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Measuring Interference from Midseason Tall Morningglory (*Ipomoea purpurea*) to Develop a Model for Teaching Weed Seedbank Effects on Chile Pepper

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Tactics that target seedbanks are important components of weed management systems; however, such tactics can be difficult to adopt because consequences of seedbank reduction are often unclear. This study developed model-based software to provide insights on the economic outcomes, in the context of chile pepper production, of additions to tall morningglory seedbanks. Data for the model were derived from this and previous studies. In this study, field experiments were conducted to determine chile pepper yield and harvest efficiency responses to mid-season tall morningglory infestations. The experimental treatments were factorial combinations of herbicide (pendimethalin-treated, nontreated) and tall morningglory density (0, 4, 8, 12, 16, 20 plants 10-m row^{-1}). Treatments were installed 9.5 weeks after crop seeding. Data collected included fresh weight of marketable chile peppers and time required for one individual to harvest 10-m of crop row, which was used to calculate the amount of chile pepper harvested in 1 min (harvest efficiency). Results indicated that crop yield was not influenced by tall morningglory density, pendimethalin treatment and interactions between tall morningglory density and pendimethalin. Harvest efficiency was influenced by tall morningglory density but was not influenced by herbicide treatment or interactions between herbicide treatment and tall morningglory density. Each additional tall morningglory plant decreased the amount of chile pepper harvested in 1 min by 9.7 g. The results of this and previous studies were used to develop model-based software that presents tall morningglory seedbank density effects on: (1) tall morningglory seedling densities after pendimethalin, (2) time requirements for hand-hoeing after pendimethalin, and (3) time requirements for hand-harvesting to acquire yield goals. The model-based software is intended to be used in the instruction of weed seedbank management strategies. By presenting seedbank density effects on weed control outcomes and crop production expenses, the model-based software might promote adoption of seedbank reduction strategies.

Nomenclature: Pendimethalin; tall morningglory, *Ipomoea purpurea* (L.) Roth PHBPU; chile pepper, *Capsicum annuum* L.

Key words: Adoption, bioeconomic modeling, chili pepper, education, extension, seedbank management, soil-applied herbicide, weed economics.

Tácticas que se enfocan en los bancos de semillas son importantes componentes de los sistemas de manejo de malezas. Sin embargo, estas tácticas pueden ser difíciles de adoptar porque las consecuencias de la reducciones en el banco de semillas son comúnmente poco claras. Este estudio desarrolló un programa computacional basado en modelos para brindar una visión profunda sobre los resultados económicos de adiciones al banco de semillas de *Ipomoea purpurea*, en el contexto de la producción de chile picante. Los datos para el modelo fueron derivados a partir de el presente estudio y estudios previos. En este estudio, se realizaron experimentos de campo para determinar las respuestas en el rendimiento de chile picante y la eficiencia en la cosecha a infestaciones de *I. purpurea* en medio de la temporada de crecimiento. Los tratamientos experimentales fueron combinaciones factoriales de herbicida (tratado con pendimethalin, sin tratamiento) y densidad de *I. purpurea* (0, 4, 8, 12, 16, 20 plantas 10-m hilera^{-1}). Los tratamientos fueron instalados 9.5 semanas después de la siembra del cultivo. Los datos colectados incluyeron peso fresco de chile comercializable y el tiempo requerido para que un individuo cosechara 10-m de hilera de cultivo, lo que fue usado para calcular la cantidad de chile cosechado por minuto (eficiencia de cosecha). Los resultados indicaron que el rendimiento del cultivo no fue influenciado por la densidad de *I. purpurea*, el tratamiento con pendimethalin ni las interacciones entre la densidad de *I. purpurea* y pendimethalin. La eficiencia de cosecha fue influenciada por la densidad de *I. purpurea*, pero no fue influenciada por los tratamientos con el herbicida o las interacciones entre la densidad de *I. purpurea* y pendimethalin. Cada planta adicional

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de *I. purpurea* disminuyó la cantidad de chile cosechado por min en 9.7 g. Los resultados de este y estudios previos fueron usados para desarrollar un programa computacional basado en modelos que presenta los efectos de la densidad del banco de semillas de *I. purpurea* sobre: (1) la densidad de plántulas de *I. purpurea* después de pendimethalin, (2) el tiempo requerido de control con azadón manual después de pendimethalin, y (3) el tiempo requerido de deshierba manual para alcanzar objetivos específicos de rendimiento. El programa basado en modelos tiene la intención de ser usado para capacitaciones en estrategias de manejo de banco de semillas de malezas. Al presentar los efectos de la densidad del banco de semillas sobre los resultados del control de malezas y los costos de producción del cultivo, este programa computacional basado en modelos podría promover la adopción de estrategias para la reducción del banco de semillas.

