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Emergence pattern of Palmer amaranth (*Amaranthus palmeri*) influenced by tillage timings and residual herbicides

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Abstract

The evolution of multiple herbicide-resistant weeds, including Palmer amaranth, has necessitated the implementation of an integrated weed management (IWM) program. Understanding weed emergence patterns is critical for developing effective IWM strategies. The objective of this study was to evaluate the effect of tillage timings and residual herbicides on cumulative emergence and emergence pattern of Palmer amaranth. Field experiments were conducted in 2015 and 2016 in a field naturally infested with photosystem (PS) II and 4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitor-resistant Palmer amaranth near Shickley, Nebraska, in a bare ground study, with no crop planted in the plots, although residues from the preceding corn crop were present on the soil surface. Treatments consisted of shallow tillage timings (early, mid, and late), three premix corn or soybean residual herbicides, and a nontreated control. The Weibull function was fitted to cumulative Palmer amaranth emergence with day of year (DOY) and thermal time (TT) as independent variables. Year by treatment interaction was significant for time to 10%, 25%, 50%, 75%, and 90% Palmer amaranth emergence and cumulative emergence. The majority of Palmer amaranth seedlings emerged early, following early tillage with 90% cumulative emergence occurring on DOY 172 compared with DOY 210 to 212 for mid- and late-tillage, and DOY 194 for the nontreated control in 2015. In 2016, 90% of cumulative emergence following early-, mid-, and late-tillage (DOYs 201 to 211) were similar, and that of the nontreated control (DOY 188) was similar to that of early tillage. Nontreated control and PRE herbicide treatments had similar DOY values for 90% emergence in both years. The number of emerged Palmer amaranth seedlings over the season was higher with shallow tillage than no tillage or with the use of PRE herbicides.

Introduction

Palmer amaranth is a C_4 dioecious weed species native to the southwestern United States and northwestern Mexico (Sauer 1957). Agricultural expansion and seed and equipment transportation in the 20th century favored the spread of Palmer amaranth from the southern to the northern United States (Culpepper et al. 2010). Biological characteristics such as prolific seed production, high growth rate, season-long emergence, and ability to survive and produce seeds under water stress conditions allowed Palmer amaranth to survive, spread, and out-compete other weed species in agronomic crops (Burke et al. 2007; Chahal et al. 2018a; Ehleringer 1983; Horak and Loughin 2000; Keeley et al. 1987). Palmer amaranth interference can cause significant crop yield reduction depending upon the level of infestation and crop species (Klingaman and Oliver 1994; Liphadzi and Dille 2006; Massinga et al. 2001). Palmer amaranth was ranked as the most troublesome weed in the southern United States by the Southern Weed Science Society in 1989 (Webster and Coble 1995) and the most troublesome weed in agronomic crops in the United States by the Weed Science Society of America by 2016 (WSSA 2016).

Before commercial cultivation of glyphosate-resistant crops, growers were relying on tillage along with residual herbicides for weed management in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] cropping systems in the midwestern United States (Gianessi 2005; Givens et al. 2009). Even though tillage is an effective method for controlling weeds, the fuel required for performing tillage can increase the cost of crop production (Gianessi 2005). In addition, tillage has some negative impacts such as soil compaction due to the repeated use of heavy machinery, soil erosion, and loss of soil moisture (Gilley and Doran 1997; Raper et al. 2000). The introduction of glyphosate-resistant crops in the late 1990s simplified weed management programs and allowed multiple in-crop applications of glyphosate, a broad-spectrum nonselective herbicide, resulting in excellent grass and broadleaf weed control (Givens et al. 2009; Johnson et al. 2000; Reddy and Whiting 2000). Growers quickly adopted glyphosate-resistant crops and glyphosate-based POST herbicide programs due to the broad-spectrum of weed control and lower cost; therefore, use of PRE residual herbicides and tillage practices for weed management dropped significantly (Young 2006).

The selection pressure imposed by the repeated use of herbicides with single sites of action resulted in the evolution of herbicide-resistant weeds (Beckie 2011; Duke 2017; Powles 2008). Palmer amaranth biotypes resistant to microtubule-, acetolactate synthase (ALS)-, photosystem II (PS II)-, 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS)-, hydroxyphenylpyruvate dioxygenase (HPPD)-, and protoporphyrinogen oxidase (PPO)-inhibiting herbicides have been reported in several states (Heap 2020), including a Palmer amaranth biotype resistant to atrazine and HPPD inhibitors in Nebraska (Jhala et al. 2014). In addition, a widespread occurrence of atrazine, ALS inhibitors, and/or glyphosate-resistant Palmer amaranth in several counties in south-central Nebraska is challenging for corn and soybean growers (Jhala et al. 2014). Palmer amaranth's dioecious nature provides an opportunity to spread herbicide-resistance alleles from herbicide-resistant males to susceptible female plants via pollen-mediated gene flow (Jhala et al. 2020; Sosnoskie et al. 2012).

Tillage is one of the components of an integrated weed management (IWM) program (Raper et al. 2000). The frequency and intensity of tillage has declined in the past decades in efforts to minimize soil erosion and to conserve moisture; however, strategic occasional tillage, also known as one-time tillage, is an agronomic practice for weed management and to reduce vertical stratification of soil acidification and nutrients (Barth et al. 2018; Blanco-Canqui and Lal 2008; Blanco-Canqui and Wortmann 2020; Chauhan et al. 2012). Previous studies have reported that the effect of tillage on emergence pattern could be species dependent. For example, Chahal and Jhala (2019) reported that rotary/shallow tillage implemented in fall or early spring reduced the cumulative emergence of glyphosate-resistant horseweed (*Erigeron canadensis* L.) in a multiyear study in southeastern Nebraska. Barnes et al. (2017) reported that rotary tillage applied in the spring at three different timings did not influence cumulative emergence or the emergence pattern of common ragweed (*Ambrosia artemisiifolia* L.) in a multiyear study conducted in Nebraska. Similarly, cumulative emergence of giant ragweed (*Ambrosia trifida* L.) and the time required for 50% of total cumulative emergence was not influenced by rotary tillage operated at a depth of 10-cm in spring in central Nebraska (Kaur et al. 2016).

