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# Residual herbicides affect critical time of Palmer amaranth removal in soybean

Jose H. S. de Sanctis[1] | Ethann R. Barnes[1,2] | Stevan Z. Knezevic[1] | Vipan Kumar[3] | Amit J. Jhala[1]

[1] Dep. of Agronomy and Horticulture, Univ. of Nebraska–Lincoln, Lincoln, NE 68583, USA

[2] Current address: GreenLight Biosciences, Research Triangle, NC 27709, USA

[3] Agricultural Research Center-Hays, Kansas State Univ., 1232 240th Avenue, Hays, KS 67601, USA

**Correspondence**
Amit J. Jhala, Dep. of Agronomy and Horticulture, Univ. of Nebraska–Lincoln, 279 Plant Science Hall, PO Box 830915, Lincoln, NE 68583, USA.
Email: Amit.Jhala@unl.edu

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**Abstract**

Glyphosate-resistant (GR) Palmer amaranth (*Amaranthus palmeri* S. Watson) is one of the most difficult to control weeds in soybean [*Glycine max* (L.) Merr.] production fields. Residual pre-emergence (PRE) herbicide applied at planting is one of the recommendations for management of herbicide-resistant Palmer amaranth; however, information is not available about the effect of residual herbicides on critical time of Palmer amaranth removal (CTPAR) to prevent an unacceptable yield loss in soybean. The objective of this study was to determine the CTPAR in soybean affected by residual PRE herbicides compared with the no PRE herbicide in southcentral Nebraska. Field experiments were conducted in 2018 and 2019 in a grower's field infested with GR Palmer amaranth near Carleton, NE. The treatments were arranged in a split-plot design with PRE herbicides (no PRE herbicide, flumioxazin, and a premix of flumioxazin/metribuzin/pyroxasulfone) as the main plot and Palmer amaranth removal timings as subplot treatments (a weed-free control; a nontreated control; and Palmer amaranth removal timing at the V1, V3, V6, R2, and R5 soybean growth stages). In the absence of a PRE herbicide, the CTPAR at 5% soybean yield loss occurred at V1 and V6 soybean growth stages, equivalent to 194 and 480 Celsius growing degrees days (GDDc) in 2018 and 2019, respectively. When flumioxazin was applied alone, the CTPAR was delayed until the V3 and V6 soybean growth stages, or 341 and 501 GDDc. When flumioxazin/metribuzin/pyroxasulfone premix was applied, the CTPAR was delayed until the V2 and R1 soybean growth stages, corresponding to 255 and 546 GDDc, in 2018 and 2019, respectively.

## 1 | INTRODUCTION

Nebraska growers contributed over 7% of the 2.07 billion kg of soybean [*Glycine max* (L.) Merr.] produced in the United States in 2018 (USDA, 2019). Soybean is the second most important crop in Nebraska and is grown on 2.0–2.4 million ha every year (USDA, 2019). Dicamba/glyphosate-resistant (DGR) soybean has been commercially available since the 2017 growing season in the United States. In 2018, DGR

**Abbreviations:** CTPAR, critical time of Palmer amarant removal; DAE, days after emergence; DGR, dicamba/glyphosate-resistant; $ED_{50}$, Celsius growing degree days where 50% response between lower and upper limit occurs; GDDc, Celsius growing degree days; GR, glyphosate-resistant; IWM, integrated weed management; ME, modeling efficiency; POST, post-emergence; PPO, protoporphyrinogen oxidase; PRE, pre-emergence.

soybean accounted for 50% of Nebraska soybean production (Werle et al., 2018); DGR soybean increased to almost 70% in 2019 (Jhala et al., 2019). In June 2020, the United States Court of Appeals for the Ninth Circuit issued a ruling that canceled the registration of three dicamba products (FeXapan, Engenia, and XtendiMax) primarily used in DGR soybean (Jhala et al., 2020); however, in October 2020, USEPA approved registration of three dicamba based products (Engenia, Tavium [a premix of *S*-metolachlor and dicamba], and XtendiMax) for 5 yr (USEPA, 2020).

Palmer amaranth (*Amaranthus palmeri* S. Watson) is native to the southwestern United States; however, over the last two decades, it has spread and has become the most troublesome weed in agronomic crops in the United States (WSSA, 2016). During this period, Palmer amaranth biotypes have evolved resistance to microtubule-inhibiting, acetolactate synthase–inhibiting, photosystem II–inhibiting, 5-enolpyruvylshikimate-3-phosphate synthase–inhibiting, hydroxyphenylpyruvate dioxygenase–inhibiting, protoporphyrinogen oxidase (PPO)-inhibiting, long chain fatty acid–inhibiting, and synthetic auxin herbicides (Chahal et al., 2015; Heap, 2019). The first GR Palmer amaranth was confirmed in 2004 in Georgia (Culpepper et al., 2006). Since then, 32 states have confirmed GR Palmer amaranth, including Nebraska (Chahal et al., 2017; Heap, 2019). This problematic weed is a prolific seed producer with the capacity to produce up to 613,000 seeds per female plant (Keeley et al., 1987). Furthermore, it is able to outcompete most crops, resulting in up to 91% yield loss in corn (Massinga et al., 2001) and 68% yield loss in soybean (Klingaman & Oliver, 1994). Glyphosate is the most commonly used herbicide in GR corn–soybean cropping systems in Nebraska (Sarangi & Jhala, 2018a); therefore, a widespread occurrence of GR Palmer amaranth requires alternate herbicides and other practices for their management (Sarangi, Sandell, et al., 2015).

To control herbicide-resistant Palmer amaranth, it is imperative to use the best management practices, including the use of effective herbicides with multiple sites of action, planting into weed-free fields, and using an integrated weed management (IWM) program (Norsworthy et al., 2012). The IWM approach is the combination of techniques to achieve the most effective and sustainable weed control (Swanton & Weise, 1991). A key element of a successful IWM program is the critical period of weed control, which defines the period of time in which weeds must be controlled to prevent unacceptable yield loss (Knezevic et al., 2002). The critical period of weed control is comprised of the critical timing of weed removal (CTWR) and the critical weed-free period (Knezevic et al., 2002). The CTWR represents the length of time weeds can compete with the crop before a yield reduction occurs. The CTWR is influenced by many factors, including the type of crop and weed species, environmental conditions (Tursun et al., 2016), soil nutrients (Evans et al., 2003; Odero & Wright, 2013), crop row spacing (Knezevic et al., 2003; Norsworthy & Oliveira, 2004), and use of residual PRE herbicides (Barnes, Knezevic, et al., 2019; Knezevic et al., 2013). A recent multilocation study in Nebraska reported that use of a PRE herbicide in soybean reduced early-season weed competition and delayed the CTWR (Knezevic et al., 2019). The CTWR in soybean across three locations in Nebraska has been reported from V1 to V2 without PRE herbicide and was delayed 2–5 wk depending on PRE herbicide used and the field location (Knezevic et al., 2019).

