akaike's information criterion. Best-fit models were used to compare descriptively preemergence herbicides at below-label rates. However, best-fit models were not used to

determine effective doses based on relative distances between upper and lower asymptotes (i.e., ED_{50}), because lower asymptotes were substantially greater than zero for some preemergence herbicides.

For the postemergence herbicide study, visual injury rating data were analyzed with Friedman's test followed by post hoc Conover tests for nonparametric data using the R library *PMCMRplus*. The R library *nlme* was used to develop a linear mixed-effects model for the effects of plant size at spraying and herbicide on seaside petunia biomass at 14 DAT. In this model, the response variable was the arcsine transformation of seaside petunia biomass expressed as a percentage of the control treatment. Visual inspections of residuals plotted against fitted values indicated that the arcsine transformation of the response variable improved model fit. Arcsine-transformed data were back-transformed for presentation in this article. Fixed effects in the model were combinations of plant size at spraying, herbicide, and run. The random effect was replicate in run. After development of the linear mixed-effects model, the R library *multcomp*

was used to generate Tukey all-pairs comparisons for fixed effects.

Results

PREEMERGENCE HERBICIDE STUDY.

Dimethenamid-P, flumioxazin, oxyfluorfen, and S-metolachlor equally suppressed seaside petunia emergence when these herbicides were applied at labeled rates for onion (Fig. 2), with fewer than 20% of seaside petunia seedlings emerged compared with the nontreated control. Percent seedling density was greater than 50% of the nontreated control for labeled rate treatments of DCPA and pendimethalin, indicating that these herbicides were the least effective for preemergence control of seaside petunia.

Best-fit models for percent seedling density responses to below-label rates differed among flumioxazin, oxyfluorfen, S-metolachlor, and dimethenamid-P (Table 1). For S-metolachlor and dimethenamid-P, application rate effects on percent seedling density were best summarized by exponential decay models. For dimethenamid-P, seaside petunia seedling density increased as application rates decreased, with percent seedling density as high as 58% of the nontreated control at $0.125\times$ the

Fig. 2. Seaside petunia emergence responses to dimethyl tetrachloroterephthalate (DCPA), dimethenamid-P, flumioxazin, pendimethalin, and S-metolachlor applied to soil at labeled rates for onion on coarse soil. Labeled rates were DCPA at 6 lb/acre, dimethenamid-P at 0.84 lb/acre, flumioxazin at 0.06 lb/acre, oxyfluorfen at 0.25 lb/acre, pendimethalin at 0.71 lb/acre, and S-metolachlor at 0.64 lb/acre. Herbicide effects on seedling emergence were determined at 30 d after treatment (DAT). The study was performed in growth chambers set to 27/17°C (80.6/62.6°F) day/night, 12-h photoperiods. Bars are means ($\pm$ SE) of eight replications from two pooled experimental runs. Means that share the same letter are not different at $P < 0.05$ according to Tukey's test performed following arcsine transformation of the response variable. Data were back-transformed for presentation in this figure; 1 lb/acre = 1.1209 kg·ha⁻¹.

Table 1. Best-fit models for herbicide application rate effects on seaside petunia seedling densities expressed as percentages of nontreated controls.

Herbicide	Best-fit model	Model formula	Model parameter	Estimate	SE	P value
Dimethenamid-P	Exponential decay	$y = a + (b - a) \times \exp\left(\frac{-x}{c}\right)$	a^z	18.39	2.95	0.02
			b^y	100	— ^u	—
			c^x	0.16	0.01	0.008
Flumioxazin	Weibull, type 1	$y = d \times \exp(-\exp(e(\log(x) - \log(f))))$	e^w	4.15	5.44×10^{-5}	< 0.001
			d^v	2.46	7.54×10^{-6}	< 0.001
			f^v	0.41	1.34×10^{-6}	< 0.001
Oxyfluorfen	Log-logistic	$y = \frac{d}{1 + \exp(e(\log(x) - \log(f)))}$	e^w	14.52	1.02	0.04
			d^v	1.63	8.55×10^{-5}	< 0.001
			f^x	0.25	3.49×10^{-6}	< 0.001
S-metolachlor	Exponential decay	$y = a + (b - a) \times \exp\left(\frac{-x}{c}\right)$	a^z	14.712	0.61	0.03
			b^y	85.54	6.86	0.05
			c^x	0.13	0.01	0.05

^zLower asymptote.

