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Management Considerations for Palmer Amaranth in a Northern Great Plains Soybean Production System

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Core Ideas

- Soybean yield loss in South Dakota was dependent on Palmer amaranth density if it emerged before canopy closure.
- Soybean yield losses were not Palmer amaranth density dependent when it emerged at the R2 soybean growth stage.
- The relative growth rate of Palmer amaranth was rapid and suggests a limited period for effective post-emergence control.
- The South Dakota biotype was insensitive to several broadleaf herbicides that typically are recommended for Palmer amaranth control.

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ABSTRACT

Palmer amaranth (*Amaranthus palmeri* S. Watson) was first observed in a South Dakota field in 2015. This study assessed Palmer amaranth growth based on planting date (PD), impact on soybean [*Glycine max* (L.) Merr.] yield, and response of seedlings of South Dakota biotype seedlings to herbicides with different mechanisms of action (MOA). Soybean yield loss was influenced by Palmer amaranth density in 2016 ($p = 0.001$), with yield losses of 33% at densities greater than 15 plants m^{-2} ($R^2 = 0.65$), although yield losses at low densities were greater than predicted by the fitted model. In 2017, yield loss was not correlated to Palmer amaranth density when Palmer amaranth established later in the season. Relative growth rates (RGR) of Palmer amaranth (based on plant volumes) were rapid just after transplanting, irrespective of the initial PD (ranging from mid-May to mid-June). Late-planted cohorts had lower final volumes (0.23 m^3) at August harvest compared with early planted cohorts (6.5 m^3), but even late-planted cohorts were two to three times larger than other common South Dakota *Amaranth* species [*A. retroflexus* L. and *A. tuberculatus* (Moq.) Sauer], which emerged at similar times. In greenhouse studies, labeled rates of atrazine (6-chloro-*N*-ethyl-*N*-(1-methylethyl)-1,3,5-triazine-2,4-diamine), glyphosate (*N*-(phosphonomethyl)glycine)), and mesotrione (2-[4-(methysulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione) did not control Palmer amaranth plants grown from SD biotype seed, but were controlled with *S*-metolachlor (2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-[(1*S*)-2-methoxy-1-methyethyl]acetamide), dicamba [3,6-dichloro-2-methoxybenzoic acid], and glufosinate (2-amino-4(hydroxymethylphosphinyl)butanoic acid). However, Palmer amaranth biotypes resistant to *S*-metolachlor, dicamba, and several other herbicides have been reported, so techniques to limit future herbicide resistance should be followed.

Abbreviations: ALS, acetolactate synthase; EPSPS, 5-enolpyruvyl-shikimate-3-phosphate synthase; GDD, growing degree days; HPPD, 4-hydroxyphenylpyruvate dioxygenase; MOA, mechanism of action; PD, planting date; PPO, protoporphyrinogen oxidase; RGR, relative growth rate.

Palmer amaranth (*Amaranthus palmeri* S. Watson) is a dioecious plant, native to northwestern Mexico and the drier regions of the southwestern United States. Northeastward expansion began during the late 1800s (Sauer, 1957). Since the early 2000s, Palmer amaranth has been reported in Virginia, Oklahoma, South Carolina, Michigan (Culpepper et al., 2010), South Dakota (authors' personal observation, 2015), Minnesota (Minnesota Department of Agriculture, 2019), and North Dakota (NDSU Agriculture Communication, 2018), evidence that this weed is growing far outside its original native range (Ward et al., 2013). In 2009, a survey of southern US cotton (*Gossypium hirsutum* L.) producers ranked Palmer amaranth as the most troublesome weed in 9 out of 10 states (Webster and Nichols, 2012). In 2016, Weed Science Society of America (WSSA) members ranked Palmer amaranth as the most troublesome and difficult to control weed in 12 cropping categories, which included broadleaf agronomic crops, fruits, and vegetables (Van Wychen, 2016).

There are multiple reasons why Palmer amaranth has a "worst weed designation" in many cropping systems. First, only a few Palmer amaranth plants per m^2 can cause high yield losses. For example, 60% soybean [*Glycine max* (L.) Merr.] yield loss has been reported with as few as three Palmer amaranth plants m^{-2} (Klingaman and Oliver, 1994) and cotton yield losses of 65% have been measured with densities less than one Palmer amaranth plant m^{-2}

(Rowland et al., 1999; Morgan et al., 2001). A second concern is that Palmer amaranth plants are prolific. A single female Palmer amaranth plant can produce an estimated 600,000 seeds when grown without competition (Keeley et al., 1987). When grown with a crop, Palmer amaranth plants can still produce 880 (Norsworthy et al., 2016) to 80,000 seeds (Keeley et al., 1987), depending on emergence date, crop, and crop and weed densities. However, Palmer amaranth biotypes evolved and became more aggressive by adapting life-history traits (e.g., time to flowering, plant height, and weight) that optimized their growth even in cropping systems designed to be more competitive with the plant (Bravo et al., 2017). A third concern is ineffective control of Palmer amaranth with herbicides. If Palmer amaranth is taller than 4 cm, control can be poor, even when using herbicides efficacious to smaller plants (Ferrell and Leon, 2016). Temperatures at and after herbicide applications have influenced Palmer amaranth response. For example, mesotrione (2-[4-(methysulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione) efficacy was reduced when applied in warm, rather than cool, conditions (Godar et al., 2015) as the plant metabolized the herbicide faster. In addition, Palmer amaranth biotypes have been reported to be resistant to several mechanisms of action (MOAs) (Shaner, 2014) including acetolactate synthase (ALS) inhibitors (Horak and Peterson, 1995), dinitroanilines (microtubule inhibitors), protoporphyrinogen oxidase (PPO) inhibitors, photosynthesis inhibitors (triazines), 5-enolpyruvyl-shikimate-3-phosphate synthase (EPSPS) inhibitor [e.g., glyphosate (*N*-(phosphonomethyl)glycine)], and 4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitors (Heap, 2019; Ward et al., 2013). Biotypes resistant to multiple MOAs (e.g., ALS and EPSPS in the same plant) are documented (Heap, 2019; Schwartz-Lazaro et al., 2017).

