Weed Technology 2015 29:844–853

Tall Morningglory (*Ipomoea purpurea*) Seedbank Density Effects on Pendimethalin Control Outcomes

Brian J. Schutte and Ashley Cunningham*

Pendimethalin control failures on tall morningglory are critical shortcomings in weed-control programs for chile pepper in New Mexico. Using weed seedbank augmentation, we conducted a field study to (1) determine if pendimethalin control of tall morningglory is affected by tall morningglory seedbank density, and (2) identify weed community factors that influence labor for removing the tall morningglory plants that escape pendimethalin. The field study was complemented with a growth chamber study conducted to clarify the effects of pendimethalin rate on the putative association between tall morningglory seedbank density and pendimethalin control outcomes. Under field conditions and after square-root transformation of the dependent variable, the effects of seedbank density on seedling escape density were described with natural logarithmic functions. Although pendimethalin control of tall morningglory decreased with increasing seedbank density, seedbank additions increased labor requirements for removing tall morningglory at only a site-year characterized by low population densities in the indigenous weed community. In growth chambers, increasing pendimethalin rate negatively influenced the effects of increasing seedbank density on pendimethalin control failures. This study shows that pendimethalin control of tall morningglory is reduced when seedbank densities of this species are high. Knowledge of seedbank density effects on specific control outcomes may influence grower attitudes on management strategies that target weed seedbanks.

Nomenclature: Pendimethalin; tall morningglory, *Ipomoea purpurea* (L.) Roth. PHBPU
Key words: Functional relationships for weed control, herbicide efficacy, seedbank management, soil-applied herbicide, weed seedbank.

Fallas en el control de *Ipomoea purpurea* con pendimethalin son limitantes críticas en los programas de control de malezas en pimiento en New Mexico. Usando una argumentación basada en banco de semillas de malezas, realizamos un estudio de campo para: 1) determinar si el control con pendimethalin de *I. purpurea* es afectado por la densidad del banco de semillas de esta maleza, e 2) identificar los factores de la comunidad de malezas que influencian la labor de remoción de plantas de *I. purpurea* que escapan a pendimethalin. El estudio de campo fue complementado con un estudio en una cámara de crecimiento realizado para aclarar los efectos de la dosis de pendimethalin sobre la asociación putativa entre la densidad del banco de semillas de *I. purpurea* y los resultados del control con pendimethalin. Bajo condiciones de campo y después de transformar con raíz cuadrada la variable dependiente, los efectos de la densidad del banco de semillas sobre la densidad de escapes de plántulas fue descrita con funciones logarítmicas naturales. Aunque el control de *I. purpurea* con pendimethalin disminuyó con el aumento de la densidad del banco de semillas, adiciones al banco de semillas aumentaron los requerimientos de labranza para remover *I. purpurea* en solamente un sitio-año, el cual estuvo caracterizado por densidades de población bajas en la comunidad indígena de malezas. En las cámaras de crecimiento, el aumentar la dosis de pendimethalin influenció negativamente los efectos de incrementos en la densidad del banco de semillas sobre las fallas en el control con pendimethalin. Este estudio muestra que el control de *I. purpurea* con pendimethalin se reduce cuando las densidades del banco de semillas de esta especie son altas. Este conocimiento de los efectos de la densidad del banco de semillas sobre los resultados específicos del control podría influenciar las actitudes de los productores sobre las estrategias de manejo que se enfocan en los bancos de semillas de malezas.

Pendimethalin is a soil-applied herbicide that inhibits growth of susceptible plant species by arresting division of root cells in emerging seedlings (Shaner et al. 2014). This herbicide is an important component of weed-control programs for chile pepper in New Mexico because pendimethalin applications near the time of chile pepper thinning can reduce the need for subsequent hoeing (Lee and Schroeder 1995). Pendimethalin is popular among chile pepper growers because, compared with other soil-applied herbicides used after chile pepper

DOI: 10.1614/WT-D-14-00161.1

* Assistant Professor and Graduate Student, Department of Entomology, Pathology and Weed Science, New Mexico State University, Las Cruces, NM 88003. Corresponding author's E-mail: bschutte@nmsu.edu

Table 1. Soil characteristics at field study sites.

Site[a]	Year	Physicochemical properties				Indigenous weed seedbank						
		Sand	Silt	Clay	Organic matter	AMAPA[b]	ANVCR	ECHCO	EPHSN	ERACN	SETLU	SORVU
		%				Seeds m^{-2}						
Las Cruces	2013	6	48	46	0.9	1,179	38	342	38	114	76	—[c]
	2014	17	26	57	0.5	50	—	746	25	25	75	75
Los Lunas	2013	66	10	24	0.6	3,555	—	—	121	323	81	—
	2014	67	10	23	0.4	316	—	—	316	2,973	—	—

[a] The field study was conducted at two New Mexico State University research farms: Leyendecker Plant Science Center near Las Cruces, NM (32.2°N, 106.75°W; elevation 1,176 m) and the Agricultural Science Center at Los Lunas, NM (34.77°N, 106.76°W; elevation 1,476 m). At each site, experiments were conducted in different fields during 2013 and 2014.

[b] Explanation of abbreviations. AMAPA, *Amaranthus palmeri*; ANVCR, *Anoda cristata*; ECHCO, *Echinochloa colona*; EPHSN, *Chamaesyce serpens*; ERACN, *Eragrostis cilianensis*; SETLU, *Setaria pumila*; SORVU, *Sorghum bicolor*.

[c] Dashes indicate that species were not found.

emergence, pendimethalin provides broad-spectrum control with relatively few limitations. Specifically, other soil-applied herbicides either provide no control of grass species (halosulfuron-methyl), or require chile pepper growers to release the manufacturer of liability and indemnification for crop damage (*S*-metolachlor), or must be mechanically incorporated (trifluralin). Increased knowledge of the factors that influence pendimethalin control outcomes will contribute to the development of improved strategies for weed management in chile pepper.