Chile peppers, which are cultivars of *Capsicum* species that can be hot or not depending on fruit final use (Bosland et al. 1996), are important components of New Mexico's agricultural economy. In 2015, chile peppers were planted on 3,360 ha in New Mexico and provided over $46 million in cash receipts (USDA NASS 2016). The chile pepper hectarage in New Mexico is approximately 42% of the total hectarage in the United States for this crop, and the chile peppers harvested in New Mexico are approximately 33% of those harvested in the United States (USDA NASS 2016).

Chile pepper production in New Mexico is challenged by tall morningglory, a broadleaf weed with a summer annual life cycle. The success of tall morningglory in chile pepper is caused by factors including physically dormant seeds that can remain viable in soil for up to 17 yr (Baskin and Baskin 2014; Burnside et al. 1996), tolerance to herbicides that can be applied after chile pepper emergence (Baucom and Mauricio 2010; Schutte and Cunningham 2015), a twining habit that is considered an adaptation to shading (Gianoli 2003), and prolonged periods of emergence that extend through the middle and later stages of the crop-growing season (J Schroeder, personal communication). This weed is especially unwanted because tall morningglory plants significantly increase time requirements for hand-hoeing (Schutte and Cunningham 2015) and can be asymptomatic hosts for chile pepper pests including *Verticillium dahliae* (causal agent of Verticillium wilt; Sanogo et al. 2009) and *Meloidogyne incognita* (root-knot nematode; Sanogo et al. 2008).

For chile pepper weeds other than tall morningglory, midseason infestations are known to reduce crop yield and disrupt crop harvest. For example, a previous study determined that spurred anoda [*Anoda cristata* (L.) Schlecht.] infestations that emerged 9 to 10 wk after chile pepper seeding caused crop yield reductions as great as 49% and increased the amount of time required for hand-harvesting, compared to that required in weed-free conditions (Schroeder 1993). Crop yield losses as great as 76% have been attributed to multi-species infestations (Palmer amaranth [*Amaranthus palmeri* S. Wats.], common lambsquarters [*Chenopodium album* L.], oakleaf datura [*Datura quercifolia* Kunth], and Wright groundcherry [*Physalis acutifolia* (Miers) Sandw.]) that emerged 8 to 9 wk after chile pepper seeding (Schroeder 1992). Tall morningglory plants that emerge midseason are likely to adversely affect chile pepper production, but this hypothesis has yet to be tested.

To control and suppress midseason weed infestations, chile pepper growers in New Mexico can apply soil-residual herbicides, including halosulfuron-methyl, *S*-metolachlor, trifluralin, and pendimethalin. Among these herbicides, pendimethalin is popular because this herbicide provides broad-spectrum control (halosulfuron-methyl does not control grasses), does not require growers to release the manufacturer of liability and indemnification for crop damage (such is required by *S*-metolachlor), and does not require mechanical incorporation (such is required by trifluralin). Although widely used in chile pepper production, pendimethalin does not sufficiently control tall morningglory (Grey and Wehtje 2005; Schutte and Cunningham 2015; Wilcut et al. 1997). For tall morningglory plants that survive pendimethalin, the effects of this herbicide on their level of interference in chile pepper are poorly understood. For many weed species, plants that escape soil-residual herbicides are less competitive than nontreated plants (Adcock and Banks 1991; Liphadzi and Dille 2006).

Tall morningglory management strategies benefit from tactics that target soil seedbanks, because such tactics suppress population growth rates of annual weeds (Davis 2006) and potentially improve outcomes of herbicidal (Dieleman et al. 1999; Schutte and Cunningham 2015) and mechanical (Davis and Williams 2007; Dieleman et al. 1999) control interventions. However, seedbank-targeting tactics can be difficult for growers to adopt, because near-term economic consequences of seedbank reduction are often unclear (Swanton et al. 2008). To address possible valuation uncertainty for weed seedbank management and help focus attention on management of soil seedbanks, the overall goal of this project was to develop model-based software for demonstrating relationships between tall morningglory seedbank density and chile pepper production expenses.