The introduction of Palmer amaranth into northern environments has been linked to seed contamination in cottonseed meal used for dairy fodder (Michigan; Sprague, 2014), pollinator seed mix (Iowa and Minnesota; Betts, 2017), seed deposition in waterfowl feces (Missouri; Farmer et al., 2017), and spread of seed-contaminated animal manure from southern state sources (e.g., Corsica, South Dakota infestation; authors' personal observation, 2015). Since Palmer amaranth was originally adapted to desert conditions and located in areas where day–night lengths are almost equal, there was an assumption that the plant would be at a competitive disadvantage compared with *Amaranthus* species in higher latitudes and/or cooler, wetter environments. Palmer amaranth, a C_4 plant, typically has lower germination and slower growth rates in cool conditions (15/10°C) compared with warm conditions (25/20°C) (Wright et al., 1999; Guo and Al-Khatib, 2003; Ward et al., 2013). When grown under cool conditions, or if emerging later in the growing season, Palmer amaranth plants were smaller and produced less seed, but still contributed enough seed to replenish the soil seed bank (Norsworthy et al., 2016). In addition, Davis et al. (2015) reported that Palmer amaranth seed from geographically diverse accessions grew well at four climatically distinct Illinois locations and concluded that only the lack of seed contributed to the plant's scarcity throughout the area.

Palmer amaranth is a relatively new invasive plant in South Dakota (2015 at Corsica, SD). Swine manure from a wash-out station that was spread on a producer's field is suspected to be the Palmer amaranth seed source for the infestation. Swine imported into South Dakota are typically at the finishing stage (50 kg), and in 2017 were valued at US$16 million (US Census Bureau, 2018). Although imported swine need a certificate of veterinary inspection (South Dakota Animal Industry Board, 2016), feed source information is not needed, nor is there a holding period suggested to eliminate weed seed contaminants from the digestive tract. The objectives of this study were to: (i) quantify soybean yield loss in a South Dakota field based on Palmer amaranth density, which remained or emerged after POST herbicide applications; (ii) determine Palmer amaranth growth rate and development if seedlings emerged at different times in the season (mid-May to mid-June); and (iii) determine efficacious herbicides on the South Dakota Palmer amaranth biotype.

MATERIALS AND METHODS

Soybean Yield Loss

This study was conducted in a producer field near Corsica, SD (south central, 43°22′ N, 98°24′ W elevation 479 m) in 2016 and 2017. Growing degree days (GDD) (base 10°C) from May to October 2016 totaled 1816, which was 12% greater than the 30-yr average (1981–2010) of 1613, with the largest deviation in June. Rainfall totaled 439 mm, which was 3% greater than the 30-yr average of 424 mm, although May had 50% more rainfall than average and June and July were 50% drier than the average. Growing degree days in 2017 totaled 1689, similar to the 30-yr average. Rainfall was near normal (402 mm), although June and July were 50% drier and August had almost 70% more rainfall (106 mm) than the 30-yr average (61 mm).

The soil at the site was an Eakin–Ethan complex (fine-silty, mixed, superactive, mesic Typic Argiustolls and fine-loamy, mixed superactive, mesic Typic Calciustolls). The sand, silt, and clay content for the area averaged 95, 675, and 230 g kg^{-1}, respectively. Soil pH and organic matter were 6.7 and 30 g kg^{-1}, respectively. Commercially available soybean varieties (relative maturity group 2; glyphosate-resistant in 2016; glyphosate + dicamba [3,6-dichloro-2-methoxybenzoic acid]-resistant in 2017) were drilled into 0.76-m rows in May 2016 and June 2017 at a recommended rate to have a final stand of 370,000 plants ha^{-1}. POST treatments (glyphosate in 2016 and glyphosate + dicamba in 2017) were applied by the producer at about the V2/V3 soybean growth stage, and control averaged about 90% of the emerged Palmer amaranth about 4 wk after application. However, Palmer amaranth plants emerged in patches after the last POST application starting in mid-June (2016) and mid-July (2017), which were not subsequently treated. Soybean yield losses based on these late emerging, uncontrolled Palmer amaranth densities were quantified.

In late July of each year, depending on the size of the infested area and Palmer amaranth density, a minimum of four to a maximum of six 1-m^2 areas per density at three landscape positions (summit, mid-slope, and footslope) were selected and marked for harvest later in the season. The chosen densities were 0 (weed-free), low (1 to 5 Palmer amaranth plants m^{-2}), medium (6 to 10 Palmer amaranth plants m^{-2}), and high (>10 Palmer amaranth plants m^{-2}). The replicated weed-free areas were selected near the infested areas (to have similar landscape positions, microclimate, soil water availability, etc. throughout the season) to assess yield loss as paired comparisons within landscape position. The experimental design was a randomized complete block with landscape position used as the block effect and Palmer amaranth density as the variable.