One of the more difficult weeds to control in chile pepper in New Mexico is tall morningglory, which is a competitive summer annual species that can serve as an alternate host for economically important chile pepper plant diseases (Sanogo et al. 2009). Tall morningglory is not adequately controlled by pendimethalin (Grey and Wehtje 2005; Wilcut et al. 1997). Working with a soil-applied herbicide other than pendimethalin and with weed species not including tall morningglory, Taylor and Hartzler (2000) determined that higher herbicide rates were needed to control weeds in sites with high seedbank densities. These findings were later corroborated by Sparks et al. (2004) and were consistent with previous studies that determined that the bioavailability of soil-applied herbicides decreased as the density of the targeted plant population increased (Hoffman and Lavy 1978; Winkle et al. 1981).

On the basis of research with other soil-applied herbicides (Hoffman and Lavy 1978; Sparks et al. 2004; Taylor and Hartzler 2000; Winkle et al. 1981), we speculate that pendimethalin control of tall morningglory might be related to the population density of this species. However, this relationship has not been determined. The objectives of this study were: (1) to determine pendimethalin control outcomes as affected by varying seedbank densities of tall morningglory in the field, (2) to identify weed community factors that influence hoeing labor for removing the tall morningglory plants that escape pendimethalin, and (3) to clarify the effects of pendimethalin rate on the putative association between tall morningglory seedbank density and pendimethalin control outcomes.

Materials and Methods

Field Study. Pendimethalin (Prowl H_2O®, BASF Corp., Research Triangle Park, NC) control responses to varying tall morningglory seedbank densities were determined at New Mexico State University (NMSU) research farms at Las Cruces, NM and Los Lunas, NM during 2013 and 2014 (Table 1). Each year, fields were subjected to a sequence of preparatory procedures that included tilling, laser leveling, listing, and shaping raised beds into rows spaced 1 m apart at Las Cruces and 0.75 m apart at Los Lunas. The width of a raised bed was 0.8 m at Las Cruces and 0.6 m at Los Lunas.

For each site-year, soil physicochemical properties and indigenous weed seedbank densities were determined by taking soil cores (2.54-cm diameter, 10-cm depth; 160 cores site-year^{-1}) at evenly spaced intervals along W-shaped patterns across the study area. Soil samples were bulked within site-year. For physicochemical properties, soil was subsampled and analyzed by a commercial laboratory (A&L Plains Agricultural Laboratories Inc., Lubbock, TX). For seedbank analyses, subsamples were elutriated using a hexametaphosphate aqueous solution (0.15 g ml^{-1}) and recovered seeds were then tested for viability with tetrazolium staining assays using a 0.6% aqueous solution of 2,3,5-triphenyl-tetrazolium chloride (Peters 2000).

Field study treatments were factorial combinations of seedbank augmentation level (described below) and herbicide treatment (pendimethalin-treated, untreated). Field study treatments were replicated four times at each site-year. Experimental units were plots (2 m by 0.5 m; hereafter referred to as "treatment plots") that were arranged in randomized complete blocks with at least 1.5-m spacing between neighboring treatment plots. In addition to treatment plots, the study included a systematic arrangement of check plots (Besag and Kempton 1986) that controlled for the study species in the existing seedbanks (hereafter, "seedbank check plots") and check plots to ensure that pendimethalin efficacy was consistent with previous studies (hereafter, "pendimethalin check plots"). Seedbank check plots were not augmented with weed seeds, were immediately adjacent to treatment plots, and were subjected to the same herbicide treatment as the adjacent treatment plot. Pendimethalin check plots were seeded with yellow foxtail (*Setaria pumila* [Poir.] Roemer & J.A. Schultes). Previous research determined that pendimethalin provides control of annual grass weeds including giant foxtail (*Setaria faberi* Herrm.) (Kapusta et al. 1993) and yellow foxtail (Schroeder et al. 2010). In this study, plots seeded with yellow foxtail were included to ensure that pendimethalin applications provided levels of control consistent with previous research.

Species-specific seedbank augmentation levels were based on estimated seed outputs from plants that escaped control during the previous growing season, with consideration of overwinter loss of physical seed dormancy for tall morningglory and physiological seed dormancy for yellow foxtail (Burnside et al. 1996; Crowley and Buchanan 1982; Kegode et al. 1999; Nadeau and Morrison 1986). Seedbank augmentation for tall morningglory was 15, 30, 60, 120, and 240 seeds m^{-2}, and for yellow foxtail, 500, 1,500, 2,500, 3,500, and 4,500 seeds m^{-2}. Because of limitations on space, the highest seedbank augmentation levels for each species were not included at Los Lunas.

Plot placement and the sequence of procedures for establishing plots differed between study sites. At Las Cruces, where plots were placed on raised beds, plots were established by first applying pendimethalin to appropriate plots. After mechanical incorporation of the herbicide, plots were seeded by evenly distributing the seeds across the soil surface and burying the seeds 1 to 2 cm using tine rakes. This burial depth was previously determined to be within the optimum for range emergence for tall morningglory (Singh et al. 2012) and foxtail species including green foxtail (*Setaria viridis* [L.] Beauv.) (Boyd and Van Acker 2003) and giant foxtail (Davis and Renner 2007). During seed burial, care was taken to not transfer untreated soil into the pendimethalin-treated plots. At Los Lunas, where plots were placed in furrows, plots were established by first augmenting seedbanks and then applying pendimethalin. Herbicide incorporation at Los Lunas was accomplished with irrigation. At both study sites, pendimethalin was applied using a CO_2-powered backpack sprayer equipped with a boom with a single nozzle (TeeJet 8002VS, TeeJet® Technologies, Wheaton, IL).