To accomplish this goal, a field study was first conducted to determine chile pepper yield and harvest efficiency responses to midseason tall morningglory infestations treated and not treated with pendimethalin. The field study was framed by the following hypotheses: 1) increasing density in midseason tall morningglory infestations reduces chile pepper yield and harvest efficiency, and 2) the effects of midseason tall morningglory on chile pepper yield and harvest efficiency are conditioned by pendimethalin applied just prior to tall morningglory emergence. The results of the field study were then combined with results from previous studies that determined seedbank density effects on pendimethalin control outcomes (Schutte and Cunningham 2015) and seedling density effects on time requirements for hand-hoeing (Schutte 2015). The aggregate data were used to develop model-based software that presents tall morningglory seedbank density effects on tall morningglory seedling densities after pendimethalin, time requirements for hand-hoeing after pendimethalin, and time requirements for hand-harvesting to acquire yield goals. In accordance with Wilkerson et al. (2002), who proposed that bioeconomic models are more valuable as educational tools rather than predictive instruments, the model developed in this study is intended to elevate concern for weed seedbank density among chile pepper growers in New Mexico.

Materials and Methods

Field Study Procedures. A field study was conducted at the New Mexico State University, Leyendecker Plant Science Research Center (32.19°N, 106.74°W) on a Belen clay loam soil (clayey over loamy, montmorillonitic [calcareous], thermic Vertic Terrifluvent) in 2014, and was repeated in 2015. Annual experimental runs occurred on different sections of the research center. In 2014, soil organic matter at the study site was 0.5%, and in 2015, soil organic matter was 0.9%. Each year, fields were subjected to a sequence of preparatory procedures that are customary for chile pepper production in the region. Field preparations included tilling, laser leveling, and listing and shaping raised beds into rows spaced 1 m apart. The width of a raised bed was 0.8 m.

The chile pepper cultivar 'New Mexico 6-4' was seeded into the center of raised beds to a depth of 2 cm at 6.7 kg ha^{-1}. Seeding was performed using a mechanical planter (MaxEmerge® Plus, John Deere, Moline, IL) and took place on May 2, 2014 and April 23, 2015. At the time of seeding, the field was uniformly treated with napropamide at 1.1 kg ai ha^{-1} to provide PRE control of small-seeded broadleaf and grass weeds. POST control of weeds that were not being studied was accomplished with cultivation, hand weeding, and herbicide (clethodim at 0.14 kg ai ha^{-1}). Throughout the duration of the study, fields were irrigated as needed using furrow irrigation, which is flood irrigation in the furrows between raised beds.

Study treatments were factorial combinations of herbicide (pendimethalin-treated or nontreated) and tall morningglory population density (0, 4, 8, 12, 16, or 20 plants per 10 meters of row). Treatments were arranged in a randomized complete block design with four replications. Treatments were installed by seeding tall morningglory and applying herbicide immediately after crop thinning, which occurred at 9.5 weeks after crop seeding. Crop thinning adjusted chile pepper stands to clumps (2 to 3 plants per clump) spaced 0.18 m apart. Experimental units were three beds by 10 m and are hereafter referred to as "plots". On the center bed of each plot, approximately 300 tall morningglory seeds were sown in a row that ran parallel to, and was 20 cm away from, the chile pepper row. The tall morningglory seeding depth was 2 cm. Prior to burial in the field, tall morninngglory seeds were hand-scarified with coarse sandpaper to remove physical seed dormancy. Pre-burial seed germination rates were determined with 14-d germination assays conducted in chambers set to 35/25 C day/night temperatures with 12 hour photoperiods. The pre-burial germination rate was 83% in 2014 and 91% in 2015. When tall morningglory seeds were sown, soil was dry (<8% volumetric moisture content) and not conducive to germination.

Immediately after tall morningglory seeding, pendimethalin (456 g ai L^{-1}, Prowl® H_2O, BASF Corp., Research Triangle Park, NC) was applied at 1.6 kg ai ha^{-1} using a CO_2-powered backpack sprayer equipped with a boom with an even-flat nozzle (TeeJet® 8002EVS, TeeJet Technologies, Wheaton, IL). Herbicide bands (30-cm width) were directed to soil areas where tall morningglory seeds were buried. Herbicide was incorporated, and tall morningglory germination stimulated, with flood irrigation occurring 4 hr after herbicide application. At 12 d after spraying (DAS), tall morningglory plants were thinned to appropriate densities. Seedlings were removed at the first leaf stage such that tall morningglory plants were spaced evenly along the length of a plot.

At 78 to 90 DAS, marketable chile peppers were harvested by hand. Marketable chile peppers were straight, free of disease symptoms, and at least 10 cm in length. Data collected at harvest included tall morningglory population density, chile pepper fresh weight (fw), and time required for one individual to harvest 10 m of crop row, which is equal to 1×10^{-3} ha. These data were used to calculate the amount of chile pepper harvested in 1 min from 10 m of crop row, which is hereafter referred to as "harvest efficiency".

Field Study Data Analysis. All statistical analyses were performed with the statistical software R version 3.3.0 (The R Foundation for Statistical Computing, http://www.r-project.org). Bartlett's test for homogeneity of variance (Zar 1999) indicated equal variances between years for crop yield and harvest efficiency, and therefore these data were pooled across years.