Palmer amaranth plants were counted and harvested from the areas when soybean was at the R7/R8 growth stage (16 Sept. 2016 and 7 Sept. 2017). Plants were placed in a forced-air drier at 60°C, and weighed after reaching constant weight. Biomass per area and per plant was calculated.

Table 1. Planting dates (PD1, PD2, PD3), plant volumes, and average plant biomass for Palmer amaranth Kansas biotype (2015), and Corsica, SD, biotype (2016). Average plant density in 2015 was 10 m^{-2} for PD1 and 11 m^{-2} for PD2 and PD3. In 2016, density was 4 plants m^{-2}. Plants for the seed source study were transplanted into the field on 10 June 2016 (PD2) with a final density of 2 plants m^{-2}. Harvest date for 2015 PD study was 1 August, and in 2016 for PD and seed source study, plants were harvested 21 August, except Urbana, IL, biotype, which was harvested 2 August due to early maturity.

Cohort	Greenhouse planting date	Field transplant	Final density	Plant volume						Plant biomass
				Sampling date						
				11 June	30 June	15 July	23 July	1 Aug.		
			plants m^{-2}				m^3			g $plant^{-1}$
2015										
PD1	7 May	22 May	10	0.0005a†	0.025a	0.41a	0.71a	0.97a		225a
PD2	26 May	10 June	11	0.0001 b	0.004 b	0.08 b	0.21 b	0.30 b		75 b
PD3	11 June	24 June	11		0.005 c	0.04 b	0.13 b	0.23 b		50 b
2016				24 June	1 July	16 July	25 July	2 Aug.	21 Aug.	
PD1	10 May	25 May	4	0.006a	0.0076a	0.11a	0.34a	0.91a	3.29a	346ab
PD2	25 May	10 June	4	0.0003b	0.0033b	0.07a	0.35a	0.84a	2.56ab	388a
PD3	10 June	24 June	4		<0.001c	0.004 b	0.13 b	0.40 b	1.66 b	253 b
Seed source	25 May	10 June		(182)‡	(252)	(421)	(553)	(653)	(854)	
Columbia, MO			2	<0.0006	0.0054abc	0.15abc	0.72ab	1.66a	6.84a	210 bc
Corsica, SD			2	<0.0006	0.0086a	0.19a	0.80a	1.45a	4.21 b	400ab
Fayetteville, AR			2	<0.0006	0.0049 bc	0.13abc	0.67ab	1.20a	1.98 cd	198 bc
Jenkins, GA			2	<0.0006	0.0035 bc	0.08 cd	0.54 b	1.16a	3.37 bc	495a
Las Cruses, NM			2	<0.0006	0.0020 c	0.04 d	0.30 c	0.47 b	1.17 d	125 c
Manhattan, KS			2	<0.0006	0.0040 bc	0.11 bc	0.57ab	1.19a	3.56 bc	280abc
Urbana, IL			2	<0.0006	0.0066ab	0.16ab	0.67ab	1.68a	na	110§ c

† Means within a year or seed source followed by different letters differed at $P < 0.05$.

‡ Numbers in parentheses are growing degree days base 10°C from field transplant (10 June) to sampling date.

§ Harvested 2 Aug. 2016.

Soybean from the delineated areas (2 rows by at least 1 m long) were harvested on 4 Oct. 2016 and 9 Oct. 2017 at physiological maturity, using a Massey Ferguson 8 (AGCO Corp., Duluth, GA) plot combine. The length of each harvest area was determined and yield standardized on a per-m^2 basis. Grain was dried, weighed, and yield per m^2 calculated using 13% adjusted moisture.

Soybean yield loss for each Palmer amaranth density was quantified by comparing the yield in the Palmer amaranth patch with the weed-free yield in the same landscape position. The rectangular hyperbolic yield-loss function (Cousens, 1985) related Palmer amaranth density to yield loss using the equation:

$$YL = (I \times D) / \left(1 + \frac{I \times D}{A}\right) \quad [1]$$

where YL (yield loss) is a function where A is the maximum estimated soybean yield loss, the incremental yield loss (I) describes the soybean yield loss as Palmer amaranth density approaches zero, and D is the density of Palmer amaranth. In addition, soybean yield loss was regressed on total dry Palmer amaranth biomass per area (g m^{-2}) and biomass per plant (g $plant^{-1}$).

Palmer Amaranth Growth in South Dakota Field Conditions

Growth rates of Palmer amaranth in South Dakota were unknown when this research was initiated. Palmer amaranth seed from a Kansas biotype (2015) and Corsica, SD, biotype (2016) was sown into peat pots filled with potting media in the greenhouse on three dates (Table 1). After emergence, plants were thinned one per pot and transplanted into a Brandt silty clay loam soil (fine-silty, mixed, superactive, frigid Calcic Hapludolls) at the Aurora, SD, research station in an area without crop competition. Transplanting into the field occurred on three dates each year, 22 May (PD1), 10 June (PD2), and 24 June (PD3) in 2015, and 25 May (PD1), 10 June (PD2), and 24 June (PD3) in 2016. Planting density started at 12 plants m^{-2} and plot size was 1 m^2 with a 0.6-m border between plots. Plants were watered with about 15 mm of water immediately after transplanting to help in establishment. Planting date (PD) treatments were arranged in a completely random design in 2015 and randomized complete block in 2016. In 2015, six replications were initially planted, but due to seedling mortality, three replicates of PD1, with an average of 10 plants m^{-2} and five replicates for PD2 and PD3, with an average of 11 plant m^{-2} were used for analysis. In 2016, plots were thinned 5 wk after each transplanting date to final densities of 1 plant m^{-2} (data not shown) and 4 plants m^{-2} with four replications of each density.