The pendimethalin rate was site specific and was the maximum label rate for pendimethalin in chile pepper with consideration of local soil textures (Table 1). At Las Cruces, pendimethalin was applied at 1.6 kg ai ha^{-1}. At Los Lunas, pendimethalin was applied at 0.8 kg ai ha^{-1}. After herbicide application and weed seedbank augmentation, study sites were flood irrigated as needed. Irrigation events occurred 1 h and 21 d after weed seedbank augmentation at Las Cruces and 1 h, 3 d, 10 d, and 17 d after herbicide application at Los Lunas. At Las Cruces, weed seedbanks were augmented on May 22, 2013 and May 16, 2014. At Los Lunas, weed seedbanks were augmented on June 24, 2013 and May 29, 2014.

At 35 d after seeding (950–1,000 cumulative growing degree units [GDUs] at Las Cruces; 850–900 cumulative GDUs at Los Lunas, GDU base temperature = 10 C), tall morningglory and yellow foxtail population densities were determined within quadrats (0.5 m by 1 m) that were placed in the centers of treatment and check plots. Plant population density data were used to determine the augmentation effect (AE):

$$AE = \varepsilon_{augmented} - \varepsilon_{nonaugmented} \quad [1]$$

where $\varepsilon_{augmented}$ represents tall morningglory or yellow foxtail population density in the treatment plot and $\varepsilon_{nonaugmented}$ represents tall morningglory or yellow foxtail population density in the seedbank check plot that was adjacent to the treatment plot. For pendimethalin-treated plots, AE indicated the number of added seeds that produced seedlings that escaped pendimethalin. Hereafter, AE in pendimethalin-treated plots is referred to as "seedling escapes in the field."

For each species within a site-year, values for AE were used to determine the percent control in the field:

$$\text{Control in the field}(\%)_{nr} = \left[(\text{Unsprayed AE}_{nr} - \text{Sprayed AE}_{nr})/\text{UnsprayedAE}_{nr}\right] \times 100 \quad [2]$$

where Control in the field $(\%)_{nr}$ is the percent control in seedbank augmentation treatment *n*, replicate *r*; Unsprayed AE_{nr} is the augmentation effect for the untreated plot in seedbank augmentation treatment *n*, replicate *r*; and Sprayed AE_{nr} is the augmentation effect for the pendimethalin-treated plots in seedbank augmentation treatment *n*, replicate *r*.

Quadrats used for counting tall morningglory plants were also used to collect population density data for weed species in the indigenous communities. At Las Cruces, weed species other than tall morningglory included: Palmer amaranth (*Amaranthus palmeri* S. Wats.), spurred anoda (*Anoda cristata* [L.] Schlecht.), creeping spurge (*Chamaesyce serpens* [Kunth] Smal), large crabgrass (*Digitaria sanguinalis* [L.] Scop.), junglerice (*Echinochloa colona* [L.] Link), kochia (*Kochia scoparia* [L.] Schrad.), sorghum (*Sorghum bicolor* [L.] Moench ssp. *bicolor*), and yellow foxtail. At Los Lunas, weed species other than tall morningglory included: Palmer amaranth, spurred anoda, yellow nutsedge (*Cyperus esculentus* L.), stinkgrass (*Eragrostis cilianensis* [All.] Vign. ex Janchen), creeping spurge, barley foxtail (*Hordeum jubatum* L.), kochia, and yellow foxtail. In addition to population densities, aboveground weed biomass was also quantified. This was accomplished by first sectioning the quadrat into four subquadrats that each measured 0.25 m by 0.25 m. From a randomly selected subquadrat, aboveground plant biomass was clipped at the soil surface and sorted according to species. Biomass was then dried for 5 to 6 d at 70 C and was then weighed.

After collection of biomass and population density data in 2014, the labor needed to remove the weed escapes in the pendimethalin-treated plots was determined by measuring both hoe times to the nearest 0.1 s and the number of hoe swipes. The number of hoe swipes was determined using a pedometer that was fastened to the hoe handle, near the head of the hoe. Hoes with pedometers were calibrated by regressing visual measurements on pedometer readings for swipe frequency.

Plant Material. Seeds were obtained by hand-harvesting seed-bearing inflorescences from plants that grew in agricultural fields during the summer of 2012. For yellow foxtail, seeds matured on plants that grew at the NMSU research farms where the field studies took place. Field studies used locally collected yellow foxtail seeds, whereas the growth chamber study (described below) used a seed population pooled across harvest locations. Because of the absence of tall morningglory at the NMSU research farms, tall morningglory seeds were collected from an agricultural field located near Las Cruces, NM (32.23°N, 106.74°W; elevation 1,170 m). After collection, tall morningglory and yellow foxtail plant materials were dried in an unheated greenhouse for 14 to 20 d. Dried inflorescences were hand thrashed and sequential combinations of sieving and forced-air separation were used to separate seeds from chaff. After forced-air separation, mean 100-seed weights were 0.19 ± 0.004 (standard error [SE]) g for yellow foxtail, 2.25 ± 0.035 g for tall morningglory. Cleaned seed populations were stored in airtight containers at 5 C. Before storage, percentages of viable seeds within seed populations were determined with tetrazolium staining assays (Peters 2000) that were described previously. Rates of viability were determined to be high ($>$ 80%) for the tall morningglory and the yellow foxtail seed populations used in this study.

Pendimethalin does not adversely affect susceptible weed species at the seed stage of the plant life cycle (Shaner et al. 2014). To ensure that seeds added to soil completed germination and produced seedlings, seed dormancy was reduced before burial through species-specific procedures that reflected

https://doi.org/10.1614/WT-D-14-00161.1 Published online by Cambridge University Press

their unique mechanisms of seed dormancy. For yellow foxtail, which is characterized by physiological dormancy (Baskin and Baskin 2014), seed dormancy was reduced with stratification at 4 C for 4 wk. For tall morningglory, which is characterized by physical dormancy (Baskin and Baskin 2014), seed dormancy was removed with scarification using course sand paper. Germination tests indicated that treatments were effective. At least 67% of treated seeds completed germination in 14-d germination assays conducted in chambers set to 35/25 C day/night 12-h photoperiods. Percent germination values were used to calibrate seedbank augmentation levels so that the indicated amounts of seeds added to seedbanks were quantities of nondormant seeds.