**Core Ideas**

- Pre-emergence herbicides delayed the critical time of Palmer amaranth removal (CTPAR).
- No difference in CTPAR was observed between pre-emergence herbicides tested.
- The CTPAR depends on many factors, including residual herbicide used and growing conditions.

Flumioxazin applied alone or in a premix has been applied PRE at planting by soybean growers for effective control of GR Palmer amaranth (Jhala et al., 2017; Norsworthy & Oliveira, 2004). In 2019, a premix of flumioxazin/metribuzin/ pyroxasulfone was labeled for PRE residual weed control in soybean (Valent, 2019). The CTWR in soybean has not been investigated where Palmer amaranth is the dominant weed species. Additionally, literature does not currently exist about critical time of Palmer amaranth removal (CTPAR) affected by commercially available single-active-ingredient PRE herbicide versus a premix of three herbicide active ingredients. The objective of this study was to determine the CTPAR affected by no PRE herbicide, a single-active-ingredient PRE herbicide (flumioxazin), and a premix of three herbicide active ingredients (flumioxazin/metribuzin/pyroxasulfone) in DGR soybean. We hypothesized that flumioxazin applied alone and as a premix of flumioxazin/metribuzin/pyroxasulfone applied PRE would delay CTPAR compared with no PRE herbicide in DGR soybean.

## 2 | MATERIALS AND METHODS

### 2.1 | Site description

Field experiments were conducted in 2018 and 2019 growing seasons near Carleton, NE (40.3067˚ N, 97.6755˚ W) in a rainfed, nonirrigated grower's field with confirmed GR Palmer amaranth infestation (Chahal et al., 2017). Palmer amaranth was the predominant weed species at the research site. The soil at the experimental site was silt loam, with 63% silt, 19% sand, 18% clay, 2.63% organic matter, and 4.8 pH. A previous crop at the research site was soybean, and no fertilizers were applied. Glyphosate plus paraquat was applied with labeled adjuvants before 3 wk of planting soybean for control of winter annual weeds, such as horseweed (*Erigeron canadensis* L.) and henbit (*Lamium amplexicaule* L.) at the research site duing both years.

## 2.2 | Experimental design and treatments

The experiment was arranged in a split-plot design with four replications with herbicide treatments as the main plot and weed removal timings as subplot. Herbicides in main plots were flumioxazin applied PRE at 107 g ai ha$^{-1}$ (Valor SX, Valent USA LLC); a premix of flumioxazin/metribuzin/pyroxasulfone at 82.75, 248.1, and 105.75 g ai ha$^{-1}$ (Fierce MTZ, Valent USA LLC), respectively; and a set of treatments without a PRE herbicide. The subplot treatments consisted of removal of Palmer amaranth at the V1, V3, V6, R2, and R5 soybean growth stages, which corresponded to 175, 303, 419, 502, and 931 Celsius growing degree days (GDDc), respectively. Subplots also included a weed-free and a nontreated control. Palmer amaranth was allowed to interefe with soybean until respective removal timings, and then plots were kept weed-free for rest of the season. Individual plots were 3 m wide and 9 m long.

Dicamba/glyphosate-resistant soybean (S29 K3X, Syngenta) from Maturity Group 2.9 was planted on 10 May 2018 and 16 May 2019 at 345,000 seeds ha$^{-1}$ with 76.2 cm between rows, followed by PRE herbicide application on the same day using a handheld $CO_2$–pressurized backpack sprayer equipped with five AIXR 110015 flat-fan nozzles (TeeJet Technologies, Spraying Systems Co.) spaced 51 cm apart and calibrated to deliver 140 L ha$^{-1}$ at 276 kPa at a constant speed of 4.8 km h$^{-1}$. Plots were sprayed with dicamba (XtendiMax with VaporGrip, Bayer Crop Science) at 560 g ae ha$^{-1}$ at the respective removal timing with the backpack sprayer equipped with five TTI 11005 flat-fan nozzles (TeeJet Technologies). Plots were kept weed free throughout the growing season following Palmer amaranth removal timing by hand-hoeing.

## 2.3 | Data collection

At each removal timing, a 1-m$^2$ quadrant was randomly placed between the middle two soybean rows within the corresponding plot, and Palmer amaranth density, height, and biomass were collected. Aboveground biomass was obtained by clipping Palmer amaranth plants at soil level, drying in paper bags at 65 ˚C for 10 d until constant mass, and weighing the samples. By the season end, soybean yield components were obtained from the samples collected from the middle two soybean rows. Five plants from the middle two rows were randomly selected to determine number of pods per plant and number of seeds per pod. Soybeans were harvested with a plot combine from the center two rows and corrected to 13% moisture. Yield loss was calculated as:

$$\mathrm{YL} = 100 \times (1 - P/C) \quad (1)$$

where YL is the yield loss relative to the weed-free control plot, $P$ is the treatment plot yield, and $C$ is the yield of the weed-free control plot.

Temperature and rainfall data for the 2018 and 2019 growing seasons were obtained from the nearest High Plains Regional Climate Center located near Hebron, NE. Temperatures were collected from soybean emergence until season end and converted to GDDc Equation 2 (Gilmore & Rogers, 1958):

$$\mathrm{GDDc} = \Sigma\{[(T_{\max} + T_{\min})/2] - T_{\mathrm{base}}\} \quad (2)$$

where $T_{\max}$ and $T_{\min}$ are the daily maximum and minimum air temperatures, respectively, and $T_{\mathrm{base}}$ is the base temperature (10 ˚C; Gilmore & Rogers, 1958).

## 2.4 | Statistical analysis

Palmer amaranth biomass, density, and height data were subjected to ANOVA to test for significance of fixed and random effects, where year and replications were treated as random effects and PRE herbicides and removal timings as fixed effects. Tukey's LSD was used to separate means at $\alpha$ = .05. Statistical analysis was performed in R (R Core Team, 2018) using the base packages and the *drc: Analysis of Dose-Response Curves* package (Ritz et al., 2015). A four-parameter log-logistic model was used to describe the relationship between soybean yield response variables and weed removal timing (in GDDc) using the following equation (Knezevic et al., 2007):

$$Y = c + (d - c)/\left\{1 + \exp\left[b(\log x - \log e)\right]\right\} \quad (3)$$

where $Y$ is the response variable (yield [kg ha$^{-1}$], plants m$^{-1}$ row, pods plant$^{-1}$, seeds pod$^{-1}$, or yield loss [YL]), $c$ is the lower limit, $d$ is the upper limit, $x$ is the duration of weed removal timing in GDDc, $e$ is the $\mathrm{ED}_{50}$ (GDDc where 50% response between lower and upper limit occurs; inflection point), and $b$ is the slope of the line at the inflection point. The CTWR in this study was determined based on an arbitrary 5% yield loss threshold (Knezevic et al., 2003, 2019).