^yUpper asymptote.

^xSteepness of decay.

^wSlope at inflection point.

^vx-Value midway between upper and lower limits.

^uUpper asymptote was constrained to 100; thus, SE and P value could not be calculated.

Herbicides were applied at 0.125×, 0.25×, 0.5×, and 1.0× labeled rates for onion. Labeled rates were 0.84 lb/acre for dimethenamid-P, 0.06 lb/acre for flumioxazin, 0.25 lb/acre for oxyfluorfen, and 0.64 lb/acre for S-metolachlor (1 lb/acre = 1.1209 kg·ha⁻¹). Graphical representations of models with data are presented in Fig. 3.

labeled rate (Fig. 3). Similar to dimethenamid-P, S-metolachlor control of seaside petunia decreased sharply as application rates decreased from 1.0×, with percent seeding density reaching 41% of the nontreated control at the 0.125× labeled rate. For oxyfluorfen and flumioxazin, best-fit nonlinear models indicated that seaside petunia seedling density, expressed as percentages of nontreated controls, was less than 3% at all application rates.

POSTEMERGENCE HERBICIDE STUDY.

Bromoxynil, oxyfluorfen, and flumioxazin equally reduced growth of seaside petunia plants that were small at the time of spraying (stem length, 1–2 cm) (Fig. 4A). For seaside petunia plants with stems measuring 5 to 16 cm, bromoxynil caused greater reductions in growth than oxyfluorfen. Bromoxynil was similarly effective on seaside petunia plants with stems measuring 1 to 12 cm, whereas oxyfluorfen was less effective on larger plants. For seaside petunia plants with stems measuring 8 to 12 cm, biomass was 4.8% of the nontreated control after the bromoxynil treatment; but, after the oxyfluorfen treatment, biomass for these plants was 53.1% of the nontreated control. Flumioxazin reduced growth of seaside petunia plants with stems measuring 5 to 7 cm to a similar degree as bromoxynil and oxyfluorfen; but, for seaside petunia plants with stems measuring 8 to 12 cm, flumioxazin caused greater reductions in biomass than oxyfluorfen. For seaside petunia plants with stems

measuring 13 to 16 cm, bromoxynil and flumioxazin caused greater reductions in aboveground biomass than oxyfluorfen.

Herbicide-induced reductions in seaside petunia biomass coincided with visible symptoms of herbicide injury, including necrotic spotting to complete shoot death. For small seaside petunia plants, visual estimates of control at 14 DAT were high and similar among the different herbicides (Fig. 4B). As plant size at spraying increased, visual estimates of control decreased for oxyfluorfen, but remained high for bromoxynil and flumioxazin. For seaside petunia plants with stems measuring 8 to 16 cm, visual estimates for bromoxynil and flumioxazin were greater than visual estimates of control for oxyfluorfen.

Discussion

This study was conducted to initiate development of herbicide recommendations for seaside petunia in onion in New Mexico. Herbicide recommendations based only on results from controlled-environment studies are unreliable because herbicide efficacy in the field is influenced by the environment before, during, and after spraying (Kudsk and Kristensen, 1992). Therefore, herbicide recommendations are generally developed from field trials that determine herbicide efficacies across a range of conditions within a defined climatic area (Ekeleme et al., 2020). Such field trials are more efficient when they

focus on herbicides to which targeted weeds are highly susceptible. Accordingly, the results of this study can streamline field trials for clarifying chemical strategies for controlling seaside petunia in onion.