Growth Chamber Study. To determine the effects of pendimethalin rate on the relationship between seedbank density and control failures, a study was conducted in plant growth chambers that were set to 35/25 C, day/night 12-h photoperiods. Such conditions were previously determined to support germination of tall morningglory (Singh et al. 2012) and yellow foxtail (Dekker 2003). As was done in the field study, yellow foxtail was included to ensure that pendimethalin efficacy was consistent with rates of control reported in previous studies (Kapusta et al. 1993; Schroeder et al. 2010). The growth chamber study included two runs per species, with each run separated in time. For each run, weed species were assigned to a chamber. Within each chamber, experimental units were arranged in a randomized complete block design with four replications. Across benches within growth chambers designated for tall morningglory, average photosynthetic photon flux density was 199 $\pm$ 13 µmol m^{-2} s^{-1} (run 1) and 214 $\pm$ 8 µmol m^{-2} s^{-1} (run 2). For the chambers designated for yellow foxtail, across-bench average photosynthetic photon flux density was 259 $\pm$ 13 µmol m^{-2} s^{-1} (run 1) and 233 $\pm$ 12 µmol m^{-2} s^{-1} (run 2).

Experimental units were plastic pots (9-cm width, 9-cm length, 6-cm depth) filled with a substrate and seeds buried 1 to 2 cm deep. Substrate included field soil (Belen clay loam [clayey over loamy, smectitic over mixed, superactive, calcareous, thermic Vertic Torrifluvents], pH 7.6, 0.7% organic matter) that was first autoclaved to remove existing weed seeds. After autoclaving, soil was sieved to collect particles that passed through a 4-mm screen. Sieved soil was mixed with sand (Quickrete® All-purpose sand No. 1152, The Quickrete Companies, Inc., Atlanta, GA) at a ratio of 2 : 1.5 (volume/volume) sand : soil. Pot bottoms included drainage holes that were lined with nylon fabric mesh ($<$ 0.1 mm opening) that prevented soil loss during watering.

For each species, there were a total of 20 treatments that resulted from a factorial combination of four pendimethalin rates (0 kg ai ha^{-1} [control], 0.5 kg ai ha^{-1}, 1.06 kg ai ha^{-1}, and 1.6 kg ai ha^{-1}) and five species-specific seedbank augmentation levels. For tall morningglory, seedbank augmentation levels were: 1, 3, 6, 12, and 20 seeds pot^{-1}, which corresponded to 136, 408, 815, 1,630, and 2,717 seeds m^{-2}, respectively. For yellow foxtail, seedbank augmentation levels were: 5, 14, 23, 32, and 41 seeds pot^{-1}, which corresponded to 679, 1,902, 3,125, 4,347 and 5,570 seeds m^{-2}, respectively. Pendimethalin was applied at labeled rates for different crops commonly grown in southern New Mexico. The rate of 0.5 kg ai ha^{-1} is used in alfalfa when this crop is at the seedling stage, 1.1 kg ai ha^{-1} in cotton, and 1.6 kg ai ha^{-1} in chile pepper.

Pendimethalin was applied using a moving-nozzle spray chamber equipped with the same nozzle type that was used in the field study. Pendimethalin was incorporated by applying 190 ml of water pot^{-1} over 10 min. After the initial irrigation, pots were transferred to the growth chambers. Once in growth chambers, pots were watered twice daily (morning and evening) by adding 25 ml of tap water to the surfaces of the sand–soil mixture. Preliminary experiments indicated that this watering regime prevented both crusting on substrate surface and leaching from pot bottoms.

An emerged plant was defined as any plant that reached the cotyledon stage. For yellow foxtail, emerged plants were counted at 21 d after spraying (DAS). By 14 DAS, many tall morningglory plants outgrew their pots, and thus, tall morningglory plants were enumerated and harvested at 14 DAS. To harvest tall morningglory, aboveground biomass was pooled within a pot, dried at 70 C for 5 d, and weighed. Percent control in the growth chamber was determined using the equation for percent control in the field (Equation 2). Emerged plant population densities in control pots were analogous to the augmentation effect for untreated plots.