Soil residual PRE herbicides are another important component of an IWM program and are applied to the soil after crop planting but before crop emergence to control germinating or emerging weed seedlings. Herbicides applied PRE at crop planting generally lose their residual activity 14 to 35 d after application depending on soil type, application rate of herbicide, weather conditions, and weed species present in the field (Jhala et al. 2015; Wiggins et al. 2015). Chahal and Jhala (2018) reported that atrazine/mesotrione/*S*-metolachlor, atrazine/fluthiacet/pyroxasulfone, acetochlor/clopyralid/flumetsulam, and saflufenacil/dimethenamid applied PRE provided 88% to 97% control of atrazine and HPPD-inhibitor (mesotrione, tembotrione, or topramezone)-resistant Palmer amaranth; however, an additional POST herbicide was needed for control of late-emerging Palmer amaranth cohorts. Recent studies have reported that PRE herbicides can delay the critical period of weed removal in corn and soybean compared with no-residual herbicide due to reduced early-season weed emergence (Knezevic et al. 2019). Similarly, the pattern of Palmer amaranth emergence over the season might be affected by residual activity of PRE herbicide applied at planting.

Soil temperature and soil moisture content are some of the most important environmental factors required for seed germination (Barnes et al. 2017; Grundy 2003). The optimum temperature for Palmer amaranth seed germination ranges from 25 to 35 C (Guo and Al-Khatib 2003). A base temperature (minimum temperature below which phenological development ceases) for Palmer amaranth germination has been reported in the range of 10 C to 16.6 C (Horak and Loughin 2000; Steinmaus et al. 2000). Soil temperature expressed as thermal time (TT) can be used as a predictor for Palmer amaranth seedling emergence. The TT can be calculated using a growing degree day equation where TT is accumulated above a base temperature (T_{base}) required for triggering germination (Barnes et al. 2017; Werle et al. 2014a). Several studies have used hydrothermal time (HTT) models to predict seedling emergence (Barnes et al. 2017; Gummerson 1986); however, Werle et al. (2014b) reported that a TT model best predicted the emergence of 17 summer annual weed species including redroot pigweed (*Amaranthus retroflexus* L.) and waterhemp [*Amaranthus tuberculatus* (Moq.) J. D. Sauer], closely related species of Palmer amaranth. Thus, the selection of a model that best predicts the emergence pattern depends on weed species and availability of site-specific microclimate information such as temperature and moisture (Barnes et al. 2017).

A statewide survey conducted in 2015 reported that 61% of surveyed growers were using no-till in Nebraska (Sarangi and Jhala 2018a). The survey also revealed that 74% and 59% of surveyed corn and soybean growers, respectively, in Nebraska have been applying residual PRE herbicides for early-season weed management. Previous studies have reported variable effects of tillage on Palmer amaranth emergence (Aulakh et al. 2013; Jha and Norsworthy 2009). In addition, research is lacking on emergence pattern of Palmer amaranth following tillage at different timings or residual herbicides. The objectives of this study were to evaluate the influence of tillage timings and corn/soybean residual herbicides with multiple sites of action on the cumulative emergence and emergence pattern of Palmer amaranth.

Materials and Methods

Field experiments were conducted in 2015 and 2016 in a grower's field naturally infested with PS II (atrazine)- and HPPD inhibitor (mesotrione, tembotrione, or topramezone)-resistant Palmer amaranth near Shickley in Fillmore County, Nebraska (40.46°N, 97.80°E). The level of Palmer amaranth resistance to atrazine applied POST was 9- to 14-fold, while the level of resistance to mesotrione, tembotrione, and topramezone applied POST was 4-fold, 4- to 6-fold, and 14- to 23-fold, respectively (Jhala et al. 2014). Soil at the research site was a Crete silt loam (fine, smectitic, mesic Pachic Udertic Argiustoll), pH 6.5, 26% sand, 57% silt, 17% clay, and 3.5% organic matter. The experiment was repeated in 2016 in an adjacent location within the same field.

The experiment was arranged in a randomized complete block design with a total of seven treatments in four replications. Treatments included three tillage timings (early-, mid-, and late-tillage) and three PRE herbicides—atrazine/bicyclopyrone/mesotrione/*S*-metolachlor premix (Acuron, Syngenta Crop Protection, Inc., Greensboro, NC) at 2,900 g ai ha^{-1}, chlorimuron/flumioxazin premix (Valor XLT, Valent USA Corporation, Walnut Creek, CA) at 141 g ai ha^{-1}, and atrazine/fluthiacet/pyroxasulfone premix (Anthem ATZ, FMC Corporation, Philadelphia, PA) at 1,740 g ha^{-1}, and a nontreated control (no herbicide and no tillage). PRE herbicides were applied to no-till soil within 4 d after emergence of first Palmer amaranth seedling in 2015 and 2016. Early-tillage also occurred on the same day of herbicide application during both years. The mid- and late-tillage occurred at 10 and 28 to 32 d after early-tillage, respectively. Tillage was accomplished using a 50-cm-wide rototiller (Honda FRC800, American Honda, Alpharetta, GA) operated at a depth of 10 cm. Herbicides were applied with a CO_2-pressurized backpack sprayer consisting of a four-nozzle boom fitted with AIXR 110015 flat-fan nozzles (TeeJet Spraying Systems Co., P.O. Box 7900, Wheaton, IL) calibrated to deliver 140 L ha^{-1} at 276 kPa. Glyphosate (Roundup PowerMax, Bayer CropScience, Research Triangle Park, NC) at 870 g ae ha^{-1} was tank-mixed with PRE herbicides to control emerged Palmer amaranth seedlings at the time of application. Palmer amaranth did not emerge at the site until first week of June during both years and PRE herbicides were applied on the same day as early-tillage timing on June 8, 2015, and June 6, 2016. Mid- and late-tillage timings occurred on June 18 and July 6 in 2015, and June 17 and July 8 in 2016, respectively.