**TABLE 1** Average air temperature and total precipitation during 2018 and 2019 growing seasons (May–September) compared with the 30-yr average at Carleton, NE

| Month | Average temperature | | | Total precipitation | | |
|---|---|---|---|---|---|---|
| | 2018 | 2019 | 30-yr average | 2018 | 2019 | 30-yr average |
| | ˚C | | | mm | | |
| May | 20.6 | 14.8 | 16.4 | 78.0 | 172.7 | 135.4 |
| June | 25.0 | 21.8 | 22.3 | 96.0 | 153.2 | 115.1 |
| July | 24.6 | 25.1 | 24.9 | 95.5 | 137.2 | 105.2 |
| Aug. | 23.3 | 23.0 | 23.7 | 92.2 | 154.9 | 94.0 |
| Sept. | 20.6 | 22.5 | 19.0 | 151.6 | 120.4 | 66.0 |
| Season average | 22.8 | 21.4 | 21.3 | 102.7 | 147.7 | 103.1 |

*Note*.Air temperature and precipitation data were obtained from the closest High Plains Regional Climate Center located in Hebron, NE.

Root mean square error and modeling efficiency (ME) were calculated to evaluate goodness of fit for soybean yield and yield loss (Barnes et al., 2018; Roman et al., 2000; Sarangi & Jhala, 2018b).

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

where $P_i$ and $O_i$ are the predicted and observed values, respectively, and $n$ is the total number of comparisons. The smaller the RMSE, the closer the model-predicted values are to the observed values. The ME was calculated using Equation 5 (Barnes et al., 2017; Mayer & Butler, 1993).

$$\text{ME} = 1 - \left[\sum_{i=1}^{n} (O_i - P_i)/ \sum_{i=1}^{n} (O_i - \bar{O}_i)^2\right] \quad (5)$$

where $\bar{O}_i$ is the mean observed value, and all other parameters are the same as equation 4. An ME value closer to 1.00 means more accurate prediction (Sarangi, Irmak, et al., 2015).

# 3 | RESULTS AND DISCUSSION

## 3.1 | Temperature and precipitation

Average temperatures in 2018 and 2019 were near the 30-yr season average at the research site; however, early-season temperatures varied between years (Table 1). The 2018 growing season started off warmer with average temperatures of 20.6 and 25.0 ˚C in May and June, respectively, compared with 14.8 and 21.8 ˚C in 2019. Monthly precipitation varied from the 30-yr average in both years of the study. The 2018 growing season started with below-average precipiration, with 78 and 96 mm in May and June, compared with the 30-yr average of 135.4 and 115.1 mm. Above-average precipitation was observed throughout the growing season of 2019 (Table 1). Palmer amaranth density, biomass, and height differed between years because of variable weather conditions in the 2018 and 2019 growing seasons; therefore, data are presented separately.

## 3.2 | Palmer amaranth density

Both PRE herbicides effectively reduced Palmer amaranth density and were comparable throughout the study. For example, Palmer amaranth densities in 2018 averaged 85, 11, and 17 plants m$^{-2}$ for no PRE herbicide, flumioxazin, and a premix of flumioxazin/metribuzin/pyroxasulfone and averaged 1,122, 15, and 268 plants m$^{-2}$, respectively, in 2019 at the V1 soybean growth stage (Table 2). Palmer amaranth emergence in 2019 at V1 was greater than the emergence observed in 2018, which can be attributed to the abundant rainfall (Table 1). Further, the effect of PRE herbicide on Palmer amaranth density could be observed at the end of the season. Both herbicides applied PRE were highly effective for controlling GR Palmer amaranth due to efficacy of flumioxazin applied alone or in a premix for controlling *Amaranthus* species. For example, Bell et al. (2016) reported 100% control of GR Palmer amaranth with flumioxazin/pyroxasulfone at 28 d after soybean planting. In addition, Sarangi et al. (2017) reported GR waterhemp [*Amaranthus tuberculatus* (Moq.) J. D. Sauer] density as low as 2 plants m$^{-2}$ at 21 d after flumioxazin plus pyroxasulfone applied PRE at 88 and 112 g ai ha$^{-1}$, respectively, compared with 307 plants m$^{-2}$ in nontreated control in soybean. Houston et al. (2019) reported up to 91% density reduction of PPO-inhibitor–resistant Palmer amaranth when flumioxazin was applied PRE.

## 3.3 | Palmer amaranth biomass

Palmer amaranth biomass increased as plants were allowed to coexist with soybean until later removal timings, as expected.

**TABLE 2** Palmer amaranth density, biomass, and height at V1, V6, and R5 soybean growth stages affected by flumioxazin at 107 g ai ha$^{-1}$, flumioxazin/metribuzin/pyroxasulfone at 436.6 g ai ha$^{-1}$, and without pre-emergence (PRE) herbicide in field experiments conducted in Carleton, NE, in 2018 and 2019