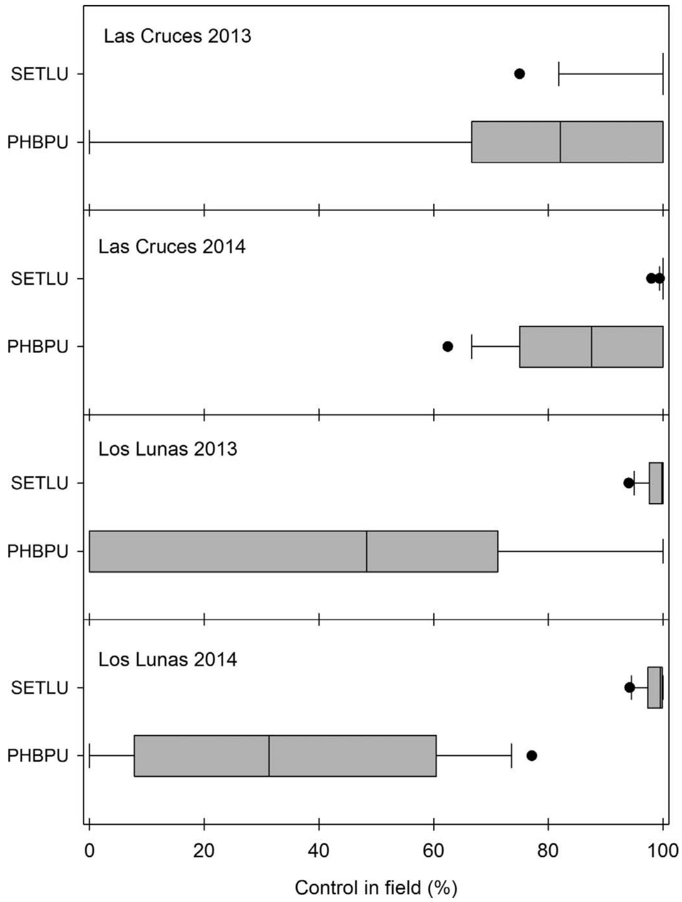

Figure 1. Box plots for data on the percent control in the field from each site-year. Shaded boxes signify the upper and lower quartiles and the medians are represented by the black lines within boxes. At Las Cruces, pendimethalin was applied at 1.6 kg ai ha^{-1}. At Los Lunas, pendimethalin was applied at 0.8 kg ai ha^{-1}. Whiskers indicate 10th and 90th percentiles of the data. For Las Cruces data, $n = 20$ and for Los Lunas data, $n = 16$. Abbreviation: PHBPU, tall morningglory; SETLU, yellow foxtail.

Emerged plant population densities in sprayed pots were analogous to the augmentation effect for the pendimethalin-treated plots. For pots that received pendimethalin, emerged plants are hereafter referred to as "seedling escapes in the growth chamber."

Data Analysis. Nonlinear regression tools in Sigma Plot 12.0 (SPSS Inc., Chicago, IL) were used to develop functional relationships for the effects of seedbank augmentation level on tall morningglory seedling escapes in the field. Specifically, nonlinear parameter estimates were obtained using an iterative ordinary least-square method, with starting values determined with automatic computations provided by the software package. Before nonlinear regression analyses and to promote homogeneity of variance among seedbank augmentation levels, data for seedling escapes in the field were square-root transformed. For each site-year, responses of mean seedling escapes to increasing seedbank augmentation level were modeled with a natural logarithmic function. Model fits to data were evaluated with pseudo-R^2 values (Schabenberger and Pierce 2002). The potential effects of year on the relationships between seedbank augmentation level and seedling escape population density were evaluated with F tests for coincidental regression (Zar 1999).

To clarify weed community factors that influenced labor for eliminating tall morningglory escapes from pendimethalin, Pearson correlation coefficients were used to evaluate the relationships between hoeing effort (hoe time and hoe swipes) and each of the following variables: tall morningglory seedbank augmentation level, tall morningglory population density, tall morningglory biomass, population density of weed species not including tall morningglory, and the biomass of weed species not including tall morningglory.

For the growth chamber study, seedbank augmentation level effects on seedling escape density and aboveground biomass were described with linear regression models that were fit separately for each pendimethalin rate. Preliminary analyses indicated that, within seedbank augmentation levels, experimental run did not influence seedling escape density or aboveground biomass ($\alpha = 0.05$). Thus, within treatments, data were pooled across runs. To determine if pendimethalin rate influenced the effects of seedbank augmentation level on both seedling escape density and aboveground biomass, F tests for coincidental regression were used to compare linear regressions (Zar 1999).

Results and Discussion

Field Study. Pendimethalin provided good control of yellow foxtail at each site-year (Figure 1). At Los Lunas, where pendimethalin was applied at 0.8 kg ai ha^{-1}, the mean percent control for yellow foxtail was 99% ± 0.5% SE in 2013 and 98% ± 0.5% in 2014. At Las Cruces, where pendimethalin was applied at 1.6 kg ai ha^{-1}, the mean percent control for yellow foxtail was 97% ± 1.8% in 2013 and 100% ± 0.1% in 2014. These rates of control for yellow foxtail were generally consistent with a

https://doi.org/10.1614/WT-D-14-00161.1 Published online by Cambridge University Press