An individual experimental plot was 1.5 m wide and 6 m long and two permanent 0.5 m^2 quadrats were spaced evenly in each plot to record Palmer amaranth emergence from the same area. Palmer amaranth seedling counts from both 0.5-m^2 quadrats were added to calculate seedlings density per square meter. No crop was planted in this study to remove the crop-shade effect on Palmer amaranth emergence; however, there was crop residue from preceding corn crop on the surface. Palmer amaranth seedlings were counted and removed from both quadrats in each plot every 10 to 12 d starting from the first week of emergence through the second week of September. The emergence data were converted to obtain percent cumulative emergence per plot for each year. The Soil Temperature and Moisture Model (STM^2) software was used to predict daily soil temperature at the 1- and 2-cm depths. Daily minimum and maximum air temperature data were obtained from the nearest High Plains Regional Climate Center station near Geneva, Nebraska, which was about 18 km from the experimental site. In addition, the soil texture properties, percent soil organic matter, latitude, longitude, and elevation (519 m) of the experimental site were also used in the software to predict daily soil temperature at the site.

Treatment Effects

The Weibull function has best described the cumulative weed emergence in previous studies (Barnes et al. 2017; Werle et al. 2014a, 2014b). Therefore, the Weibull function was fitted to the percent cumulative Palmer amaranth emergence data from each plot using the "nls" function in R statistical software (R version 3.3.1, R Foundation for Statistical Computing, Vienna, Austria), with DOY as the explanatory variable:

$$y = asym \times \{1 - exp[-exp(lrc) \times (x^{pwr})]\} \quad [1]$$

where y is the percent cumulative emergence, x is the independent variable (DOY), and $asym$ is the upper asymptote fixed to 100%, lrc and pwr are the natural logarithms for the rate of increase and power to which x is raised, respectively. Time to 10%, 25%, 50%, 75%, and 90% of the cumulative Palmer amaranth emergence is denoted as T_{10}, T_{25}, T_{50}, T_{75}, and T_{90}, respectively (and collectively as the emergence pattern), were predicted for each plot. Cumulative emergence data were subjected to ANOVA and T_{10}, T_{25}, T_{50}, T_{75}, and T_{90} to multivariate analysis of variance (MANOVA) in R software, with treatments as fixed factor and replications nested within years as random factor in the model. Pillai's trace test was used to determine significant effects in MANOVA.

Modeling Procedure

Accumulated TT was calculated using daily minimum and maximum soil temperature from January 1 to December 31 for both years using the following equation (Gummerson 1986):

$$TT = \sum_{i=1}^{n} [(T) \times (T_{mean} - T_{base})] \quad [2]$$

where T represents soil temperature and T = if $T_{mean} \geq T_{base}$, otherwise T = 0. T_{mean} is the average daily soil temperature (C) at 1- or 2-cm depth and T_{base} is the minimum threshold temperature required for Palmer amaranth germination. The T_{base}value for Palmer amaranth germination has been reported in a range of 10 C to 16 C (Horak and Loughin 2000; Steinmaus et al. 2000); therefore, 19 different T_{base} values ranging from 7 C to 25 C were selected for the model. During the growing season, there was no variation between the experimental years for predicted soil temperature (Figure 1).

Fitting the Model

Year-by-treatment interaction was significant for Palmer amaranth emergence; therefore, the Weibull function [Equation 1] was fitted only to the nontreated control data to select a model with T_{base} and depth value that best described the percent cumulative Palmer amaranth emergence. The best selected model was then used to describe the emergence pattern of Palmer amaranth in other treatments. The independent variable, x, consisted of 38 combinations of TT (19 temperature and 2 depth values) and DOY for a total of 39 possible models (Figure 2). The "nls" function in R software was used to estimate model parameters, lrc and pwr. The best Weibull model with T_{base} and depth value was selected based on the Akaike information criterion (AIC) model comparison approach (Anderson 2008). The corrected AIC (AICc) and model probability (AICw) were obtained for 39 models using the aictabCustom function in the AICcmodavg package in R software. AICc was calculated using the following equation (Anderson 2008):

$$AICc = -2LL + 2K(n/[n - K - 1]) \quad [3]$$

where LL is the log-likelihood of the model parameters (calculated with logLik function in R version 3.3.1 [R foundation]), K is the number of model parameters, and n is the sample size. TT and DOY were used as explanatory variables and a penalty cost of 1 was added to the number of parameters ($K = K + 1$) when calculating the AICc values.

Model Goodness of Fit

Root mean square error (RMSE) and modeling efficiency coefficient (ME) were calculated to estimate the goodness of fit for the top model. RMSE was calculated using following equation (Roman et al. 2000):

$$RMSE = \left[1/n \sum_{i=1}^{n} (Pi - Oi)^2\right]^{1/2} \quad [4]$$

where Pi and Oi are the predicted and observed values, respectively, and n is the total number of comparisons. The closer the

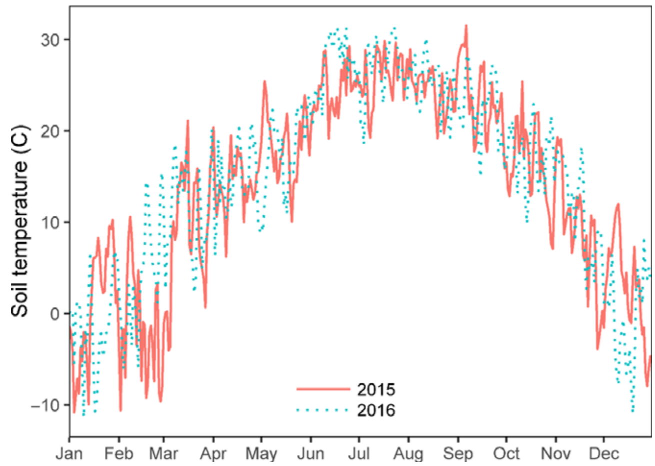

Figure 1. Daily soil temperature (C) at 1-cm depth estimated using STM2 (soil temperature and moisture model) software during Palmer amaranth emergence period in field studies conducted near Shickley, Nebraska, in 2015 and 2016.