| Soybean growth stage[a] | PRE treatment | 2018 | | | 2019 | | |
|---|---|---|---|---|---|---|---|
| | | Density | Biomass | Height | Density | Biomass | Height |
| | | plants m$^{-2}$ | g m$^{-2}$ | cm | plants m$^{-2}$ | g m$^{-2}$ | cm |
| V1 | no PRE herbicide | 85 (50.10)A | 28.74 (8.65)A | 1.50 (1.22) | 1122 (544.53)A | 18.65 (5.32)A | 8.00 (3.56) |
| | flumioxazin | 11 (15.10)B | 3.20 (4.18)B | 0.50 (1.00) | 15 (5.03)B | 1.05 (0.52)C | 4.87 (1.44) |
| | flumioxazin/metribuzin/pyroxasulfone | 17 (16.12)B | 8.01 (6.71)B | 2.25 (2.22) | 268 (167.71) | 6.55 (3.23)B | 4.37 (1.70) |
| Significance | | * | ** | –[b] | ** | *** | – |
| V6 | no PRE herbicide | 716 (389.38)A | 205.71 (53.31)A | 13.28 (6.08) | 758 (311.56)A | 131.80 (30.44)A | 26.67 (16.13) |
| | flumioxazin | 85 (62.51)B | 62.66 (59.54)B | 13.89 (7.00) | 26 (14.79)B | 31.45 (16.89)B | 45.72 (14.51) |
| | flumioxazin/metribuzin pyroxasulfone | 34 (26.23)B | 41.26 (56.46)B | 19.47 (5.29) | 24 (8.64)B | 46.70 (19.05)B | 36.19 (10.85) |
| | | ** | ** | – | *** | *** | – |
| R5 | no PRE herbicide | 252 (160.73)A | 405.90 (100.07)A | 107.31 (61.53) | 229 (62)A | 357.35 (166.60)A | 107.28 (17.25) |
| | flumioxazin | 60 (40)B | 137.54 (99.38)B | 71.75 (16.89) | 7 (2.00)B | 71.70 (25.73)B | 129.27 (22.95) |
| | flumioxazin/metribuzin/pyroxasulfone | 32 (13.06)B | 265.60 (116.35)AB | 90.80 (40.44) | 16 (7.30)B | 245.50 (17.70)A | 136.25 (14.36) |
| | | * | * | – | * | ** | – |

*Note*. Means presented within the same soybean growth stage and same column and with no common letter(s) are significantly different according to Fisher's protected LSD. Values in parentheses are ±SE.

[a]R5, soybean at beginning seed development stage; soybean growth stage; V1, soybean at first trifoliate stage; V6, soybean at six trifoliate stage._

[b]Nonsignificant at $\alpha = .05$.

*Significant at the .05 probability level.

**Significant at the .01 probability level.

***Significant at the .001 probability level.

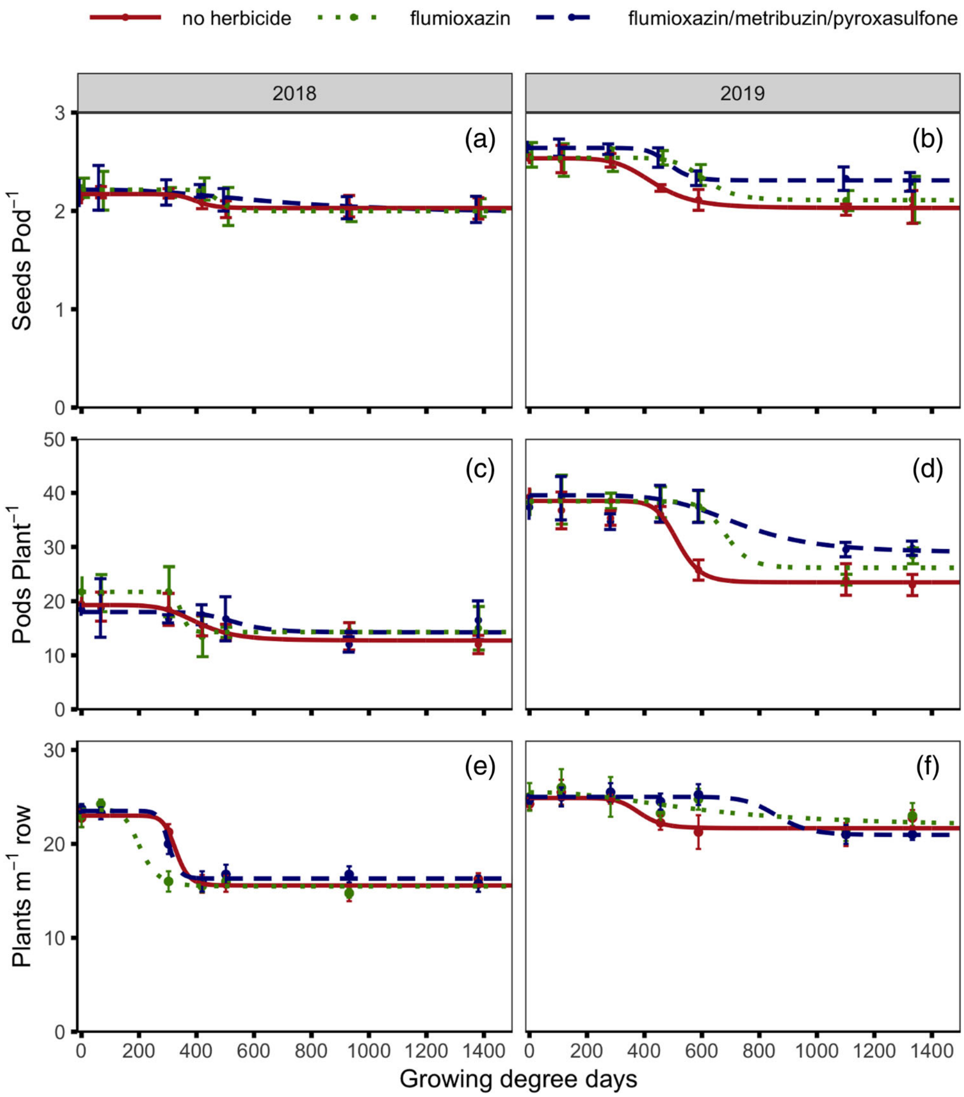


**FIGURE 1** Soybean number of seeds per pod in (a) 2018 and (b) 2019, pods per plant in (c) 2018 and (d) 2019, and soybean plants $m^{-1}$ of row in (e) 2018 and (f) 2019 in response to increasing duration of glyphosate-resistant Palmer amaranth interference as represented by growing degree days (GDD after emergence in degree Celcius) in no pre-emergence (PRE) herbicide, flumioxazin (107 g ai $ha^{-1}$), and flumioxazin/metribuzin/pyroxasulfone (436.6 g ai $ha^{-1}$) applied PRE in field experiments conducted near Carleton, NE. Regression lines represent the fit of a four-parameter log-logistic model.

For example, in 2018 at the V1 soybean growth stage, Palmer amaranth biomass in no PRE herbicide was 29 g $m^{-2}$ (Table 2). By the R5 soybean growth stage, Palmer amaranth biomass for the same treatment was 406 g $m^{-2}$.