Growing degree days from May through August were 1081 and 1194 for 2015 and 2016, respectively, which were similar to the 30-yr (1981–2010) average of 1077. Rainfall from PD 1 to harvest in 2015 totaled 420 mm, which was 21% greater than the 30-yr average of 345 mm. August rainfall was 50% above the 30-yr average of 78 mm, whereas June was 50% below the 109-mm average. Rainfall in 2016 from PD1 to harvest totaled 128 mm, 62% below the 30-yr average, with deficits of 39% (July), 66% (June), 69% (August), and 76% (May).

Plant height from the soil surface to the tallest point and two perpendicular widths (to estimate plant diameter) of each plant were measured at intervals ranging from 8 to 20 d (Table 1). Bussler et al. (1995) used plant volume to quantify weed interference in corn (*Zea mays* L.) as a nondestructive measurment. In this study, we used plant volume to examine growth rates of Palmer amaranth. Plant volume (V) was calculated using the radius (r) and height (h) in the equation:

$$V = \pi \times r^2 \times h \quad [2]$$

In 2016, seed from the Corsica biotype and six Palmer amaranth biotypes used by Davis et al. (2015) in a common garden experiment were planted to coincide with planting of the PD2 cohort (Table 1). Initially, 6 plants m^{-2} were transplanted into the field, and 5 wk after transplanting, due to seedling mortality, were thinned to a uniform 2 plants m^{-2}. Biotype plots were replicated four times. Plant volumes were measured during the season as described above. Plants of the Urbana, IL, biotype were harvested 2 August due to early maturity and the possibility of seed shed, with all the other biotypes harvested 21 August. Biomass per plant was quantified after drying at 60°C to constant weight.

Relative growth rates (RGRs) (Hunt, 1990) based on plant volumes between sampling times were calculated using the formula:

$$\text{RGR} = \frac{(\ln \text{volume Day 2}) - (\ln \text{volume Day 1})}{t_2 - t_1} \quad [3]$$

where volume is the average m^3 $plant^{-1}$, and $(t_2 - t_1)$ is the number of days between sampling. The RGRs for planting date study were based on replicates that had 9 to 11 plants m^{-2} in 2015 and 4 plants m^{-2} in 2016, as density may influence growth rate (Benjamin and Hardwick, 1986) and other growth characteristics (Korres and Norsworthy, 2017). For the biotype seed location study, the RGRs were based on the 2 plants m^{-2} density used.

Greenhouse Herbicide Trials

The source of seed for the Corsica infestation was conjectured to be a southern US biotype. Many southern biotypes have been reported to be resistant to one or more herbicide MOAs, so we wanted to examine control with a spectrum of commonly used herbicide MOAs.

Seeds of Palmer amaranth were collected from Corsica plants in the fall of 2016 and placed in cold (0°C) storage until planting (spring and fall of 2017). About 20 seeds were planted in 10 × 10 cm pots using a greenhouse potting mix (for PRE- and POST-emergence herbicide treatments) or sand (for PRE-emergence herbicide treatments) media. Nine treatments, representing seven herbicide MOAs and a nontreated control (Table 2), were replicated in 10 pots $trial^{-1}$ with pots placed in the greenhouse in a completely random design, and moved among tables and locations on the table every few days to minimize any greenhouse location bias on plant growth.

Treatments were mixed with the appropriate additives and rates suggested on the label and applied in a spray booth (EDA, Inc., Folsom, CA). The carrier rate was 225 L ha^{-1} at 197 kPa using a single TeeJet 8001(TeeJet Technologies, Wheaton, IL) flat fan nozzle. The distance from the nozzle to the application target was 76 cm and the nozzle moved at a speed of 1.6 km h^{-1}. The PRE treatments were applied immediately after planting (spring and fall). One atrazine (6-chloro-*N*-ethyl-*N*-(1-methylethyl)-1,3,5-triazine-2,4-diamine) treatment consisted of a PRE application followed by a POST application 21 d later. For all other spring POST treatments, plants at the 3- to 4-leaf growth stage ranged in height from 3 to 10 cm. Plants were thinned to about 15 plants pot^{-1} just prior to application, and sprayed 23 d after planting.

In the fall trial, POST treatments were applied 22 d after planting. Although fall planting was done only once, plant height at POST ranged from 5 to 20 cm. The average plant height for each pot was noted at application to observe if injury differed between short (5–9 cm) and tall (10–20 cm) plants. All plants were evaluated 21 d after POST herbicide applications with control based on injury (0, no injury; 100%, complete death of plants).

Data Analysis

The influence of Palmer amaranth density on soybean yield data were separated by year due to differential soybean yield response to density, and analyzed by regression. Regression analyses also were conducted using a ln/ln transformation of Palmer amaranth density (plants m^{-2}) compared with total biomass (g m^{-2}) and individual plant biomass (g $plant^{-1}$) in the soybean field study.

Treatments for planting date, seed source, and herbicide response studies were considered fixed variables, and blocks random variables. The planting date study data were analyzed by year due to differences

Table 2. Herbicide timing (PRE, PRE+ POST, or POST), herbicide, mechanism of action, and Weed Science Society of America (WSSA) HRAC (HRAC) classification (Shaner, 2014), rate, surfactant addition, and percentage control, based on plant injury (0 = no injury; 100 = all plants dead), of Palmer amaranth grown from seeds from Corsica, SD, biotype under greenhouse conditions. All PRE-herbicide treatments were applied to both sand and potting soil media planted with Palmer amaranth seed. POST-herbicide treatments were applied to 4 cm (spring), short (5–9 cm), and tall (10–20 cm) Palmer amaranth established in potting soil media. Control was similar and averaged among the two trials and plant heights, except for mesotrione when spring differed from fall control.