The R library *lme4* was used to produce linear mixed-effects models (LMMs) for crop yield and harvest efficiency responses to tall morningglory density and pendimethalin treatment. Applications and principles of LMMs have previously been reviewed in the context of weed science (Luschei and Jackson 2005). In this study, mixed-effects modeling was selected as the data analysis approach because the resulting models provided parameter estimates for influential factors that were independent of year (Luschei and Jackson 2005). Such generalized understanding was desired for the bioeconomic model. Fixed effects in the LMMs were tall morningglory density, pendimethalin treatment, and interactions between tall morningglory density and pendimethalin treatment. Random effects in the LMMs were the hierarchical structures of sampling, which were year and replication within year.

LMMs were assessed for parsimony by comparing Akaike's information criteria (AIC) between models with intercepts, fixed effects, and random effects (AIC_{full}) and models with only intercepts and random effects (AIC_{null}) (Nakagawa and Schielzeth 2013). LMMs were assessed for goodness of fit by evaluating the proportions of total variance explained by fixed effects alone (marginal R^2) and the proportions of total variance explained by both fixed and random effects (conditional R^2) (Nakagawa and Schielzeth 2013). Standard errors for fixed effect estimates were used to determine 95% confidence intervals (Pinheiro and Bates 2000). Confidence intervals (95%) that included zero were indicative of nonsignificant fixed effects.

Bioeconomic Model. Software that presents possible economic implications of tall morningglory seedbank additions was created by considering a system featuring state variables and user-defined variables (Fig. 1). Rates that regulate transitions between state variables were from the current and previous studies. For the transition from seedbank density to seedling density, a previous study determined that 4% of nondormant seeds buried 1 to 2 cm produced seedlings that escaped pendimethalin applied at 0.16 kg ai ha^{-1}, and that 26% of nondormant seeds produced seedlings that escaped pendimethalin applied at 0.8 kg ai ha^{-1} (Schutte and Cunningham 2015). It is important to note that Schutte and Cunningham (2015) determined seedbank density effects on pendimethalin control outcomes with tall morningglory seeds that were collected from one site-year and buried to depths that were within the optimum range for emergence. Thus, seedling establishment parameters used in this model do not reflect age and depth structures of natural seedbanks and are not recommended for use in predictive instruments involving tall morningglory population dynamics. For hoeing requirements, prior research showed that each additional tall morningglory seedling increased the time required to hand hoe 10 m of crop row by 3.6 s (Schutte 2015). Harvest data from the current study indicated that each additional tall morningglory plant increased the amount of time to harvest 1 kg of chile pepper from 10 m of crop row by 0.84 s. User-defined variables, as well as model outputs, utilize units of measurement that are customary for chile pepper growers in

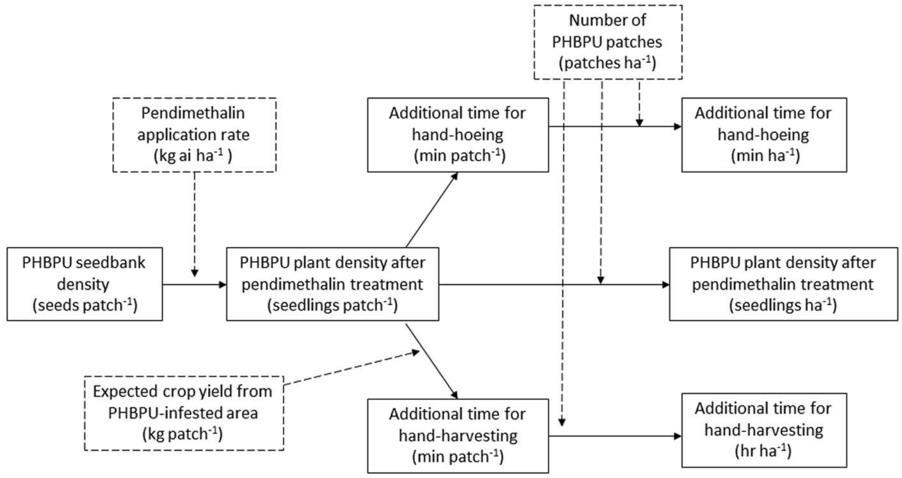

Figure 1. Underlying model for software that presents relationships between tall morningglory seedbank density and weed-control cost parameters in chile pepper production. The model initiates with the number of nondormant tall morningglory seeds buried at optimal depths for emergence within a 10-m^2 area that is hereafter referred to as a "patch". Users interact with the model by specifying the patches per hectare, pendimethalin application rate, and expected crop yield from a tall morningglory patch. User-defined variables, which are depicted with dashed-line boxes. Solid-line boxes present state variables. Rates that regulate transitions between state variables are provided in the text. Abbreviation: PHBPU, tall morningglory (*Ipomoea purpurea*).