By the V6 soybean growth stage, no PRE herbicide, flumioxazin, and flumioxazin/metribuzin/pyroxasulfone resulted in 206, 63, and 41 g $m^{-2}$ Palmer amaranth biomass in 2018 and 132, 31, and 47 g $m^{-2}$ in 2019, respectively. During the 2019 growing season, Palmer amanrath biomass in plots with flumioxazin was lower than the plots where the flumioxazin/metribuzin/pyroxasulfone premix was applied, which can be atribuited to the higher rate (107 g ai $ha^{-1}$) of flumioxazin when applied alone, compared with 82.75 g ai $ha^{-1}$ of flumioxazin in the premix. Further, Sarangi and Jhala (2019) reported 86% Palmer amaranth biomass reduction with flumioxazin + pyroxasulfone applied PRE at 88 + 112 g ai $ha^{-1}$, respectively, in conventional soybean in a multiyear study in Nebraska. Similarly, Umphres et al. (2018) reported 98 and 100% biomass reduction of PPO-inhibitor–resistant and susceptible Palmer amaranth biotype, respectively. Despite the difference between years, Palmer amaranth density and biomass were reduced by PRE herbicides, which supports previous studies that obtained a high level of Palmer amaranth control using flumioxazin + pyroxasulfone (Bernards et al., 2010; Hay, 2017; Jenkins et al., 2017; Mahoney et al., 2014; Young et al., 2010).

### 3.4 | Palmer amaranth height

No difference in Palmer amaranth height was observed among herbicide treatments; however, Palmer amaranth height increased with the delayed removal timing. For example, at the V1 soybean growth stage, Palmer amaranth height varied from 0.5 to 2 cm in 2018 and from 4 to 8 cm in 2019 and at the R5 soybean growth stage varied from 72 to 107 cm in 2018 and from 107 to 136 cm in 2019 (Table 2). On average, Palmer amaranth plants were taller in 2019 compared with 2018 due to an abundance of rainfall (Table 1). Chahal et al. (2018), while studying the effects of water stress on Palmer amaranth growth and fecundity, reported that height varied from 88 to 178 cm when plants were exposed to moderate water stress and no water stress, respectively, which supports the difference in Palmer amaranth heights observed between 2018 and 2019 growing seasons. Despite the results of this study, previous studies reported weed height reduction after PRE herbicide application. For instance, Liphadzi and Dille (2006) reported 40–71% reduction in Palmer amaranth height by isoxaflutole applied PRE but no affect with flumetsulam treatment. Barnes, Jhala, et al. (2019) reported that Palmer amaranth in nontreated control was 130 cm tall compared with 105 cm with atrazine/S-metolachlor applied PRE in popcorn (*Zea mays* L. 'everta').

### 3.5 | Soybean yield components

The impact of the duration of Palmer amaranth interference on soybean yield components varied between years for number of plants m$^{-1}$ row, number of pods plant$^{-1}$, and number of seeds pod$^{-1}$ (Figure 1; Table 3). Despite the variability observed among some of the parameter estimates, similar results have been reported in the literature, in which the use of a PRE herbicide at planting delayed the $ED_{50}$ and/or prevented greater losses from the yield components compared with treatments without PRE herbicide.

The PRE herbicides resulted in similar lower limits for the number of plants m$^{-1}$ row in 2018, ranging from 15.5 to 16.3 plants m$^{-1}$ row; however, the $ED_{50}$ was delayed when PRE herbicides were applied (Table 3; Figure 1e,f). In absence of a PRE herbicide, the $ED_{50}$ occurred at 205 GDDc, and it was delayed to 304 and 328 GDDc, respectively, with flumioxazin and flumioxazin/metribuzin/pyroxasulfone. Similarly, Knezevic et al. (2019) reported that saflufenacil/imazethapyr/pyroxasulfone and sulfentrazone/imazethapyr applied PRE delayed the $ED_{50}$ to 699 and 850 GDDc, respectively, compared with 222 GDDc when no PRE herbicide was applied, with common weed species across the research sites being common lambsquarters (*Chenopodium album* L.), velvetleaf (*Abutilon theophrasti* Medik.), and waterhemp [*Amaranthus tuberculatus* (Moq.) J.D. Sauer].

The number of pods per plant in the nontreated control with no PRE herbicide was 13 and 24 pods plant$^{-1}$, and the $ED_{50}$ occurred at 405 and 515 GDDc in 2018 and 2019, respectively. The use of PRE herbicide delayed the $ED_{50}$, preventing reduction in the number of pods per plant (Figure 1c,d; Table 3). Similarly, Gustafson et al. (2006), in a multilocation study, consistently observed reduction in the number of pods per plant when weeds were competing with soybean until the V2 to V4 growth stage. Additionally, Trezzi et al. (2015) reported the reduction of number of pods per plant as the most affected yield parameter due to weed interference. Peer et al. (2013) observed 42 pods plant$^{-1}$ in nontreated control compared with 51 and 47 pods plant$^{-1}$ when fluchloralin and pendimethalin were applied PRE, respectively.

Number of seeds per pod was reduced due to weed interference. In 2018 growing season, the number of seeds per pod resulted in similar lower limits, with 2 seeds pod$^{-1}$; however, the $ED_{50}$ for nontreated control with no PRE herbicide occurred at 399 GDDc, compared with 476 and 667 when flumioxazin and flumioxazin/metribuzin/pyroxasulfone were applied, respectively. In 2019 growing season, when no PRE herbicide was applied, nontreated control resulted in 2 seeds pod$^{-1}$, and the $ED_{50}$ occurred at 434 GDDc. When flumioxazin was applied, the $ED_{50}$ occurred at 609 GDDc, compared with 486 GDDc with a premix of flumioxazin/metribuzin/pyroxasulfone (Figure 1a,b; Table 3). In a similar study, Silva et al. (2008) observed significant reductions in number of soybean seeds per pod at 42 and 49 d after emergence (DAE) in high and low weed density scenarios, respectively.

### 3.6 | Soybean yield and yield loss

Soybean yield in 2018 was lower compared with 2019 due to dryer and warmer weather conditions observed in May and June of 2018 (Table 1). In the 2018 growing season, weed-free plots yielded 1,788, 1,563, and 1,391 kg ha$^{-1}$ compared with 4,922, 4,764, and 4,844 kg ha$^{-1}$ in 2019, respectively, in no-PRE herbicide, flumioxazin, and flumioxazin/metribuzin/pyroxasulfone (Figure 2a,b; Table 4). In contrast, when Palmer amaranth was allowed to coexist with soybean throughout the season, yields were 1,073, 730, and 1,390 kg ha$^{-}{}_{1}$ in 2018 and 2,961, 3,737, and 3,314 in 2019 in no-PRE herbicide, flumioxazin, and flumioxazin/metribuzin/pyroxasulfone, respectively. In a similar study, Knezevic et al. (2003) reported soybean yield from the nontreated control ranging from 440 to 2,330 kg ha$^{-1}$ compared with a range of 2,650–3,520 kg ha$^{-1}$ in weed-free control; additionally, yield differences between locations were