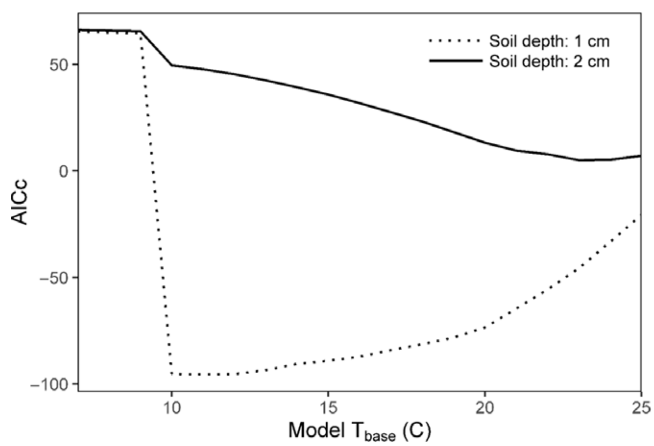

Figure 2. Corrected Akaike information-theoretic model comparison criterion (AICc) of models for Palmer amaranth emergence with threshold soil temperature (T_{base}) ranging from 7 C to 25 C at 1- and 2-cm soil depth. Lower AICc values indicate a better fit of the model.

predicted values to the observed values, the lower the RMSE. The ME was calculated using the following equation (Mayer and Butler 1993):

$$ME = 1 - \left[\sum_{i=1}^{n} (Oi - Pi)^2 / \sum_{i=1}^{n} \left(Oi - \overline{O}i\right)^2\right] \quad [5]$$

where $\overline{O}i$ is the mean observed value. The closer the value of ME to 1, more precise is the prediction.

Results and Discussion

The emergence pattern of Palmer amaranth was best described by DOY followed by the TT model with a T_{base} of 11 C based on the AICc and AICw criteria (Table 1; Figure 3). Werle et al. (2014b) also reported DOY as the explanatory variable describing emergence pattern of *Amaranthus* species such as waterhemp and redroot pigweed. The germination of waterhemp and Palmer amaranth have been reported to be greater at varying temperature compared with constant temperature (Guo and Al-Khatib 2003; Leon et al. 2004); however, the effect of fluctuating temperatures on seed

Table 1. Comparison of K, AICc, AICw, and LL for the six best models (from 39 possible models) to predict Palmer amaranth emergence with different tillage timings and residual herbicides.[a,b]

Model[c]	T_{base}	K	AICc	AIC_W	LL
DOY	—	3	−114.55	0.70	60.47
TT 1 cm	11	3	−95.51	0.22	155.38
TT 1 cm	10	3	−95.37	0.17	155.09
TT 1 cm	12	3	−95.34	0.09	154.43
TT 1 cm	13	3	−93.50	0.05	153.95
TT 1 cm	14	3	−90.54	0.03	153.50

[a]Abbreviations: AICc, corrected Akaike information-theoretic model comparison criterion; AICw, model probability; DOY, day of year; K, number of model parameters; LL, log-likelihood; T_{base}, threshold soil temperature; TT, thermal time.
[b]Data were collected from field experiments in 2015 and 2016 near Shickley, Nebraska.
[c]Models are arranged from the lowest to the highest AICc with the lowest being the best fit (top model). The top model was based on DOY due to similar experimental years. The second-best fit model had a T_{base} of 11 C.

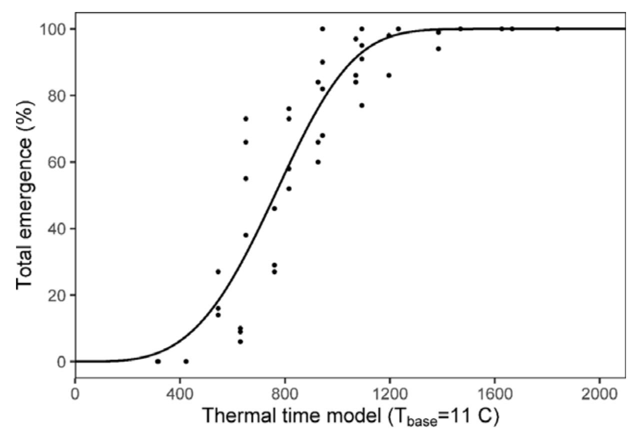

Figure 3. Weibull function fitted to percent cumulative emergence of Palmer amaranth from nontreated control combined over 2015 and 2016 with thermal time calculated with a threshold soil temperature of 11 C. Model parameter asym (horizontal asymptote) was normalized to 100%, while the model parameters lrc (natural logarithm for the rate of increase) and pwr (power to which thermal time is raised) were −24.9 and 3.7, respectively. The root mean squared error (RMSE) and modeling efficiency (ME) coefficient for this model were 0.11 and 0.92, respectively.

germination of weed species including Palmer amaranth also depend on after-ripening period of seed (Cristaudo et al. 2007; Jha et al. 2010). In addition, light quality (red:far-red) reaching the seeds lying on soil surface or buried at shallow depths can affect germination of several weed species including Palmer amaranth, redroot pigweed, and waterhemp (Gallagher and Cardina 1998; Jha et al. 2010; Leon and Owen 2003).