New Mexico. However, all variables and outputs are herein presented in SI units.

The model produces per-hectare estimates for 1) tall morningglory seedling densities after pendimethalin treatment, 2) additional time required for hand-hoeing after pendimethalin treatment, and 3) additional time required for hand-harvesting to achieve yield goals if tall morningglory escapes from pendimethalin are not controlled. Model projections are presented across tall morningglory seedbank densities ranging from 0 to 1000 seeds per patch. Additional times required for hoeing and harvesting are multiplied by the New Mexico minimum wage (\$7.50 hr^{-1}) plus taxes (Social Security, 6.20%; Medicare, 1.45% [IRS 2016]; and workers' compensation, 6.29% [NCCI 2016]) to provide information on potential financial consequences of additions to tall morningglory seedbanks.

The model is implemented in Microsoft® Excel and is available on the World Wide Web (http://aces.nmsu.edu/faculty/schutte/index.html). The Excel file also provides nontechnical background information on tall morningglory biology, seedbank management, and model construction. The bioeconomic model does not account for environmental variability that might influence growth of tall morningglory and chile pepper. Further, the model-based software does not provide technical guidance on specific weed management practices. Thus, the model-based software is not intended for use as a decision-support system.

Results and Discussion

Field Study. Censuses at harvest indicated that tall morningglory densities were identical to those established 12 DAS (data not shown). Overall mean crop yield was 23,910 (± SE 879) kg fw ha^{-1}, which was comparable to previous reports of crop yield for chile pepper produced under similar conditions (20,982 ± SE 743 kg fw ha^{-1}; Schroeder 1993). Also, the overall mean crop yield for the current study was, to some degree, similar to the average chile pepper yield for New Mexico in 2014 (17,023 kg ha^{-1}) and 2015 (19,600 kg ha^{-1}; USDA NASS 2016). Crop yields from this study were expected to be greater than New Mexico averages, because state-level data included weights of fresh and dry chile peppers.

Statistical models for crop yield and harvest efficiency responses to tall morningglory density and pendimethalin were more parsimonious than models that did not include these independent variables (Table 1). Further, the proportions of variances explained by statistical models in this study were consistent with models used in previous ecological studies (Calcada et al. 2015; Garfinkel and Johnson 2015; Levesque

Table 1. Summary of linear mixed-effects models for crop yield and harvest efficiency responses to pendimethalin treatment and tall morningglory density.

Response	Factor	Coefficient	95% Confidence limits	AIC_{full}[a]	AIC_{null}[b]	Marginal R^2 [c]	Conditional R^2 [d]
Crop yield	Intercept	23899	13790 to 34007	1608	1899	0.09	0.74
	Pendimethalin (treated)[e]	819	−3399 to 5038				
	PHBPU[f] density	−92	−312 to 128				
	Pendimethalin × PHBPU density	107	−212 to 427				
Harvest efficiency	Intercept	1046	900 to 1193	1039	1242	0.10	0.54
	Pendimethalin (treated)	−65	−186 to 56				
	PHBPU density	−12	−18 to −6				
	Pendimethalin × PHBPU density	6	−3 to 15				

[a] Akaike information criterion for models with intercepts, fixed effects, and random effects.

[b] Akaike information criterion for models with only intercepts and random effects.

[c] The proportion of variance explained by fixed effects.

[d] The proportion of variance explained by both fixed and random effects.

[e] The study included two pendimethalin treatments (pendimethalin-treated and nontreated). The coefficient for the factor "pendimethalin" represents the effects of the pendimethalin treatment.

[f] Abbreviation: PHBPU, tall morningglory (*Ipomoea purpurea*).

et al. 2016). Model results indicated that crop yield was not influenced by tall morningglory density, pendimethalin treatment, or interactions between pendimethalin treatment and tall morningglory density. Harvest efficiency was diminished by tall morningglory density, but was not influenced by pendimethalin treatment or interactions between pendimethalin treatment and tall morningglory density, which indicated that the effects of tall morningglory on harvest efficiency were not conditioned by pendimethalin. Within a 10-m crop row, each additional tall morningglory plant decreased the amount of chile pepper harvested in 1 min by 9.7 g (Fig. 2).