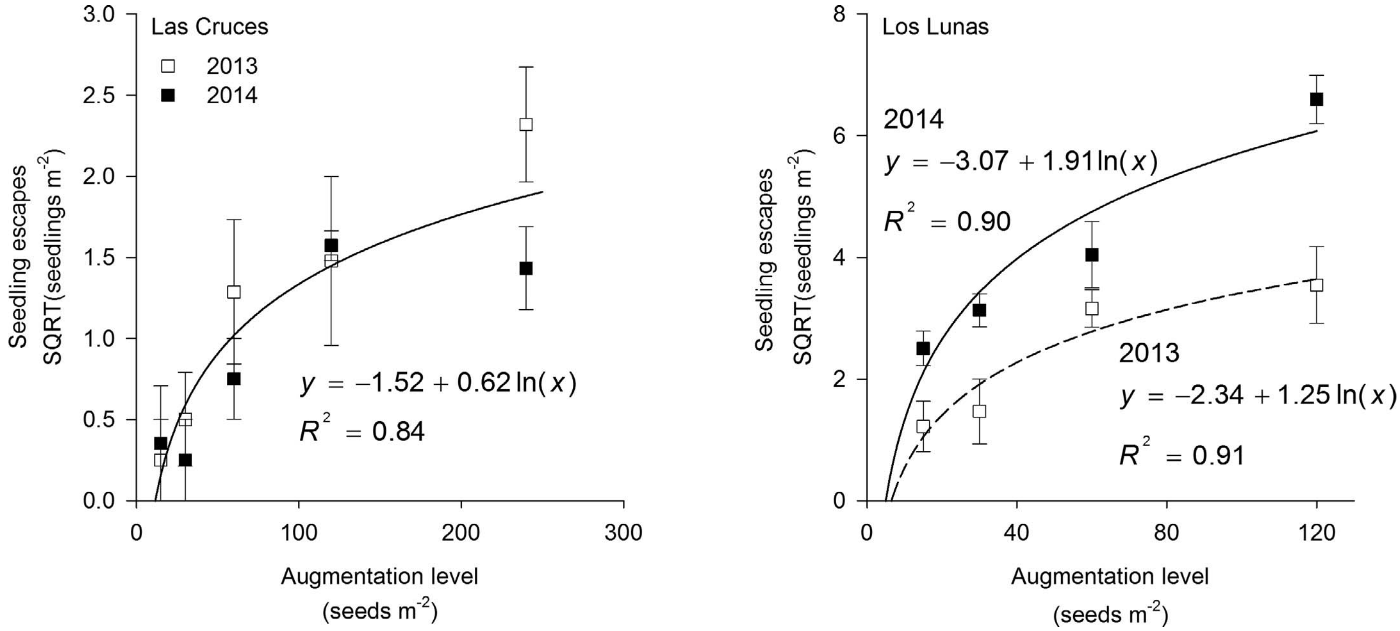

Figure 2. The effects of increasing tall morningglory seedbank augmentation level on tall morningglory seedling escapes in the field (i.e., population densities after pendimethalin application) at Las Cruces and Los Lunas. At Las Cruces, pendimethalin was applied at 1.6 kg ai ha^{-1}. At Los Lunas, pendimethalin was applied at 0.8 kg ai ha^{-1}. Tall morningglory population density data were square-root transformed before regression analyses. For the Las Cruces data, the *F* test for coincidental regression indicated that year did not influence the relationship between seedbank augmentation level and seedling escape density (P = 0.26), and thus, the regression model was fit to data for both years. For the Los Lunas data, the *F* test for coincidental regression indicated that year did influence the relationship between seedbank augmentation level and seedling escape density (P = 0.03), and thus, regression models were fit to data from each year.

previous study that determined that pendimethalin at 1.7 kg ai ha^{-1} can provide high rates of control (98 to 99%, visual control rating) of giant foxtail (Kapusta et al 1993). In this study, the high rates of control of yellow foxtail indicated that the methodology led to pendimethalin activity on susceptible plants.

For tall morningglory, the mean percent control at Los Lunas was 43% ± 9.2% in 2013 and 34% ± 6.8% in 2014. At Las Cruces the mean percent control for tall morningglory was 74% ± 6.9% in 2013 and 86% ± 3.1% in 2014. Rates of control in this study differed from a previous study that determined that pendimethalin provided no control of tall morningglory (Wilcut et al. 1997) and a previous study that determined that pendimethalin did not control tall morningglory above the 10% level (Grey and Wehtje 2005). The variation in rates of control between this study and previous studies may have been caused by differences in pendimethalin application timing. In this study, pendimethalin was applied at the time of tall morningglory germination, whereas in previous studies (Grey and Wehtje 2005; Wilcut et al. 1997) pendimethalin applications occurred before crop planting and may not have influenced tall morningglory that germinated later in the growing season.

Tall morningglory seedling escapes increased with higher seedbank densities at all site-years (Figure 2). The natural logarithmic model fit all data sets well and provided functional relationships for the effects of seedbank density on pendimethalin control outcomes under field conditions. The *F* test for coincidental regression indicated that there was not a year effect at Las Cruces (P = 0.26), but year did influence the relationship between seedling escape and seedbank density at Los Lunas (P = 0.03). The difference between years in tall morningglory escape density at Los Lunas coincided with changes in the indigenous weed community. In 2013, there were fewer tall morningglory escapes and the most abundant species in the indigenous weed community was Palmer amaranth, which had a mean population density of 33 ± 5 plants m^{-2}. In 2014, there were more tall morningglory escapes and the

Table 2. Pearson correlation coefficients for the relationships between hoe time, hoe swipes, and variables hypothesized to influence the labor effort needed to eliminate weed escapes from pendimethalin. Data were collected during 2014 at two study sites: Las Cruces and Los Lunas. Significance levels indicated as: * $P \leq 0.05$; ** $P \leq 0.01$; *** $P \leq 0.001$.

	Las Cruces		Los Lunas	
Correlate	Hoe time	Hoe swipes	Hoe time	Hoe swipes
PHBPU[a] seedbank augmentation level	< 0.01 NS	−0.05 NS	0.56*	0.68**
PHBPU population density	−0.22 NS	−0.27 NS	0.59*	0.74***
PHBPU aboveground biomass	−0.27 NS	−0.34 NS	0.49*	0.67**
Other weed population density[b]	0.50*	0.80***	0.10 NS	−0.10 NS
Other weed biomass[c]	0.35 NS	0.60**	−0.25 NS	−0.23 NS

[a] PHBPU, tall morningglory.

[b] Population density of weed species not including tall morningglory.

[c] Biomass of weed species not including tall morningglory.

most abundant species in the indigenous weed community was stinkgrass, which had a mean population density of 54 ± 14 plants m^{-2}. Previous research determined that higher herbicide rates were needed to control weed infestations with high seedbank densities (Sparks et al. 2004; Taylor and Hartzler 2000) because increased plant population densities can reduce the bioavailability of a soil-applied herbicide (Hoffman and Lavy 1978; Winkle et al. 1981). Accordingly, year-to-year differences in tall morningglory escape density at Los Lunas might have been consequences of variability in pendimethalin bioavailability caused by changes in density in the indigenous weed community.

Hoeing in chile pepper is necessary if weeds are not sufficiently controlled with pendimethalin (Lee and Schroeder 1995). In this study, labor needed to control escapes was correlated with seedbank densities of tall morningglory under specific circumstances (Table 2). At Las Cruces, where tall morningglory comprised only 13% of the weed community, hoeing effort was not correlated with the population density of the tall morningglory seedbank but was correlated with the density and biomass of weed species other than tall morningglory. At Los Lunas, where tall morningglory comprised 98% of the weed community, hoeing effort was correlated with the population density of the tall morningglory seedbank. These results indicate that additions to tall morningglory seedbanks are more likely to increase hoeing efforts under conditions where the indigenous weed community is characterized by low population densities; but, where the indigenous weed community features high population densities, additions to tall morningglory seedbank might not have a noticeable effect on hoeing effort.