Year-by-treatment interaction was significant for T_{10}, T_{25}, T_{50}, T_{75}, and T_{90} ($P = 0.022$; Table 2) as well as for Palmer amaranth cumulative seedling emergence ($P < 0.001$; Table 2); therefore, data were presented separately for both years. Early-tillage resulted in earlier emergence of Palmer amaranth seedlings compared with mid- and late-tillage timings in 2015 (Table 2). For instance, T_{50} was predicted at DOY 169 (June 17) with early-tillage compared with DOY 199 (July 17) for mid-tillage and DOY 186 (July 4) for late-tillage. Emergence after early-tillage was statistically similar to that of the nontreated control with T_{50} at DOY 174 (June 22; Table 2). Similarly, T_{90} was predicted earlier at DOY 172 (June 20) with early-tillage timing compared with the nontreated control at DOY 194. Mid- and late-tillage timings had similar DOYs for T_{90} of 212 (July 30) and 210 (July 28), respectively (Table 2). In other words, it took 13 d to reach T_{90} after

Table 2. Influence of tillage timings and residual herbicides on time to 10, 25, 50, 75, and 90% (T_{10}, T_{25}, T_{50}, T_{75}, and T_{90}) of total emergence and cumulative Palmer amaranth emergence in field experiments conducted in 2015 and 2016 near Shickley, Nebraska.[a]

Year[b]	Herbicide or tillage-timing treatments[c]	T_{10}[d]	T_{25}[d]	T_{50}[d]	T_{75}[d]	T_{90}[d]	Cumulative emergence[b]
		Day of year calendar date					
							plants m^{-2}
2015	Nontreated	148 c	161 c	174 d	186 c	194 c	23 bc
		May 27	June 09	June 22	July 04	July 12	
	Atrazine/fluthiacet/pyroxasulfone	159 bc	171 bc	181 cd	191 bc	198 bc	7 c
		June 07	June 19	June 29	July 09	July 16	
	Atrazine/bicyclopyrone/mesotrione/*S*-metolachlor	165 abc	178 b	190 abc	201 ab	209 ab	11 c
		June 13	June 26	July 08	July 19	July 27	
	Chlorimuron/flumioxazin	165 ab	179 ab	193 ab	204 a	213 a	10 c
		June 13	June 27	July 11	July 22	July 31	
	Early-tillage	165 abc	167 bc	169 d	171 d	172 d	128 a
		June 13	June 15	June 17	June 19	June 20	
	Mid-tillage	180 a	190 a	199 a	207 a	212 a	116 a
		June 28	July 08	July 17	July 25	July 30	
	Late-tillage	153 bc	170 bc	186 bc	199 ab	210 ab	68 ab
		June 01	June 18	July 04	July 17	July 28	
2016	Nontreated	163 ab	171 bc	177 bc	183 b	188 b	269 cd
		June 11	June 19	June 25	July 01	July 06	
	Atrazine/fluthiacet/pyroxasulfone	157 ab	168 bc	178 bc	186 b	192 b	49 d
		June 05	June 16	June 26	July 04	July 10	
	Atrazine/bicyclopyrone/mesotrione/*S*-metolachlor	169 ab	182 ab	193 a	203 a	211 a	67 cd
		June 17	June 30	July 11	July 21	July 29	
	Chlorimuron/flumioxazin	153 b	164 c	175 c	184 b	192 b	88 cd
		June 01	June 12	June 23	July 02	July 10	
	Early-tillage	171 ab	180 ab	189 ab	196 ab	201 ab	1,674 a
		June 19	June 28	July 07	July 14	July 19	
	Mid-tillage	168 ab	181 ab	193 a	203 a	211 a	533 bc
		June 16	June 29	July 11	July 21	July 29	
	Late-tillage	174 a	185 a	195 a	204 a	211 a	869 b
		June 22	July 03	July 13	July 22	July 29	
		P-values[e]					
	Treatment			0.004			<0.001
	Year			0.882			0.030
	Treatment × Year			0.022			<0.001

[a]Abbreviations: DOY, day of year; T_{10}, T_{25}, T_{50}, T_{75}, or T_{90}, time to 10, 25, 50, 75, or 90% Palmer amaranth emergence, respectively.
[b]Year by treatment interaction was significant for T_{10}, T_{25}, T_{50}, T_{75}, and T_{90}; therefore, data were analyzed separately for each year. Year by treatment interaction was significant for cumulative emergence of Palmer amaranth; therefore, data were presented separately for each year.
[c]Early tillage and residual herbicides were applied on June 8, 2015 and June 6, 2016. Mid- and late-tillage timings occurred on June 18 and July 6 in 2015 and June 17 and July 8 in 2016, respectively. Tillage was accomplished using a 50-cm-wide rototiller (Honda FRC800, American Honda, Alpharetta, GA) operated at a depth of 10 cm.
[d]Means within columns for each year with no common letter(s) are significantly different at $P \leq 0.05$.
[e]P-values were determined with multivariate analysis of variance (MANOVA) based on Pillai's trace test.

implementation of early tillage compared to 43 d after mid-tillage, and 23 d after late-tillage timing in 2015.

In 2016, the T_{90} for early tillage was predicted at DOY 201 (July 19), similar to that for mid- and late-tillage (DOY 211; July 29) and the nontreated control (DOY 188; July 6; Table 2). Palmer amaranth took 43 d to reach T_{90} after implementation of early tillage compared with 42 d after mid-tillage and 21 d after late-tillage timing in 2016. Overall, early-, mid-, and late-tillage delayed the emergence pattern of Palmer amaranth in 2016 compared with 2015 when only mid- and late-tillage were effective delaying the emergence compared to the nontreated control.