Timing	Herbicide	Mechanism of action†	WSSA HRAC classification	Rate‡	Surfactant§	Control
				g a.i. ha^{-1}		%
PRE	Atrazine	Photosystem II site A	5	2243		0
	S-metolachlor	Inhibits very long-chain fatty acid synthesis	15	2142		95
PRE + POST	Atrazine			2243 + 2243	COC + NPD	25
POST	Atrazine			2243	COC + NPD	25
	Mesotrione	Inhibitor of HPPD	27	105	COC + NPD + AMS + NIS	90/40
	Dicamba	Synthetic auxin	4	560	COC + NPD + AMS + NIS	100
	Thifensulfuron	ALS inhibitor	2	280	NPD + AMS + NIS	0
	Glufosinate	Inhibits glutamine synthetase	10	738	NPD + AMS + NIS	90
	Glyphosate	EPSPS inhibitor	9	1261	COC + NPD + AMS + NIS	60

† Abbreviations: HPPD, 4-hydroxyphenylpyruvate dioxygenase; ALS, acetolactate synthase; EPSPS, 5-enolpyruvyl-shikimate-3-phosphate synthase.

‡ Rates are in g a.i. ha^{-1}, except for dicamba and glyphosate, which are reported in g a.e. ha^{-1}.

§ Surfactants included with post-emergent applications at rates recommended on the herbicide label were COC, crop oil concentrate; NPD, nonpolymer deposition adjuvant; AMS, ammonium sulfate; NIS, nonionic surfactant.

in plant density. Statistical analysis was done using RStudio (version 3.2.2) using the appropriate ANOVA analysis that determined differences among treatments. Means were separated using Fisher's least significant difference at the 95% confidence level when *F*-tests indicated treatment significance.

RESULTS AND DISCUSSION

Soybean Yield Loss

Palmer amaranth infestations in the selected field in both years were a blend of plants that were injured but regrew following early POST treatments and later emerging plants that were not treated with herbicides. Scattered patches that ranged in densities from 1 to 23 plants m^{-2} were selected each year across different landscape positions to determine yield loss.

In 2016, soybean yield in weed-free areas of the Corsica field averaged 379 g m^{-2}. When soybean yield data were fitted to the rectangular hyperbolic yield–loss function (Fig. 1), the model indicated that Palmer amaranth density explained 65% of the loss. Incremental yield loss (*I*) was 11% for low densities, with a maximum predicted yield loss (*A*) of 33%, which occurred when densities were greater than 15 plants m^{-2}. Interestingly, when densities ranged from 7 to 15 Palmer amaranth plants m^{-2}, yield losses were above the predicted maximum value and ranged from 35 to 45%.

In 2017, soybean yield in weed-free areas averaged 248 g m^{-2}, 34% less than 2016 due to late planting. Yield losses in areas with Palmer amaranth varied from 0 to 17% but were not correlated with Palmer amaranth density (Fig. 1). Regardless of density, Palmer amaranth biomass in infested areas averaged 260 g m^{-2}, 40 to 60% less than the biomass recorded in 2016. The lack of correlation between density and yield may be explained by several in-season occurrences. First, dicamba plus glyphosate was applied to 30-cm tall Palmer amaranth (soybean at V4; 25 June) with an estimated 90% control. Later, a second flush of Palmer amaranth was observed in late July (soybean at R3 growth stage), which emerged after soybean's critical weed-free period (often reported as VE–V4) (Van Acker et al., 1993), thus dampening the impact of the late-emerging plant to soybean yield. However, these late-emerging plants made up most of the density and biomass of the plants harvested in September rather than the larger, more robust plants controlled early in the season.

In 2016, yield loss at densities ranging from 5 to 15 plants m^{-2} (Fig. 1) was greater than the predicted maximum yield loss (33%), which may be partially explained by intraspecific competition among Palmer amaranth plants as density increased. For example, Palmer amaranth biomass per plant ranged from >130 g (2016) and 240 g (2017) at 1 plant m^{-2} to <30 g when densities were >15 m^{-2}. The ln/ln relationship between total Palmer amaranth plant biomass m^{-2} and plant density had a slope of 0.25 (adj. R^2 = 0.31) (Fig. 2) and indicates that total biomass per area was similar across all densities. However, the slope of the ln density vs. ln individual plant relationship was –0.75 (adj. R^2 = 0.81), indicating that as densities increased, individual plant biomass decreased exponentially. As intraspecific interference among Palmer amaranth plants began to limit plant size, the cumulative influence of plants in high-density areas on soybean yield was reduced.

Intraspecific competition among Palmer amaranth plants has been reported by Klingaman and Oliver (1994). Inference among Palmer amaranth plants in their study began at densities between 2 and 3.3 plants m^{-1} of row (2.6 and 4.3 m^{-2}, respectively, in 76-cm row plots). Examining biomass data from our study, indicated a 50% decrease in biomass when 5 plants m^{-2} (50 g $plant^{-1}$) was compared with 2 plant m^{-2} densities (100 g $plant^{-1}$), and at 20 plants m^{-2} plant biomass was about 12 g $plant^{-1}$. We reported a maximum soybean loss of 45% at 15 plants m^{-2} in 2015, whereas Klingaman and Oliver (1994) (Arkansas) reported a 68% yield loss at 10 plants m^{-1} row (equivalent to 13 plants m^{-2} in the current study). The lesser yield loss in our study most likely was due to later-emerging plants, so that interference did not occur from the beginning of the season.