Growth Chamber Study. Under growth chamber conditions, pendimethalin provided high levels of control of yellow foxtail. Across seedbank addition treatments and pendimethalin application rates, mean percent control for yellow foxtail in the growth chamber was 92% ± 1.6% in run 1 and 96% ± 1.6% in run 2. High levels of yellow foxtail control indicated that the methodology utilized in the growth chamber study led to pendimethalin activity on susceptible plants. Tall morningglory plants escaped pendimethalin control in growth chamber assays (Figure 3). *F* tests for coincidental regression indicated that regressions for seedbank augmentation level effects on seedling escape differed among pendimethalin rates ($P = 0.002$). Similarly, *F* tests for coincidental regression indicated that regression for seedbank augmentation level effects on aboveground biomass differed among pendimethalin rates ($P < 0.001$). These results indicate that, although pendimethalin control failures increase with higher seedbank densities, the effects of seedbank density on control outcomes can be lessened with increased pendimethalin rates.

Management Implications. Overall, this study indicated that pendimethalin suppression of tall morningglory is influenced by the rate at which pendimethalin is applied and the population density in the tall morningglory seedbank. Pendimethalin rate is constrained by soil conditions and crop type, and thus, strategies for improving pendimethalin control outcomes for tall morningglory should focus on tall morningglory seedbank reduction. Targeting the tall morningglory seedbank can be expected to

https://doi.org/10.1614/WT-D-14-00161.1 Published online by Cambridge University Press

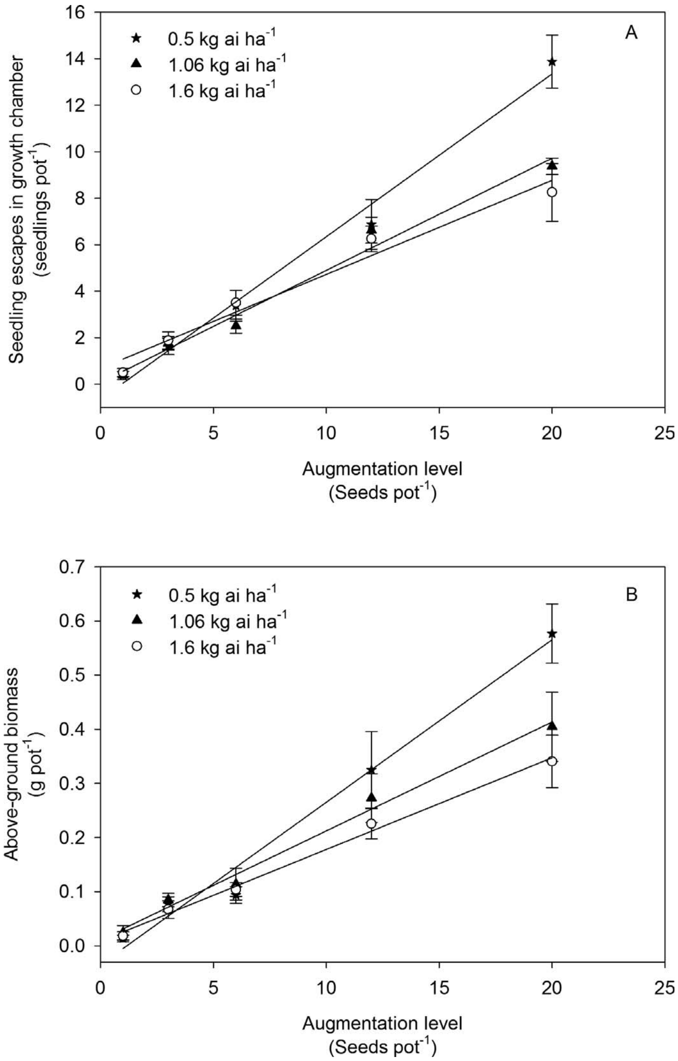

Figure 3. The effects of increasing tall morningglory seedbank density on tall morningglory seedling escape in the growth chamber (A) and tall morningglory aboveground biomass in the growth chamber (B) after treatment with pendimethalin applied at 0.5 kg ai ha^{-1} (★), 1.06 kg ai ha^{-1} (▲), and 1.6 kg ai ha^{-1} (○). Regressions for seedling escape data: 0.5 kg ai ha^{-1}, $y = -0.66 + 0.70x$, $R^2 = 0.99$, $P < 0.001$; 1.06 kg ai ha^{-1}, $y = 0.08 + 0.48x$, $R^2 = 0.98$, $P < 0.001$; 1.6 kg ai ha^{-1}, $y = 0.68 + 0.41x$, $R^2 = 0.98$, $P < 0.001$. Regressions for biomass data: 0.5 kg ai ha^{-1}, $y = -0.04 + 0.03x$, $R^2 = 0.98$, $P < 0.001$; 1.06 kg ai ha^{-1}, $y = 0.01 + 0.024x$, $R^2 = 0.99$, $P < 0.001$; 1.6 kg ai ha^{-1}, $y = 0.01 + 0.020x$, $R^2 = 0.99$, $P < 0.001$. Data points are means ± standard error, $n = 8$.

reduce labor requirements for weeding at sites characterized by weed communities with low population densities.

General methods for diminishing the soil seedbank include, but are not limited to, stale seedbed practices (Caldwell and Mohler 2001), soil heating (Egley 1983; Peruzzi et al. 2012), windrow flaming (Walsh and Newman 2007), and removal by crop harvest machinery (Walsh et al. 2013). Despite the availability of tactics that potentially reduce soil seedbank densities, these tactics are often not used because management focuses on controlling weeds in the crop. Under such circumstances, improved knowledge of the consequences of changes in soil seedbank density might encourage adoption of weed seedbank reduction strategies (Llewellyn et al. 2005). Accordingly, functional relationships for seedbank density effects on herbicide control outcomes may benefit educational programs that are intended to influence grower attitudes on management strategies that target weed seedbanks.