Among the six herbicides evaluated for preemergence control, seaside petunia was most susceptible to oxyfluorfen and flumioxazin. This was consistent with previous studies that indicated oxyfluorfen or flumioxazin provided more control of selected broadleaf annual weeds than pendimethalin, S-metolachlor, or dimethenamid-P. For example, Richardson and Zandstra (2006) determined that flumioxazin provided greater control of common ragweed (*Ambrosia artemisiifolia*) than pendimethalin or S-metolachlor. Taylor-Lovell et al. (2002) observed that control of velvetleaf (*Abutilon theophrasti*), common cocklebur (*Xanthium strumarium*), and ivy-leaf morningglory (*Ipomoea hederacea*) was greater with flumioxazin than pendimethalin. When compared against dimethenamid-P, Grichar et al. (2002) determined that flumioxazin provided greater control of citronmelon (*Citrullus lanatus* var. *citroides*), and Khamare et al. (2020) determined that flumioxazin provided greater control of praxelis (*Praxelis clematidea*). Eclipta (*Eclipta prostrata*) was better controlled by oxyfluorfen than pendimethalin (Gilreath et al., 2008), and oxyfluorfen gave the best pre-emergence control of weeds at a site

Fig. 3. Seaside petunia emergence responses to dimethenamid-P, flumioxazin, oxyfluorfen, and S-metolachlor applied at proportions of labeled rates for onion on coarse soil. Labeled rates were dimethenamid-P at 0.84 lb/acre, flumioxazin at 0.06 lb/acre, oxyfluorfen at 0.25 lb/acre, and S-metolachlor at 0.64 lb/acre. Herbicide effects on seedling emergence were determined at 30 d after treatment (DAT). The study was performed in growth chambers set to 27/17 °C (80.6/62.6 °F) day/night, 12-h photoperiods. Data points are means ($\pm$ SE) of eight replications from two pooled experimental runs. Regression equations can be found in Table 1; 1 lb/acre = 1.1209 kg·ha⁻¹.

where the most common weed was nettleleaf goosefoot (*Chenopodium murale*) (Qasem, 2007). Broadleaf weed control outcomes for pendimethalin, S-metolachlor, and dimethenamid-P can be improved with additional herbicides in the spray solution (Grichar, 2007; Hutchinson, 2012); however, some tank mixtures may increase risk of onion injury compared with herbicides applied alone (Herrmann et al., 2017).

Oxyfluorfen and flumioxazin are broad-spectrum, diphenyl-ether herbicides that inhibit protoporphyrinogen oxidase, an enzyme that catalyzes the biosynthesis of chlorophyll and heme compounds in plants (Zhao et al., 2020). The results of our study suggest that seaside petunia is especially susceptible to preemergence herbicides that interfere with protoporphyrinogen oxidase activity. Oxyfluorfen is registered for over-the-top applications in onions that have at least two true leaves, or at least one true leaf in states with a specific Special Local Needs label (Dow AgroScience, 2014). In only Michigan, New York, North Dakota, and Wisconsin, flumioxazin can be applied to transplanted onions with two to six leaves, and direct-seeded onions with three to six leaves

(Valent U.S.A., 2019). The onion growth stages at which flumioxazin and oxyfluorfen can be applied coincide with seaside petunia emergence, and thus, flumioxazin and oxyfluorfen are candidate herbicides for preemergence control of seaside petunia in onion.

Onion in New Mexico is typically grown on coarse soils with relatively low levels of organic matter compared with muck soils supporting onion production in the U.S. Midwest and Northeast. For soil-applied herbicides, soil organic matter influences rates effective for weed control, with effective rates generally increasing as levels of soil organic matter increase (Gonese and Weber, 1998). Accordingly, the rates for flumioxazin and oxyfluorfen in our study may not be suitable for seaside petunia control on muck soils or other soils with high levels of organic matter.

Low emergence after low-rate treatments of oxyfluorfen and flumioxazin should not be considered as evidence supporting field applications at below-label rates. This is because below-label rate applications may contribute to the development of herbicide-resistant biotypes in weed populations (Norsworthy et al., 2012). Also, below-label rates may not provide high levels of weed control

in the field because preemergence herbicides can be more effective under greenhouse conditions than in the field (Zhao et al., 2017). Nonetheless, low emergence after below-label rate applications suggests that flumioxazin and oxyfluorfen control of seaside petunia is less influenced by processes that reduce amounts of herbicide available for plant absorption compared with the other pre-emergence herbicides evaluated in our study.