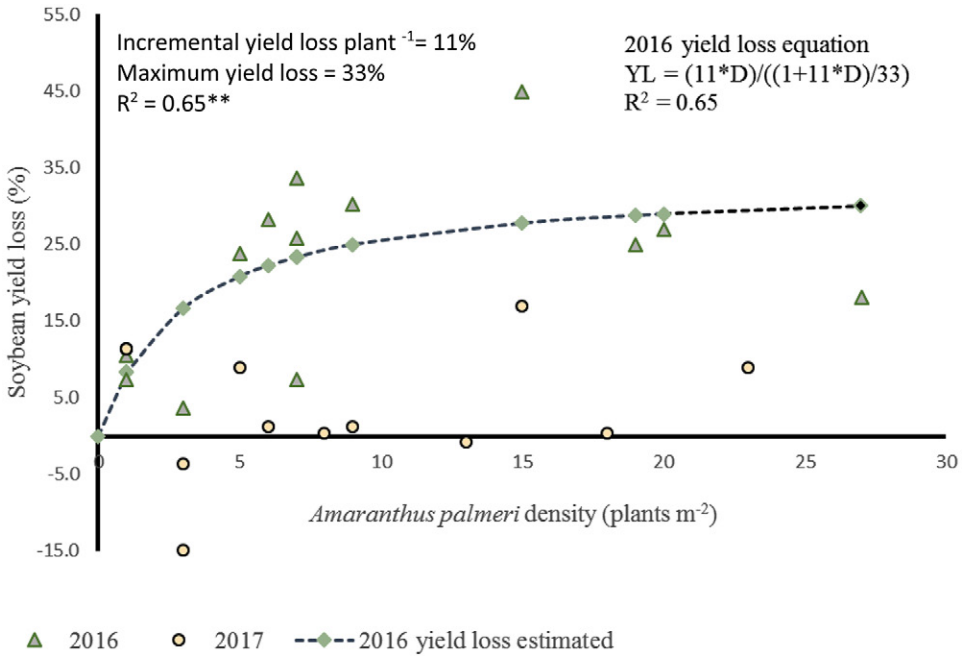

Fig. 1. Soybean yield loss vs. Palmer amaranth density at Corsica, SD, in 2016 and 2017. Equation provided was developed using the hyperbolic yield loss equation (Eq. [1]) (Cousens, 1985) and data from 2016 only.

Influence of Planting Date and Seed Source on Palmer Amaranth Growth

Korres and Norsworthy (2017) reported that Palmer amaranth density (ranging from 33 to 1178 plants m^{-2}) influenced seedling mortality, growth, total biomass, male/female sex ratios, flowering initiation, and plant fecundity. In this study, lower densities (2–12 plants m^{-2}) were used and these reported phenomena were not observed. However, Palmer amaranth PD1 transplants in both years had the highest mortality during field establishment compared with PD2 and PD3 transplants. In 2015, one plot had a final density of 4 plants m^{-2} and was removed from analysis, as the other three plots averaged 10 plants m^{-2} (range from 9 to 11 plants m^{-2}). Final densities for PD2 and PD3 were 11 plants m^{-2} (four replicates). In 2016, although transplanted at 12 plants m^{-2}, plots were thinned to 4 plants m^{-2} for all planting dates.

In 2015, the RGR of PD1 (transplanted 22 May, Julian Calendar Day 142) plants was most rapid between Day 162 to Day 180 (11–30 June) (Fig. 3), with a volume increase of about 1640% (Table 1). The RGR for PD2 plants (transplanted 10 June, Day 162) was greater than PD1 plants from Day 198 (15 July) to harvest (Fig. 3). The PD3 plants had a rapid RGR starting 21 d after transplanting and remained higher than PD1 and PD2 through harvest. At harvest, the average volume of PD1 plants (0.97 m^3) was 3.7 times greater than volumes of PD2 and PD3 plants, which were similar and averaged 0.26 m^3 (Table 1). Plant biomass at harvest was greatest for PD1 (225 g $plant^{-1}$), whereas PD2 and PD3 plants were similar and averaged 62.5 g $plant^{-1}$ (Table 1). Final biomass of male and female plants was similar within a planting date (data not shown).

In 2016, the RGRs were somewhat higher than 2015 due to higher GDD, although trends over the season were similar (Fig. 3). Plant volumes on Day 213 (1 August) for PD1 in 2015 and 2016 were similar (averaging 0.94 m^3). However, in 2016 harvest did not occur until 21 August, so that volumes at harvest of PD1, PD2, and PD3 were two or three times greater than those of 2015 (Table 1). Plant biomass averaged 360 g $plant^{-1}$ for 2016 PD1 and PD2 plants, and 253 g $plant^{-1}$ for PD3 plants.

These PD data are similar to those of common waterhemp [*A. tuberculatus* (Moq.) Sauer], another diecious amaranth species, grown in Minnesota (Uscanga-Mortera et al., 2007). In that study, when common waterhemp established early (early to mid-May), plants were very robust and grew above the soybean canopy compared with later (mid- to late June) established cohorts, which stayed at or below the soybean canopy. Early established common waterhemp (Uscanga-Mortera et al., 2007) and Palmer amaranth (Norsworthy et al., 2016), in competition with a crop produced 100 to 1000 times more seed than those that established later. Although this study did not involve crop competition nor examine seed yield, we observed similar growth responses in plant size for early established Palmer amaranth plants. In addition, even though later established plants were reduced in size, the possibility for high seed production was noted. Van De Stroet (2018) also compared volumes and biomass of Palmer amaranth, common waterhemp (emerged at PD3), and redroot pigweed (*A. retroflexus* L.) (emerged at PD2) at 1 plant m^{-2}. At harvest (21 August), solitary common waterhemp and redroot pigweed plants had volumes and biomass that were 2- to 10-fold less, respectively, than solitary Palmer amaranth plants, which had been transplanted at the same time as their field emergence (data not shown).