**TABLE 3** Parameter estimates and of a four-parameter log-logistic model, root mean square error, and modeling efficiency of soybean yield components for flumioxazin at 107 g ai $ha^{-1}$, flumioxazin/metribuzin/pyroxasulfone at 436.6 g ai $ha^{-1}$, and without pre-emergence (PRE) herbicide treatments in field experiments conducted in Carleton, NE, in 2018 and 2019

| Yield component | Year | PRE herbicide | Slope | Lower limit | Upper limit | $ED_{50}$ | RMSE | ME |
|---|---|---|---|---|---|---|---|---|
| | | | | | | GDDc | | |
| Plants $m^{1}$ row | 2018 | no PRE herbicide | 6.73 (11.86) | 15.47 (0.43) | 23.63 (0.56) | 204.73 (134.10) | 1.46 | 0.95 |
| | | flumioxazin | 17.47 (29.76) | 16.30 (0.43) | 23.50 (0.60) | 303.67 (9.07) | 1.58 | 0.94 |
| | | flumioxazin/metribuzin/pyroxasulfone | 14.56 (14.64) | 15.57 (0.47) | 23.00 (0.55) | 328.27 (29.62) | 1.44 | 0.95 |
| | 2019 | no PRE herbicide | 2.26 (3.29) | 21.78 (3.19) | 25.49 (1.08) | 598.30 (670.57) | 5.18 | 0.64 |
| | | flumioxazin | 15.24 (30.62) | 20.95 (0.87) | 25.00 (0.37) | 862.03 (499.62) | 1.52 | 0.89 |
| | | flumioxazin/metribuzin/pyroxasulfone | 9.58 (13.89) | 21.67 (0.64) | 25.88 (0.72) | 384.43 (138.81) | 7.45 | 0.81 |
| Pods plant $^{1}$ | 2018 | no PRE herbicide | 6.06 (7.27) | 12.73 (1.52) | 19.29 (1.40) | 405.32 (83.10) | 9.83 | 0.86 |
| | | flumioxazin | –26.94 (61.41) | 14.30 (1.54) | 21.72 (91.93) | 346.97 (127.27) | 7.36 | 0.68 |
| | | flumioxazin/metribuzin/pyroxasulfone | –8.54 (24.20) | 14.26 (2.12) | 18.00 (1.81) | 533.79 (222.46) | 9.4 | 0.70 |
| | 2019 | no PRE herbicide | 13.15 (7.79) | 23.50 (1.81) | 38.50 (1.48) | 515.29 (42.44) | 5.18 | 0.88 |
| | | flumioxazin | 12.87 (43.63) | 26.48 (1.96) | 38.45 (1.33) | 710.10 (457.79) | 7.84 | 0.87 |
| | | flumioxazin/metribuzin/pyroxasulfone | 5.43 (10.62) | 28.96 (5.23) | 39.55 (1.96) | 729.34 (339.81) | 77.45 | 0.82 |
| Seeds pod $^{1}$ | 2018 | no PRE herbicide | 12.00 (20.57) | 2.03 (0.04) | 2.17 (0.04) | 399.35 (89.14) | 0.14 | 0.87 |
| | | flumioxazin | 18.79 (31.21) | 1.99 (0.08) | 2.21 (0.06) | 475.75 (66.94) | 0.22 | 0.66 |
| | | flumioxazin/metribuzin/pyroxasulfone | 2.62 (6.30) | 1.97 (0.33) | 2.21 (0.09) | 666.73 (1,059.30) | 0.24 | 0.60 |
| | 2019 | no PRE herbicide | 6.15 (4.84) | 2.03 (0.07) | 2.53 (0.06) | 433.61 (60.31) | 0.17 | 0.87 |
| | | flumioxazin | 11.39 (26.73) | 2.11 (0.09) | 2.54 (0.07) | 608.84 (93.69) | 0.25 | 0.75 |
| | | flumioxazin/metribuzin/pyroxasulfone | 13.31 (16.75) | 2.31 (0.06) | 2.64 (0.05) | 486.06 (54.96) | 0.15 | 0.90 |

*Note*. $ED_{50}$, Celsius growing degree days where 50% response between lower and upper limit occurs; GDDc, Celsius growing degree days; ME, modeling efficiency. The subplot treatments consisted of removal of Palmer amaranth at V1, V3, V6, R2, and R5 soybean growth stages, which corresponded to 175, 303, 419, 502, and 931 GDDc, respectively. Values in parentheses are ±SE.

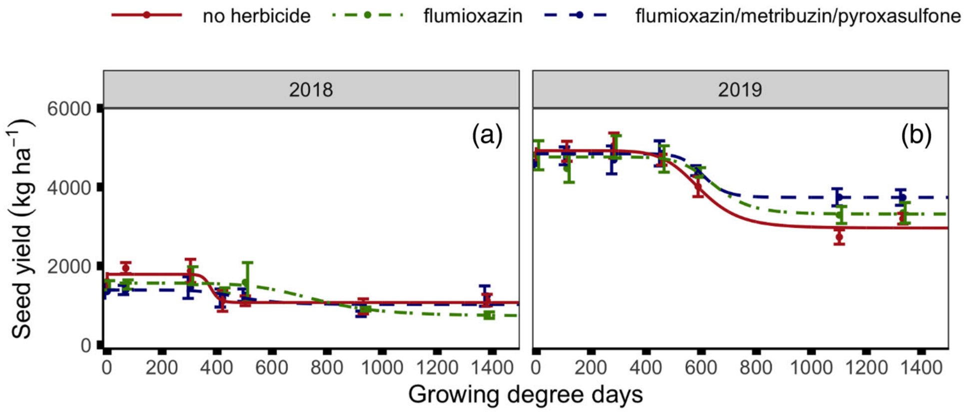


**FIGURE 2** Soybean yield in response to increasing duration of Palmer amaranth interference as represented by growing degree days (GDD after emergence in degree Celcius) in no pre-emergence (PRE) herbicide, flumioxazin (107 g ai ha$^{-1}$), and flumioxazin/metribuzin/pyroxasulfone (436.6 g ai ha$^{-1}$) applied PRE during (a) 2018 and (b) 2019 in field experiments conducted near Carleton, NE. Regression lines represent the fit of a four-parameter log-logistic model