Foliar applications of bromoxynil, oxyfluorfen, and flumioxazin showed similar effectiveness on seaside petunia plants with stems 1 to 2 cm in length. However, for seaside petunia plants with stems 5 to 12 cm in length, the greatest reductions in seaside petunia biomass were caused by bromoxynil. Bromoxynil also caused total shoot death to seaside petunia plants with stems 5 to 12 cm in length, which was consistent with previous studies that indicated bromoxynil controlled weeds in the nightshade family, including hairy nightshade (*Solanum physalifolium*), eastern black nightshade (*Solanum ptychanthum*), and garden huckleberry (*Solanum melanocerasium*) (Eberlein et al., 1993; Zhou et al., 2006). Bromoxynil can be applied over the top of onions that have two to five true leaves (Winfield Solutions, 2016). Depending on crop planting date, the two- to five-leaf stage of onion coincides in part with the period of seaside petunia emergence, and thus bromoxynil is a candidate herbicide for controlling seaside petunia in onion.

Differences in seaside petunia control and biomass between bromoxynil and oxyfluorfen could have been caused in part by the application spray volumes. Postemergence herbicides in our study were applied using minimum spray volumes for onion indicated on product labels. This means bromoxynil was applied at 50 gal/acre (Winfield Solutions, 2016), and oxyfluorfen was applied at 20 gal/acre (Dow AgroScience, 2014). For herbicide applications directed to leaves, higher spray volumes increase the proportion of targeted foliage covered by the herbicide solution (Legleiter and Johnson, 2016) and potentially increase the efficacy of herbicides after foliar applications. A spray volume greater than 20 gal/acre may increase oxyfluorfen efficacy, although previous studies determined

Fig. 4. (A) The effects of herbicide and plant size at spraying on aboveground biomass at 14 d after treatment (DAT) for seaside petunia plants grown in a greenhouse. **(B)** Visual estimates of seaside control at 14 DAT, with 0 indicating no injury and 10 representing shoot death. Herbicide treatments were bromoxynil at 0.37 lb/acre, flumioxazin at 0.06 lb/acre, and oxyfluorfen at 0.25 lb/acre with 0.25% v/v nonionic surfactant. Bars are means ($\pm$ SE) of eight replications from two pooled experimental runs. For a particular response variable, means with the same letter are not different at $P < 0.05$ according to Tukey's test performed following arcsine transformation of the response variable. Data were back-transformed for presentation in this figure; 1 lb/acre = 1.1209 kg·ha⁻¹, 1 cm = 0.3937 inch.

that weed control outcomes from oxyfluorfen were not influenced (Schumacher and Hatterman-Valenti, 2007), or were minimally influenced (Zandstra and Wallace, 1989), by spray volume.

Another possible strategy for increasing seaside petunia susceptibility to foliar applications of oxyfluorfen is to apply an emulsifiable concentrate (EC) formulation of oxyfluorfen rather than the water-based suspension concentrate (SC) formulation used in our study, because a previous study determined that an EC formulation of oxyfluorfen improved control of specific broadleaf

weeds when compared against a SC formulation (Herrmann et al., 2017). The EC formulation also caused more foliar injury on onions, but there was no difference in onion bulb yield between the EC and SC formulations of oxyfluorfen (Herrmann et al., 2017). Seaside petunia susceptibility to flumioxazin might be enhanced by adjuvants that promote foliar retention of herbicide solutions (Nelson and Penner, 2006); however, flumioxazin labels specify that applications after onion emergence should not include adjuvants added to spray mixtures (Winfield Solutions, 2016).

Based on the results of our study, a promising herbicide program for seaside petunia in onion includes oxyfluorfen or flumioxazin for control of seaside petunia plants yet to emerge, and bromoxynil for control of seaside petunia plants that have already emerged. Future field trials should identify optimized application rates and application timings for controlling seaside petunia in onion with bromoxynil, flumioxazin, and oxyfluorfen. As herbicide recommendations are developed, additional research will be required to identify preventive measures and cultural practices to suppress population growth of this competitive weed.

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