PRE herbicides atrazine/bicyclopyrone/mesotrione/*S*-metolachlor and chlorimuron/flumioxazin delayed Palmer amaranth emergence compared to emergence in the nontreated control in 2015. For instance, T_{50} was predicted at DOY 190 to 193 (July 8 to 11) with atrazine/bicyclopyrone/mesotrione/*S*-metolachlor and chlorimuron/flumioxazin compared to DOY 174 (June 22) for the nontreated control (Table 2). Atrazine/fluthiacet/pyroxasulfone did not delay the emergence pattern of Palmer amaranth compared to the nontreated control. Similarly, T_{90} was predicted at DOY 209 to 213 (July 27 to 31) with atrazine/bicyclopyrone/mesotrione/*S*-metolachlor and chlorimuron/flumioxazin compared to DOY 194 (July 12) for the nontreated control in 2015 (Table 2). T_{90} predictions for atrazine/fluthiacet/pyroxasulfone did not differ from that of the nontreated control. In 2016, atrazine/bicyclopyrone/mesotrione/*S*-metolachlor delayed Palmer amaranth emergence compared to chlorimuron/flumioxazin, atrazine/fluthiacet/pyroxasulfone, and the nontreated control. T_{90} was predicted at DOY 211 (July 29) with atrazine/bicyclopyrone/mesotrione/*S*-metolachlor compared to DOY 188 to 192 (July 6 to 10) with atrazine/fluthiacet/pyroxasulfone, chlorimuron/flumioxazin, and the nontreated control (Table 2). Residual herbicides applied PRE usually provide residual activity for 14 to 35 d after application depending on a number of factors including type of herbicide, application rate, soil type, soil moisture, etc. (Curran 2016; Ogle and Warren 1954; Walker 1976). This explains the delay in Palmer amaranth emergence pattern following PRE herbicides. However, Palmer amaranth has an extended period of emergence (Jha and Norsworthy 2009; Keeley et al. 1987) and it continues emerging after residual activity of PRE herbicides diminish in the soil.

The mid-tillage timing delayed the Palmer amaranth emergence pattern similar to that of the PRE herbicides atrazine/bicyclopyrone/mesotrione/*S*-metolachlor and chlorimuron/flumioxazin compared to the nontreated control in 2015 (Table 2). In 2016, mid- and late-tillage delayed Palmer amaranth emergence to a degree that was similar to atrazine/bicyclopyrone/mesotrione/*S*-metolachlor compared to the nontreated control.

All tillage timings resulted in the highest cumulative Palmer amaranth emergence of 68 to 128 plants m^{-2} compared with 7 to 11 plants m^{-2} with the residual herbicides and 23 plants m^{-2} in the nontreated control in 2015. In 2016, early-tillage resulted in the greatest emergence (1,674 plants m^{-2}) followed by mid- and late-tillage timings (533 to 869 plants m^{-2}), and residual herbicides (49 to 88 plants m^{-2}). This might be because tillage operation brings the weed seeds to the soil surface and increases the chance of their exposure to light and diurnal temperature fluctuations required for Palmer amaranth seed germination (Jha et al. 2010).

Cumulative Palmer amaranth emergence was greater in 2016 possibly due to the soil seed bank replenishment from seeds produced by a large number of surviving female Palmer amaranth plants in the same field area planted with corn in 2015. Residual herbicides resulted in similar Palmer amaranth cumulative emergence as the mid-tillage and nontreated control in 2016; however, emergence was numerically lower with residual herbicides. Surprisingly, Palmer amaranth cumulative emergence in the nontreated control in 2015 (23 plants m^{-2}) and 2016 (269 plants m^{-2}) was statistically comparable with that of residual herbicides (7 to 88 plants m^{-2}) in both years; however, emergence values were comparatively two to three times higher in 2015 and three to five times higher in 2016 in the nontreated control (Table 2). Residual herbicides used in this study were a premix of two to four herbicide active ingredients and were selected for their efficacy for controlling atrazine- and HPPD inhibitor-resistant Palmer amaranth. Chahal and Jhala (2018) reported 93% and 74% control of atrazine- and HPPD inhibitor-resistant Palmer amaranth at 21 and 101 d after application, respectively, at the same experimental site with atrazine/fluthiacet/pyroxasulfone. Sarangi and Jhala (2018b) reported no Palmer amaranth plants at 14 d and 6 plants m^{-2} 42 d after application of atrazine/bicyclopyrone/mesotrione/*S*-metolachlor.

Palmer amaranth biotypes that are resistant to multiple herbicide sites of action are difficult to control with the use of single herbicides in corn-soybean cropping systems and requires an IWM program. Information about emergence pattern of Palmer amaranth affected by management strategies such as tillage timings or residual herbicide could help growers plan an IWM program. Tillage with a 50-cm-wide rototiller operated at a depth of 10 cm stimulated additional emergence of Palmer amaranth, which can be later controlled using effective multiple sites of action herbicides. In addition, other management strategies such as the use of PRE residual herbicides that use multiple sites of action followed by a POST herbicide tank-mixed with a residual herbicide should be adopted (Chahal et al. 2018b; Norsworthy et al. 2012). This is not needed in every field because it increases the cost of herbicide program but could be implemented as a proactive, integrated approach to reduce the selection pressure of single-site-of-action herbicides on weed populations.

Studies related with Palmer amaranth emergence pattern conducted in other regions of the United States have demonstrated variable results depending on tillage method (shallow versus deep), soil type, and microclimate. For example, Aulakh et al. (2013) reported that a double disk operation reduced early-season Palmer amaranth emergence compared with disking followed by chisel plow, disking followed by field cultivator, and no-tillage in multiyear field experiments conducted in Alabama. A study conducted by Jha and Norsworthy (2009) in South Carolina reported no effect of shallow rotary-tillage on cumulative Palmer amaranth emergence. Franca (2015) reported that shallow rotary-tillage at different timings influenced the emergence pattern of Palmer amaranth in southern Illinois.