The results of this study, combined with results from a previous study (Schroeder 1993), indicate that potential weed species in midseason infestations differ in competitiveness with chile pepper. Schroeder (1993) showed that, at densities similar to those used in this study, midseason infestations of spurred anoda caused linear reductions in chile pepper yield. Differences in interference between spurred anoda and tall morningglory might reflect species-level variation in growth habit. Specifically, spurred anoda plants feature upright habits that may be more competitive in established chile pepper than the twining habits of tall morningglory. A similar conclusion can be inferred from previous studies that compared functions for soybean yield loss in response to increasing densities of different weed species (Schutte et al. 2010; Stoller et al. 1987). In these previous studies, ivyleaf morningglory (*Ipomoea hederacea* Jacq.), which is a climbing summer annual closely related to tall morningglory, was found to affect crop yield less than did some weeds with upright habits (Schutte et al. 2010; Stoller et al. 1987).

The absence of tall morningglory effects on crop yield might partly reflect enhanced pollination of chile pepper plants in close proximity with tall morningglory. Tall morningglory plants attract insect pollinators, such as bumble bees (*Bombus*; Galetto and Bernardello 2004), that can also pollinate flowers on chile pepper plants (Tanksley 1984). This study did not measure pollinator abundance and behavior, and thus, further research is required to clarify the alleged associations among midseason tall morningglory, chile pepper yield, and pollinator activity.

Tall morningglory–induced reductions in harvest efficiency were consistent with previous studies that reported severe disruptions to cotton (*Gossypium hirsutum* L.) harvest caused by tall morningglory (Buchanan and Burns 1971; Crowley and Buchanan 1978). In commercial chile pepper production,

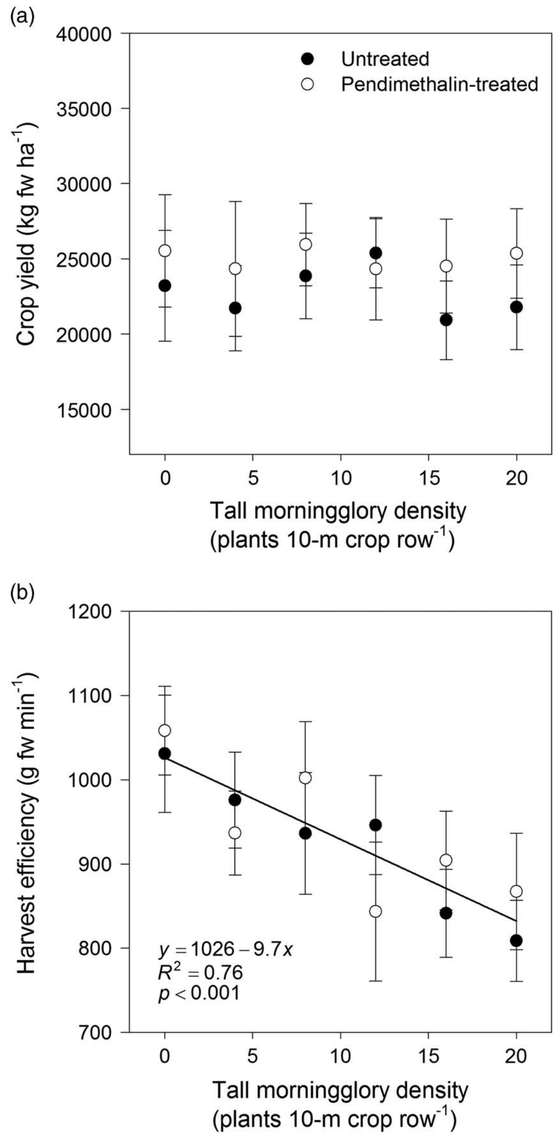

Figure 2. a) Crop yields and b) harvest efficiencies for chile pepper plots that differed in tall morningglory density and pendimethalin treatment. Data are means (± SE) from a study that was conducted near Las Cruces, NM during 2014 and 2015 (four plots per treatment per year).

professional laborers might not pick areas of the field that are heavily infested with weeds. By using amateur pickers to harvest all chile peppers in research plots, this study potentially underestimated the consequences of tall morningglory on crop pepper yield. Nonetheless, this field study indicated that if a producer chooses to harvest an area that contains midseason tall morningglory, increases in tall morningglory density will prolong the physical activity of harvesting.

A previous study determined that pendimethalin reduced the number of tall morningglory seedlings (Schutte and Cunningham 2015), whereas results from the current study indicated that interference characteristics of surviving tall morningglory were not affected by pendimethalin. The absence of pendimethalin effects on chile pepper yield and harvest efficiency was inconsistent with previous studies that showed that weed interference potentials were attenuated by exposure to pendimethalin. Specifically, Schmenk and Kells (1998) determined that pendimethalin at 0.6 and 1.1 kg ai ha^{-1} reduced velvetleaf (*Abutilon theophrasti* Medik.) growth and competitiveness in corn (*Zea mays* L.). Adcock et al. (1990) determined that pendimethalin at 0.84 kg ai ha^{-1} reduced aboveground fresh weights of tall morningglory and common cocklebur (*Xanthium strumarium* L.) grown with soybean (*Glycine max* [L.] Merr.) under greenhouse conditions. Because the interference characteristics of midseason tall morningglory in chile pepper were not conditioned by pendimethalin, projections of tall morningglory interference in this study's bioeconomic model did not require a parameter for the presence of pendimethalin.