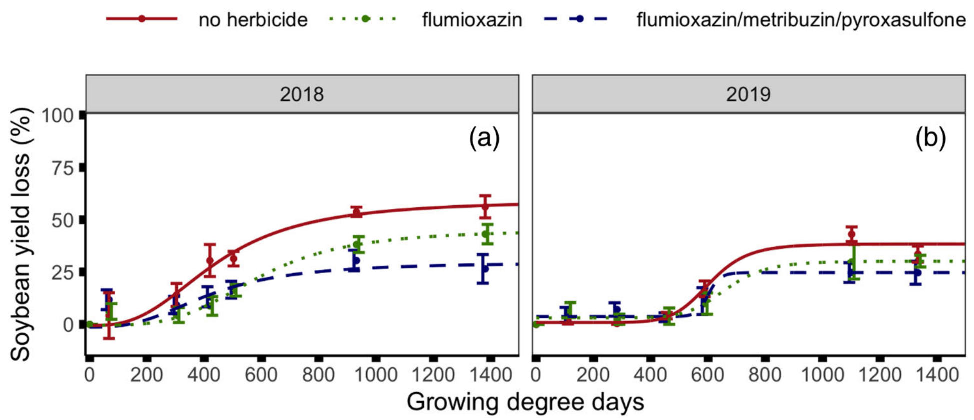


**FIGURE 3** Soybean yield loss in response to increasing duration of Palmer amaranth interference represented by growing degree days (GDD after emergence in degree Celcius) in no pre-emergence (PRE) herbicide, flumioxazin (107 g ai ha$^{-1}$), and flumioxazin/metribuzin/pyroxasulfone (436.6 g ai ha$^{-1}$) applied PRE during (a) 2018 and (b) 2019 in field experiments conducted near Carleton, NE. Regression lines represent the fit of a four-parameter log-logistic model

attributed to dry weather reported in one of the study sites. The incremental increase in soybean yield when PRE herbicides were applied is attributed to the effective control of Palmer amaranth, which reduced crop-weed competition (Table 2). Sarangi and Jhala (2018b) reported that nontreated control yielded 2,247 and 560 kg ha$^{-1}$ in 2016 and 2017, respectively, compared with 3,757 and 933 kg ha$^{-1}$ when flumioxazin/pyroxasulfone was applied PRE at 88 and 112 g of ai ha$^{-1}$, in 2016 and 2017, respectively.

In the absence of PRE herbicide, yield loss in the nontreated control was 58 and 38%, compared with 45 and 30% and 30 and 25% with flumioxazin and flumioxazin/metribuzin/pyroxasulfone, respectively, in 2018 and 2019 (Figure 3a,b; Table 5). This might be because above-average precipitation was observed throughout the growing season in 2019 (Table 1), resulting in relatively better soybean growth and development that might have outcompeted Palmer amaranth. Moreover, a four-parameter log-logistic model fit the data well, with RMSE ranging from 7.36 to 9.40 and from 5.18 to 7.84 and ME ranging from 0.91 to 0.96 and from 0.90 to 0.96, respectively, in 2018 and 2019. Elezovic et al. (2012) reported 79% yield loss in imidazolinone-resistant sunflower (*Helianthus annuus* L.) where weeds were allowed to compete until the R5 growth stage compared with 55% yield loss when *S*-metolachlor and fluorchloridon were applied PRE. Mulugeta and Boerboom (2000) reported up to 81% soybean yield loss in nontreated control compared with 24% yield loss where weeds were allowed to compete until the R1 growth stage. Yield loss in soybean has also been studied with interference from other weed species. For example, Eaton

**TABLE 4** Parameter estimates and of a four-parameter log-logistic model, RMSE, and modeling efficiency for soybean yield affected by flumioxazin applied at 107 g ai $ha^{-1}$, flumioxazin/metribuzin/pyroxasulfone at 436.6 g ai $ha^{-1}$, and without pre-emergence (PRE) herbicide in a field experiment conducted at Carleton, NE, in 2018 and 2019

| Year | PRE herbicide | Slope | Lower limit | Upper limit | $ED_{50}$ | RMSE | ME |
|---|---|---|---|---|---|---|---|
| | | | kg $ha^{-1}$ | | GDDc | | |
| 2018 | no PRE herbicide | 24.92 (40.32) | 1,072.68 (107.12) | 1,787.69 (118.34) | 377.72 (82.46) | 341.3 | 0.82 |
| | flumioxazin | 6.22 (8.86) | 730.13 (233.18) | 1,563.20 (109.78) | 759.13 (224.16) | 327.5 | 0.82 |
| | flumioxazin/metribuzin/pyroxasulfone | 6.41 (7.24) | 1,020.41 (147.40) | 1,390.71 (128.50) | 481.32 (173.73) | 371.8 | 0.88 |
| 2019 | no PRE herbicide | 8.32 (4.70) | 2,961.00 (157.10) | 4,922.47 (126.23) | 595.99 (35.60) | 402.9 | 0.92 |
| | flumioxazin | 9.91 (20.48) | 3,314.62 (208.74) | 4,763.68 (154.85) | 648.94 (148.05) | 521.8 | 0.87 |
| | flumioxazin/metribuzin/pyroxasulfone | 15.03 (47.10) | 3,737.73 (191.92) | 4,843.7 (142.75) | 606.56 (74.62) | 502.5 | 0.88 |

*Note*. $ED_{50}$, Celsius growing degree days where 50% response between lower and upper limit occurs; GDDc, Celsius growing degree days; ME, modeling efficiency. The subplot treatments consisted of removal of Palmer amaranth at V1, V3, V6, R2, and R5 soybean growth stages, which corresponded to 175, 303, 419, 502, and 931 GDDc, respectively. Values in parentheses are ±SE.

**TABLE 5** Parameter estimates and SE of a four-parameter log-logistic model, RMSE, and modeling efficiency used to determine the critical time of Palmer amaranth removal in soybean affected by flumioxazin applied at 107 g ai $ha^{-1}$ flumioxazin/metribuzin/pyroxasulfone at 436.6 g ai $ha^{-1}$, and without pre-emergence (PRE) herbicide in field experiments conducted at Carleton, NE, in 2018 and 2019

| Year | PRE herbicide | Slope | Yield loss | | $ED_{50}$ | RMSE | ME |
|---|---|---|---|---|---|---|---|
| | | | Lower limit | Upper limit | | | |
| | | | % | | GDDc | | |
| 2018 | no PRE herbicide | –3.02 (1.45) | 0.42 (4.19) | 58.18 (7.25) | 437.15 (62.77) | 10.0 | 0.92 |
| | flumioxazin | –4.21 (2.09) | –0.21 (2.81) | 44.57 (7.58) | 568.29 (8,445) | 7.35 | 0.96 |
| | flumioxazin/metribuzin/pyroxasulfone | –2.75 (1.92) | –1.30 (3.75) | 29.62 (6.17) | 419.03 (103.94) | 9.40 | 0.93 |
| 2019 | no PRE herbicide | –9.07 (4.16) | 0.89 (1.61) | 38.37 (2.01) | 604.91 (25.53) | 5.18 | 0.96 |
| | flumioxazin | –9.27 (21.29) | 3.08 (2.42) | 30.15 (3.61) | 661.23 (193.66) | 7.84 | 0.90 |
| | flumioxazin/metribuzin/pyroxasulfone | –29.28 (306.91) | 3.75 (2.02) | 24.70 (2.84) | 600.50 (132.76) | 7.45 | 0.91 |