This study was conducted in bare ground in a grower's field without competition of Palmer amaranth or other weeds and without a crop, thus exposing Palmer amaranth seeds to high levels of light and soil temperature. The corn residues from the preceding corn crop present on the surface at the experimental site could have affected the emergence of Palmer amaranth, especially in the treatment when no tillage operations were performed. Therefore, future studies should evaluate the effect of residual herbicides and tillage timings on the emergence pattern of Palmer amaranth under different cropping systems and environmental conditions.

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References

Anderson DR (2008) Model based inference in the life sciences: primer on evidence. New York: Springer. 184 p

Aulakh JS, Price AJ, Enloe SF, Wehtje G, Patterson MG (2013) Integrated Palmer amaranth management in glufosinate-resistant cotton: II. primary, secondary and conservation tillage. Agron 3:28–42

Barnes ER, Werle R, Sandell LD, Lindquist JL, Knezevic SZ, Sikkema PH, Jhala AJ (2017) Influence of tillage on common ragweed (*Ambrosia artemisiifolia*) emergence pattern in Nebraska. Weed Technol 31:623–631

Barth VP, Reardon CL, Coffey T, Klein AM, McFarland C, Huggins DR, Sullivan TS (2018) Stratification of soil chemical and microbial properties under no-till after liming. Appl Soil Ecol 130:169–177

Beckie HJ (2011) Herbicide-resistant weed management: focus on glyphosate. Pest Manag Sci 67:1037–1048

Blanco-Canqui H, Lal R (2008) No-Tillage and carbon sequestration: an on-farm assessment. Soil Sci Soc Am J 72:693–701

Blanco-Canqui H, Wortmann CS (2020) Does occasional tillage undo the ecosystem services gained with no-till? A review. Soil Till Res 198: Article 104534

Burke IC, Schroeder M, Thomas WE, Wilcut JW (2007) Palmer amaranth interference and seed production in peanut. Weed Technol 21:367–371

Chahal PS, Irmak S, Jugulam M, Jhala AJ (2018a) Evaluating effect of degree of water stress on growth and fecundity of Palmer amaranth (*Amaranthus palmeri*) using soil moisture sensors. Weed Sci 66:738–745

Chahal PS, Ganie ZA, Jhala AJ (2018b) Overlapping residual herbicides for control of photosystem II and 4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitor-resistant Palmer amaranth (*Amaranthus palmeri* S. Watson) in glyphosate-resistant maize. Front Plant Sci 8:2231, 10.3389/fpls.2017.02231

Chahal PS, Jhala AJ (2018) Economics of management of photosystem II- and HPPD-inhibitor-resistant Palmer amaranth in corn. Agron J 110:1905–1914

Chahal PS, Jhala AJ (2019) Integrated management of glyphosate-resistant horseweed (*Erigeron canadensis*) with tillage and herbicides in soybean. Weed Technol 33:859–866

Chauhan BS, Singh RG, Mahajan G (2012) Ecology and management of weeds under conservation agriculture: a review. Crop Prot 38:57–65

Cristaudo, A, Gresta F, Luciani F, Restuccia A (2007) Effects of after harvest period and environmental factors on seed dormancy of *Amaranthus* species. Weed Res 47:327–334

Culpepper AS, Webster TM, Sosnoskie LM, York AC (2010) Glyphosate-Resistant Palmer amaranth in the US. Pages 195–212 *in* Nandula VK, ed. Glyphosate resistance: evolution, mechanisms, and management. Hoboken, NJ: J. Wiley. doi:10.1002/9780470634394.ch11

Curran WS (2016) Persistence of herbicides in soil. Crops Soil 49:16–21

Duke SO (2017) The history and current status of glyphosate. Pest Manag Sci 74:1027–1034

Ehleringer J (1983) Ecophysiology of *Amaranthus palmeri*, a Sonoran desert summer annual. Oecologia 57:107–112

Franca LX (2015) Emergence patterns of common waterhemp and Palmer amaranth in southern Illinois. M.S. thesis. Carbondale, IL: Southern Illinois University. 44 p

Gallagher RS, Cardina J (1998) Phytochrome-Mediated *Amaranthus* germination, I: effect of seed burial and germination temperature. Weed Sci 46:48–52

Gianessi LP (2005) Economic and herbicide use impacts of glyphosate-resistant crops. Pest Manag Sci 61:241–245

Gilley JE, Doran JW (1997) Tillage effects on soil erosion potential and soil quality of a former conservation reserve program site. J Soil Water Cons 52:184–188

Givens WA, Shaw DR, Kruger GR, Johnson WG, Weller SC, Young BG, Wilson RG, Owen MD, Jordan D (2009) Survey of tillage trends following the adoption of glyphosate-resistant crops. Weed Technol 23:150–155

Grundy AC (2003) Predicting weed emergence: a review of approaches and future challenges. Weed Res 43:1–11

Gummerson RJ (1986) The effect of constant temperatures and osmotic potential on the germination of sugar beet. J Exp Bot 41:1431–1439

Guo PG, Al-Khatib K (2003) Temperature effects on germination and growth of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*). Weed Sci 51:869–875

Heap I (2020) Herbicide resistant Palmer amaranth globally. http://www.weedscience.org/Summary/Species.aspx. Accessed: November 2, 2020

Horak MJ, Loughin TM (2000) Growth analysis of four *Amaranthus* species. Weed Sci 48:347–355

Jha P, Norsworthy JK (2009) Soybean canopy and tillage effects on emergence of Palmer amaranth (*Amaranthus palmeri*) from a natural seed bank. Weed Sci 57:644–651

Jha P, Norsworthy JK, Riley MB, Bridges W Jr (2010) Annual changes in temperature and light requirements for germination of Palmer amaranth (*Amaranthus palmeri*) seeds retrieved from soil. Weed Sci 58:426–432