Acknowledgments

We gratefully acknowledge Nina Klypina, Drey Clark, Israel Marquez, and Victor Zamora for their assistance in field data collection. We thank Dr. Jill Schroeder and Dr. Jamshid Ashigh for their helpful insights throughout this project. Appreciation is also extended to Dawn VanLeeuwen for her statistical guidance and to reviewers for their thoughtful comments on a previous version of this manuscript. Salaries and research support were provided by state and federal funds appropriated to the New Mexico Agricultural Experiment Station.

Literature Cited

Baskin CC, Baskin JM (2014) Seeds: Ecology, Biogeography, and Evolution of Dormancy and Germination. New York: Elsevier. 1600 p

Besag J, Kempton (1986) Statistical analysis of field experiments using neighboring plots. Biometrics 42:231–251

Boyd NS, Van Acker RC (2003) The effects of depth and fluctuating soil moisture on the emergence of eight annual and six perennial plant species. Weed Sci 51:725–730

Burnside OC, Wilson RG, Weisberg S, Hubbard KG (1996) Seed longevity of 41 weed species buried 17 years in eastern and western Nebraska. Weed Sci 44:74–86

Caldwell B, Mohler CL (2001) Stale seedbed practices for vegetable production. Hortscience 36:703–705

Crowley RH, Buchanan GA (1982) Variations in seed production and the response to pests of morningglory (*Ipomoea*) species and small-flower morningglory (*Jacquemontia tamnifolia*). Weed Sci 30:187–190

Davis AS, Renner KA (2007) Influence of seed depth and pathogens on fatal germination of velvetleaf (*Abutilon theophrasti*) and giant foxtail (*Setaria faberi*). Weed Sci 55:30–35

Dekker J (2003) The foxtail (*Setaria*) species-group. Weed Sci 51:641–656

Egley GH (1983) Weed seed and seedling reductions by soil solarization with transparent polyethylene sheets. Weed Sci 31:404–409

Grey TL, Wehtje GR (2005) Residual herbicide weed control systems in peanut. Weed Technol 19:560–567

Hoffman DW, Lavy TL (1978) Plant competition for atrazine. Weed Sci 26:94–99

Kapusta G, Krausz RF, Matthews JL (1993) Mon-13200 early preplant controls giant foxtail (*Setaria faberi*) season-long in no-till soybean (*Glycine max*). Weed Technol 7:872–878

Kegode GO, Forcella F, Clay S (1999) Influence of crop rotation, tillage, and management inputs on weed seed production. Weed Sci 47:175–183

Lee RD, Schroeder J. 1995. Weed Management in Chile. New Mexico State University Agricultural Experiment Station Circular 548

Llewellyn RS, Pannell DJ, Lindner RK, Powles SB (2005) Targeting key perceptions when planning and evaluating extension. Aust J Exp Agric 45:1627–1633

Nadeau LB, Morrison IN (1986) Influence of soil moisture on shoot and root growth of green and yellow foxtail (*Setaria viridis* and *Setaria lutescens*). Weed Sci 34:225–232

Peruzzi A, Raffaelli M, Frasconi C, Fontanelli M, Barberi P (2012) Influence of an injection system on the effect of activated soil steaming on *Brassica juncea* and the natural weed seedbank. Weed Res 52:140–152

Peters, J 2000. Tetrazolium Testing Handbook. Contrib. No. 29 to the Handbook on Seed Testing. Lincoln, NE: Association of Official Seed Analysts. Pp 1–21

Sanogo S, Etarock BF, Clary M (2009) Recovery of *Verticillium dahliae* from tall morningglory (*Ipomoea purpurea*) in New Mexico and its pathogenicity on chile pepper. Plant Dis 93:428–428

Schabenberger O, Pierce FJ (2002) Contemporary Statistical Models for the Plant and Soil Sciences. New York: CRC Press. 790 p

Schroeder J, Ashigh J, Fiore C (2010) Weed Science Field Research Report. Department of Entomology, Plant Pathology and Weed Science. New Mexico State University. Available at http://eppws.nmsu.edu/research-programsreports/. Accessed December 20, 2014

Shaner D, Jachetta J, Senseman S, Burke I, Hanson B, Jugulam M, Tan S, Glenn B, Turner P (2014) Herbicide Handbook. 10th edn. Lawrence, KS: Weed Science Society of America

Singh M, Ramirez AHM, Sharma SD, Jhala AJ (2012) Factors affecting the germination of tall morningglory (*Ipomoea purpurea*). Weed Sci 60:64–68

Sparks OC, Barrentine JL, Burgos NR, McClelland MR (2004) Effect of Palmer amaranth (*Amaranthus palmeri*) seedbank density on the performance of pendimethalin and fluometuron. *In* Oosterhuis DM, ed. Summaries of Arkansas Cotton Research 2003. Fayetteville, AR: Arkansas Agricultural Experiment Station, University of Arkansas

Taylor KL, Hartzler RG (2000) Effect of seed bank augmentation on herbicide efficacy. Weed Technol 14:261–267

Walsh M, Newman P (2007) Burning narrow windrows for weed seed destruction. Field Crop Res 104:24–30

Walsh M, Newman P, Powles S (2013) Targeting weed seeds in-crop: a new weed control paradigm for global agriculture. Weed Technol 27:431–436

Wilcut JW, Jordan DL, Vencill WK, Richburg JS (1997) Weed management in cotton (*Gossypium hirsutum*) with soil-applied and post-directed herbicides. Weed Technol 11:221–226

Winkle ME, Leavitt JRC, Burnside OC (1981) Effects of weed density on herbicide absorption and bioactivity. Weed Sci 29:405–409

Zar, JH (1999) Biostatistical Analysis. 4th edn. Upper Saddle River, NJ: Prentice Hall. 663 p

Received December 29, 2014, and approved June 1, 2015.

Associate Editor for this paper: Randy L. Anderson, USDA-ARS.

https://doi.org/10.1614/WT-D-14-00161.1 Published online by Cambridge University Press