Bioeconomic model. Central to the bioeconomic model were projections for hoeing time and harvest efficiency responses to tall morningglory seedbank density in 10 m of crop row (Fig. 3). These patch-level relationships represent rates of increase in hoeing time and decrease in harvest efficiency caused by one additional tall morningglory plant, that were then superimposed on rates of tall morningglory escape from pendimethalin. Patch-level relationships for hoeing time and harvest efficiency were the foundations for hectare-scale projections for economic implications of tall morningglory seedbank density (Fig. 1).

To demonstrate the model-based software, a simulation was conducted with the following user-provided variables: tall morningglory infestation severity, 3 tall morningglory patches ha^{-1}; pendimethalin application rate, 0.8 kg ai ha^{-1}; expected yield from tall morningglory infested areas, 150 kg fw $patch^{-1}$ (Fig. 4). Under these conditions, the model projects that as tall morningglory seedbanks increase from 0 to 1000 seeds per patch, tall morningglory density after pendimethalin treatment increases from 0 to 780 plants ha^{-1}. Because additional seedlings require more time for hand hoeing, hoeing is prolonged 47 min ha^{-1} as tall morningglory seedbanks

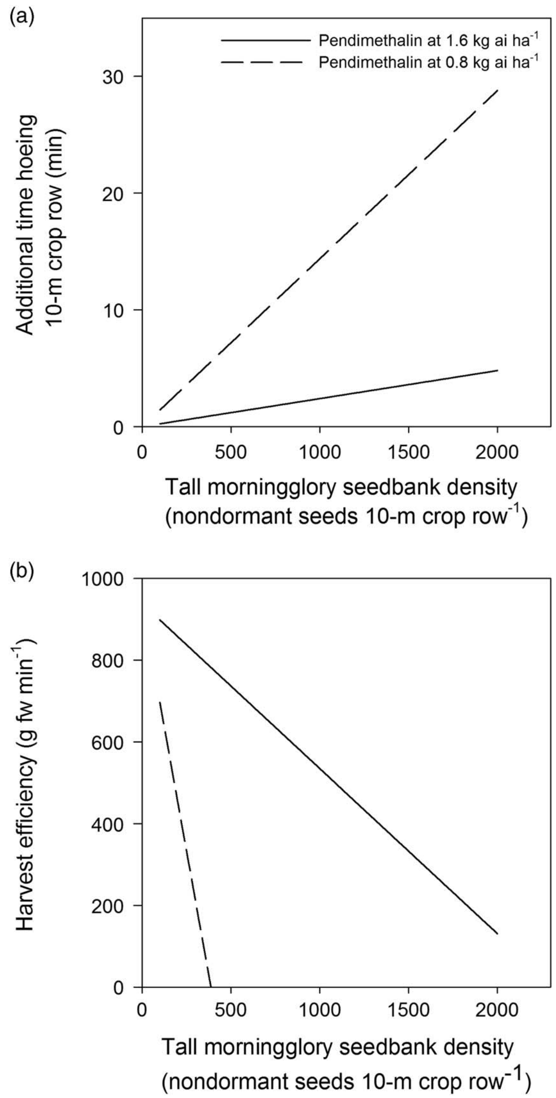

Figure 3. Projected responses of a) hoeing time and b) harvest efficiency to increasing density in tall morningglory seedbanks. Projections combine rates of escape from pendimethalin with midseason tall morningglory effects on hoeing and harvesting. Midseason tall morningglory emerged approximately 10.5 weeks after chile pepper seeding. At 9.5 weeks after chile pepper seeding, chile pepper stands were thinned to clumps (2 to 3 plants per clump) spaced 0.18 m apart. Underlying rates supporting the projections were determined in this study and in previous studies. Schutte and Cunningham (2015) determined that 4% of nondormant seeds buried 1 to 2 cm produce seedlings that escape pendimethalin applied at 0.16 kg ai ha^{-1}, and 26% of nondormant seeds produce seedlings that escape pendimethalin applied at 0.8 kg ai ha^{-1}. Schutte (2015) determined that, for midseason tall morningglory, one additional plant per 10 m of crop row increased hoeing time by 3.6 s. The current study determined that one additional midseason tall morningglory plant per 10 m of crop row decreased the amount of chile pepper harvested in 1 min by 9.7 g.

increase from 0 to 1000 seeds per patch. If plants that survive pendimethalin are not controlled, increases in tall morningglory seedbanks from 0 to 1000 seeds per patch extend hand-harvesting by 27 hr ha^{-1}.