The location study biotypes were transplanted into the field on 10 June (Day 162) 2016 (PD2 of the planting date study) at a density of 2 plants m^{-2}. On 24 June (Day 176) all plants were similar in size (Table 1). On Day 182 the RGR for all locations were similar, except the Las Cruses seedlings, which had a 50% lower RGR (Fig. 4). The highest RGR for all plants was similar among biotypes and observed from Day 182 to 198, after which RGR slowed. Although seeds came from different geographic locations with day length ranging from 14 h 14 min (Las Cruces and Jenkins) to 15 h 21 min (Corsica) on 10 June, time of flowering was quite similar among biotypes. Male inflorescences first were observed on 16 July for all biotypes except Manhattan, KS (first seen 25 July). Female inflorescences were observed on 25 July for all biotypes except Columbia, MO (first seen 16 July). Plant volumes for each biotype at each in-season sampling date were similar except for the Las Cruces, NM, biotype, which was smaller by 50 to 60% all season long (Table 1). At harvest, the

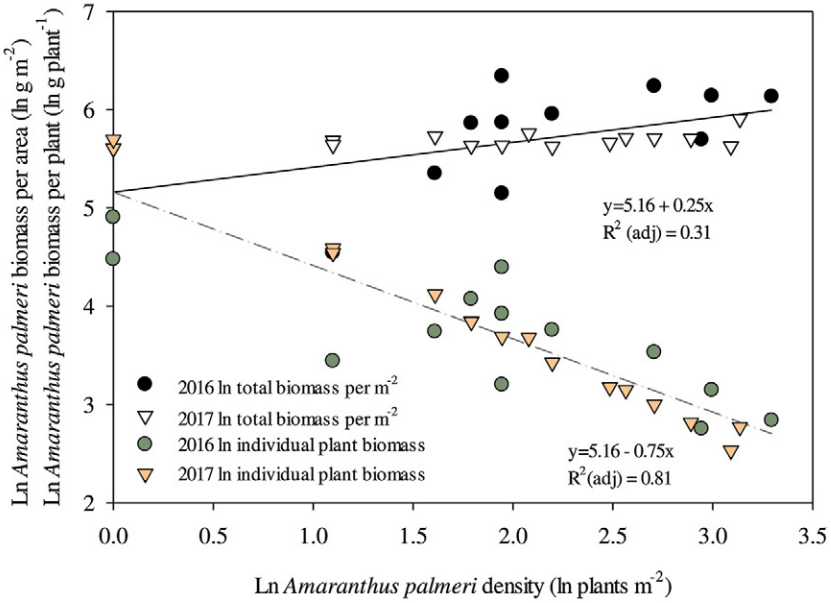

Fig. 2. Natural log (ln) transformation of Palmer amaranth biomass (g m^{-2}) and biomass of individual plants (g $plant^{-1}$) regressed on ln Palmer amaranth density (plants m^{-2}) for 2016 and 2017 in a soybean field at Corsica, SD.