Jhala AJ, Norsworthy JK, Ganie ZA, Sosnoskie LM, Beckie HJ, Mallory-Smith CA, Liu J, Wei W, Wang J, Stoltenberg DE (2020) Pollen-Mediated gene flow and transfer of resistance alleles from herbicide-resistant broadleaf weeds. Weed Technol https://doi.org/10.1017/wet.2020.101

Jhala AJ, Sandell LD, Rana N, Kruger GR, Knezevic SZ (2014) Confirmation and control of triazine and 4-hydroxyphenylpyruvate dioxygenase-inhibiting herbicide-resistant Palmer amaranth (*Amaranthus palmeri*) in Nebraska. Weed Technol 28:28–38

Jhala AJ, Malik MS, Willis JB (2015). Weed control and crop tolerance of microencapsulated acetochlor applied sequentially in glyphosate-resistant soybean. Can J Plant Sci 95:973–981

Johnson WG, Bradley PR, Hart SE, Buesinger ML, Massey RE (2000) Efficacy and economics of weed management in glyphosate-resistant corn (*Zea mays*). Weed Technol 14:57–65

Kaur S, Werle R, Sandell L, Jhala AJ (2016) Spring-Tillage has no effect on the emergence pattern of glyphosate-resistant giant ragweed (*Ambrosia trifida* L.) in Nebraska. Can J Plant Sci 96:726–729

Keeley PE, Carter CH, Thullen RJ (1987) Influence of planting date on growth of Palmer amaranth (*Amaranthus palmeri*). Weed Sci 35:199–204

Klingaman TE, Oliver LR (1994) Palmer amaranth (*Amaranthus palmeri*) interference in soybeans (*Glycine max*). Weed Sci 42:523–527

Knezevic SZ, Pavlovic P, Osipitan OA, Barnes ER, Beiermann C, Oliveira MC, Lawrence N, Scott JE, Jhala A (2019) Critical time for weed removal in glyphosate-resistant soybean as influenced by preemergence herbicides. Weed Technol 33:393–399

Leon RG, Knapp AD, Owen MDK (2004) Effect of temperature on the germination of common waterhemp (*Amaranthis tuberculatus*), giant foxtail (*Setaria faberi*), and velvetleaf (*Abutilon theophrasti*). Weed Sci 52:67–73

Leon RG, Owen MDK (2003) Regulation of weed seed dormancy through light and temperature interactions. Weed Sci 51:752–758

Liphadzi KB, Dille JA (2006) Annual weed competitiveness as affected by preemergence herbicide in corn. Weed Sci 54:156–165

Massinga RA, Currie RS, Horak MJ, Boyer J Jr (2001) Interference of Palmer amaranth in corn. Weed Sci 49:202–208

Mayer DG, Butler DG (1993) Statistical validation. Ecol Model 68:21–32

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60 (SI I):31–62

Ogle RE, Warren GF (1954) Fate and activity of herbicides in soils. Weeds 3:257–273

Powles SB (2008) Evolved glyphosate-resistant weeds around the world: lessons to be learnt. Pest Manag Sci 64:360–365

Raper RL, Reeves DW, Burmester CH, Schwab EB (2000) Tillage depth, tillage timing, and cover crop effects on cotton yield, soil strength, and tillage energy requirements. Appl Eng Agric 16:379–385

Reddy KN, Whiting K (2000) Weed control and economic comparisons of glyphosate-resistant, sulfonylurea-tolerant, and conventional soybean (*Glycine max*) systems. Weed Technol 14:204–211

Roman ES, Murphy SD, Swanton CJ (2000) Simulation of *Chenopodium album* seedling emergence. Weed Sci 48:217–224

Sarangi D, Jhala AJ (2018a) A Statewide survey of stakeholders to assess the problem weeds and weed management practices in Nebraska. Weed Technol 32:642–655

Sarangi D, Jhala AJ (2018b) Comparison of a premix of atrazine, bicyclopyrone, mesotrione, and *S*-metolachlor with other preemergence herbicides for weed control and corn yield in no-tillage and reduced-tillage production systems in Nebraska, USA. Soil Till Res 178:82–91

Sauer JD (1957) Recent migration and evolution of the dioecious *Amaranthus*. Evolution 11:11–31

Sosnoskie LM, Webster TM, MacRae AW, Grey TL, Culpepper AS (2012) Pollen-Mediated dispersal of glyphosate-resistance in Palmer amaranth under field conditions. Weed Sci 60:366–373

Steinmaus SJ, Prather TS, Holt JS (2000) Estimation of base temperatures for nine weed species. J Exp Bot 51:275–286

Walker A (1976) Simulation of herbicide persistence in soil.I. simazine and prometryne. Pest Manag Sci 7:41–49

Webster TM, Coble HD (1995) Changes in the weed species composition of the southern United States: 1974 to 1995. Weed Technol 11:308–317

Werle R, Bernards ML, Arkebauer TJ, Lindquist JL (2014a) Environmental triggers of winter annual weed emergence in the Midwestern United States. Weed Sci 62:83–96

Werle R, Sandell LD, Buhler DD, Hartzler RG, Lindquist JL (2014b) Predicting emergence of 23 summer annual weed species. Weed Sci 62:267–279

Wiggins MS, McClure MA, Hayes RM, Steckel LE (2015). Integrating cover crops and POST herbicides for glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) control in corn. Weed Technol 29:412–418

[WSSA] Weed Science Society of America (2016) WSSA survey ranks Palmer amaranth as the most troublesome weed in the U.S., Galium as the most troublesome in Canada. http://wssa.net/2016/04/wssa-survey-ranks-palmer-amaranth-as-the-most-troublesome-weed-in-the-u-s-galium-as-the-most-troublesome-in-canada/. Accessed: January 28, 2019

Young BG (2006) Changes in herbicide use patterns and production practices resulting from glyphosate-resistant crops. Weed Technol 20:301–307