According to the projected additional times for hoeing and harvesting, and if field labor expenses are New Mexico minimum wage plus taxes, increases in tall morningglory seedbanks from 0 to 1000 seeds per patch add $6.67 to per-hectare expenses for hand-hoeing, and add $223.29 to per-hectare expenses for hand-harvesting. In other words, one seed added in each tall morningglory patch increases per-hectare labor expenses by $0.007 for hand-hoeing, and $0.23 for hand-harvesting. Considering the number of seeds potentially produced by individual plants (26,000 seeds per plant in the absence of competition [Crowley and Buchanan 1982], and 3500 seeds per plant in competition with chile pepper [Schutte 2015]), tall morningglory seed rains can be costly. It is important to note that implied costs of seed rains are likely upper limits, because the model does not account for seed dormancy, burial depths that are suboptimal for emergence, and postdispersal seed mortality. Future studies that combine this study's bioeconomic model with models that project seed fates and movements (e.g., Renton et al. 2008; Spokas et al. 2007) will enable detailed understanding of economic consequences of tall morningglory seed rains.

Rogers (2003) indicated that the decision to adopt a new practice is a multistage process that often begins with recognition of the need for change. This initial stage of the adoption process, as indicated by Rogers (2003), is the intended target for the model-based software presented in this study. The model is not meant to be a predictive tool but rather a component of broader educational effort on weed seedbank management in agricultural systems in New Mexico. Providing growers information on relationships between weed seedbank density and labor requirements for chile pepper production might promote adoption of seedbank reduction strategies, because costs and availability of labor are primary constraints on chile pepper production in New Mexico (Skaggs et al. 2000), and adoption of an integrated weed management practice is generally influenced by grower perceptions of the practice's economic value in the context of the local cropping system (Llewellyn et al. 2005).

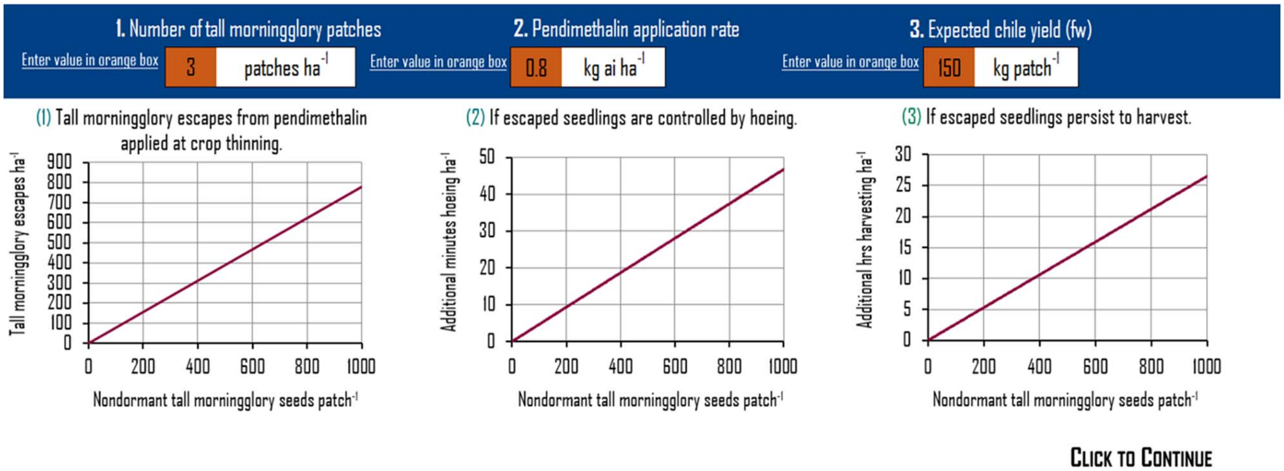

Figure 4. Screenshot from the Excel spreadsheet for projecting the effects of tall morningglory seedbank density on weed control outcomes and production expenses in chile pepper production. This Excel sheet allows users to customize model outputs by providing site-specific information. User inputs include patches per hectare, pendimethalin application rate, and expected chile pepper yield from a patch infested with tall morningglory. Model outputs are presented in figures that change according to the user-provided inputs. The "Click to Continue" option advances users to an Excel sheet that provides site-specific financial consequences of one-seed additions to tall morningglory seedbanks.

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