*Note*. $ED_{50}$, Celsius growing degree days where 50% response between lower and upper limit occurs; GDDc, Celsius growing degree days; ME, modeling efficiency. The subplot treatments consisted of removal of Palmer amaranth at V1, V3, V6, R2, and R5 soybean growth stages, which corresponded to 175, 303, 419, 502, and 931 GDDc, respectively. Values in parentheses are ±SE.

**TABLE 6** The critical time of Palmer amaranth removal in soybean affected by flumioxazin at 107 g ai ha$^{-1}$, flumioxazin/metribuzin/pyroxasulfone at 436.6 g ai ha$^{-1}$, and without pre-emergence (PRE) herbicide based on the modeled data and obtained for 5% of yield loss in field experiments conducted at Carleton, NE, in 2018 and 2019

| Year | PRE herbicide | $GDD_c$ | SGS | DAE |
|---|---|---|---|---|
| 2018 | no PRE herbicide | 194 | V1 | 18 |
| | flumioxazin | 351 | V3 | 33 |
| | flumioxazin/metribuzin/pyroxasulfone | 255 | V2 | 24 |
| 2019 | no PRE herbicide | 480 | V6 | 40 |
| | flumioxazin | 501 | V6 | 42 |
| | flumioxazin/metribuzin/pyroxasulfone | 546 | R1 | 45 |

*Note*. DAE, days after crop emergence; $GDD_c$, growing degree days in Celsius; R5, soybean at beginning seed development stage; SGS, soybean growth stage; V1, soybean at first trifoliate stage; V6, soybean at six trifoliate stage. The subplot treatments consisted of removal of Palmer amaranth at V1, V3, V6, R2, and R5 soybean growth stages, which corresponded to 175, 303, 419, 502, and 931 GDDc, respectively.

et al. (1976) reported up to 32% yield loss when velvetleaf (*Abutilon theophrasti* Medik.) was competing with soybean throughout the growing season.

## 3.7 | Critical time of Palmer amaranth removal

The critical time of Palmer amaranth removal (CTPAR) based on a 5% soybean yield loss varied between years; therefore, data were analyzed separately for both years (Table 6; Figure 3). Dose-response curves demonstrated that the CTPAR without PRE herbicide occurred at 194 GDDc, which corresponded to the V1 soybean growth stage or 18 DAE in 2018. When flumioxazin and flumioxazin/metribuzin/pyroxasulfone were applied, a 5% yield loss occurred at 351 and 255 GDDc, which corresponded to the V3 and V2 soybean growth stages or 33 and 24 DAE, respectively (Table 6). Similarly, Silva et al. (2009) reported CTWR in GR soybean occurred between 11 and 24 DAE for high and low weed density scenarios, respectively. In 2019, the CTPAR without PRE herbicide was observed at 480 GDDc, which corresponded to V6 or 40 DAE. The PRE herbicides delayed the CTPAR until 501 and 546 GDDc, which corresponded to the V6 and R1 soybean growth stages or 42 and 45 DAE for flumioxazin and flumioxazin/metribuzin/pyroxasulfone, respectively. Knezevic et al. (2019), in a multilocation study in Nebraska, reported that CTWR in soybean ranged from the V4 to R5 growth stages when imazethapyr/sulfentrazone or imazethapyr/pyroxasulfone/saflufenacil were applied PRE. The critical period of weed removal can vary due to environmental conditions; in this study the unusual dry conditions observed in 2018 and the unusual rainfall during 2019 contributed to the variability between years, which may explain the CTPAR starting at the V1 soybean growth stage in 2018 and at V6 in 2019. Similarly, Van Acker et al. (1993) reported variability in the CTWR, ranging from V3 to R3 or from 9 to 38 DAE, which was attributed to differences in weather conditions and weed populations observed between years.

## 3.8 | Recommendations and practical implications

Results of this study suggest that when no PRE herbicide was applied, Palmer amaranth should not be allowed to compete with soybean for more than 194 and 480 GDDc, which was equivalent to the V1 and V6 soybean growth stages or 18 and 40 DAE, respectively, in 2018 (relatively dry year) and 2019 (wet year) (Tables 1 and 6). The PRE herbicide can delay the CTPAR depending on the residual herbicide used and the growing conditions. In this study, flumioxazin delayed the CTPAR to 341 and 501 GDDc, which corresponded to the V3 (32 DAE) and V6 (42 DAE) soybean growth stages, respectively, in 2018 and 2019. In addition, flumioxazin/metribuzin/pyroxasulfone delayed the CTPAR to 255 (V2; 24 DAE) and 546 GDDc (R1; 45 DAE). Despite some differences between the CTPAR influenced by flumioxazin and flumioxazin/metribuzin/pyroxasulfone, best management practices require the use of herbicide with multiple sites of action to minimize new herbicide-resistant weed biotypes, which can be obtained by carefully selecting PRE and POST herbicides.

Similar studies have shown that the CTWR in soybean without PRE herbicide could range from 14 to 30 DAE (Gustafson et al., 2006; Knezevic et al., 2003); however, many factors can influence the CTWR, such as weed density, weed composition, and time of crop and weed emergence. The CTWR in crop fields with high weed density and early weed emergence is expected to occur earlier compared with locations with low weed density and late weed emergence (Jeschke et al., 2011; Soltani et al., 2017). By reducing early-season weed competition, the PRE herbicide can partially protect soybean yield and can delay the time of POST herbicide application. Selection of a PRE herbicide based on known weed composition of the field may increase PRE herbicide efficacy and further delay the CTWR.

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## CONFLICT OF INTEREST

No conflicts of interest have been declared.

## ORCID

*Ethann R. Barnes* https://orcid.org/0000-0002-6697-3839
*Vipan Kumar* https://orcid.org/0000-0002-8301-5878
*Amit J. Jhala* https://orcid.org/0000-0001-8599-4996

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