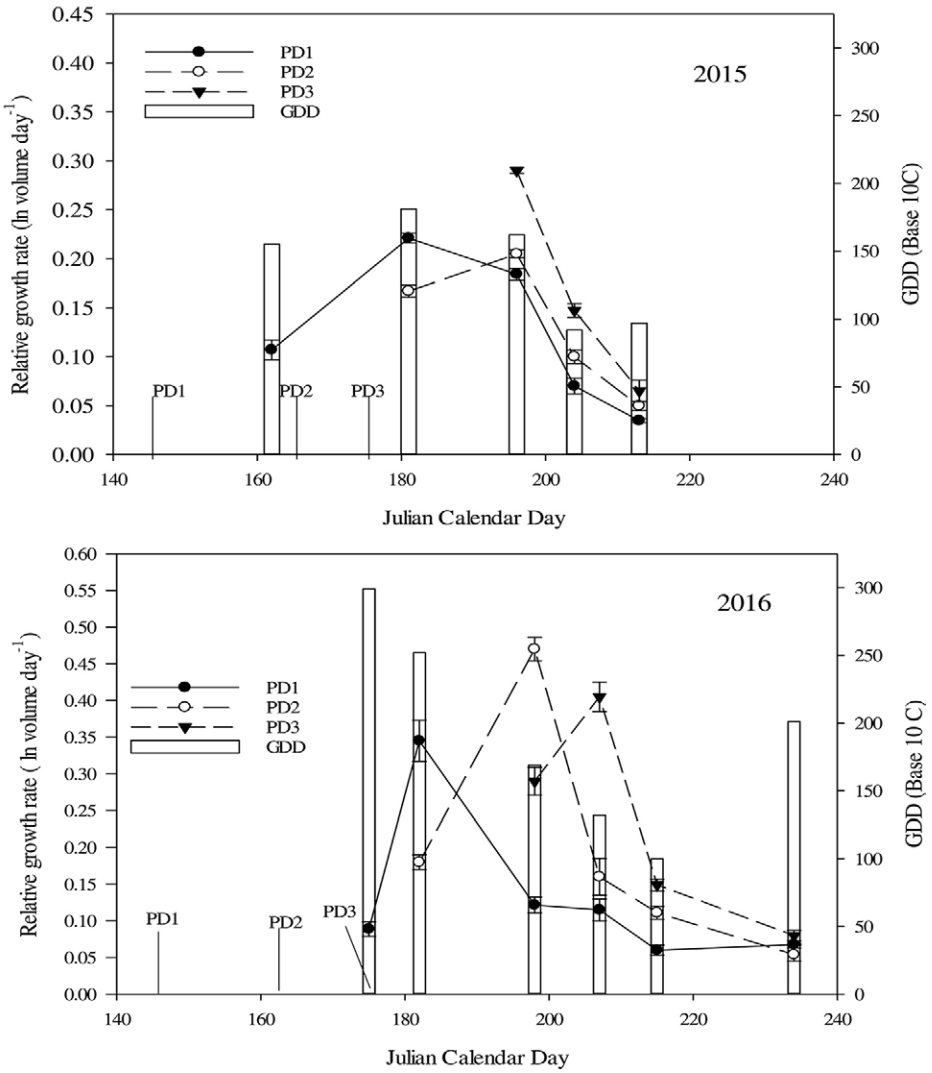

Fig. 3. Relative growth rates (ln volume d^{-1}) (with standard errors of the means) for Palmer amaranth in plots containing an average of 11 plants m^{-2} (2015) and 4 plants m^{-2} (2016) in an Aurora, SD, field. One-leaf plants started in the greenhouse were transplanted on 22 May (PD1, Day 142), 11 June (PD2, Day 162), and 24 June (PD3, Day 175) 2015 and 25 May (PD1, Day 145), 10 June (PD2, Day 162), and 24 June (PD3, Day 175) 2016. Growing degree days (base 10°C) (vertical bars) provided for sampling intervals, with the gray bar in 2016 indicating the GDD between Day 176 (first sampling) and Day 182 (second sampling) for PD1, and clear bar for GDD between PD2 planting and first sampling.

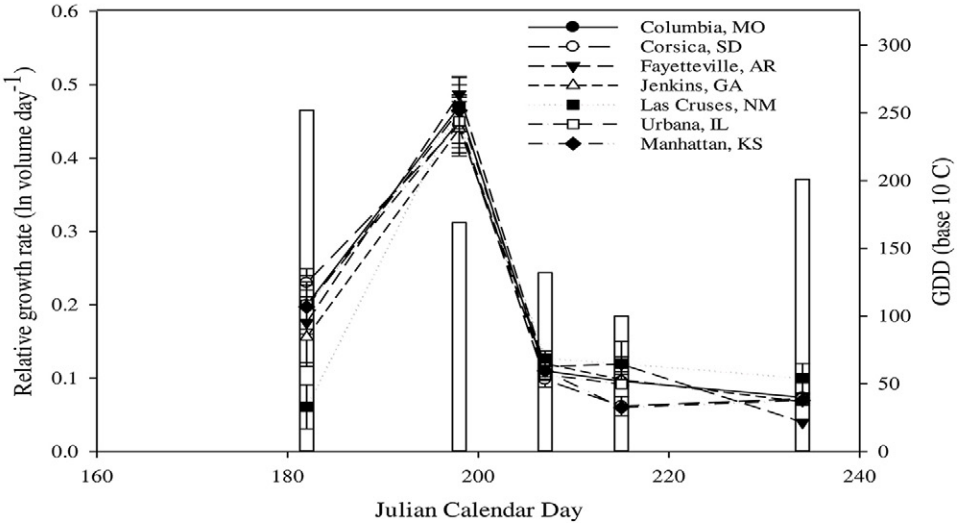

Fig. 4. Relative growth rates (ln volume d^{-1}) (with standard error of the means) for seven Palmer amaranth biotypes transplanted at 2 plants m^{-2} at Aurora, SD, in 2016. Seeds were planted in the greenhouse on 25 May and transplanted into the field on 10 June (Day 162). Plants were harvested 21 August (Day 234), except the Urbana, IL, biotype harvested 2 August (Day 215) due to early maturity.

Columbia, MO, biotype had the greatest volume (6.8 m^3), whereas the Fayetteville, AR, Manhattan, KS, and Urbana, IL, biotype had the least volume (average volume 1.5 m^3). Biomass per plant was similar for Jenkins, GA, Corsica, SD, and Manhattan, KS, biotypes and averaged about 375 g $plant^{-1}$, whereas Urbana, IL, and Las Cruces, NM, biotypes had the least biomass and averaged 110 g $plant^{-1}$.

Greenhouse Herbicide Trials

Similar control was observed between runs and plant sizes, so control data were combined across the two trials for each herbicide, except for mesotrione (Table 2). Nearly 100% control was observed with the *S*-metolachlor (2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-[(1*S*)-2-methoxy-1-methyethyl]acetamide) PRE application in both potting mix and sand media, and glufosinate (2-amino-4(hydroxymethylphosphinyl)butanoic acid) and dicamba POST applications. Poor or no control was noted with atrazine applied either once PRE (0% control in both potting medias) or twice (PRE + POST; 25% control). Plants treated with thifensulfuron (methyl 3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino] carbonyl]amino]sulfonyl]-2-thiophenecarboxylate) also showed no injury (0% control), whereas glyphosate averaged 60% control.

Plants treated with mesotrione (POST) had the most variable ratings, 90% control was achieved in the spring trial, but in the fall, injury was rated at 40% irrespective of initial plant size. This may be due to ambient temperatures at and after application. Godar et al. (2015) reported that mesotrione efficacy was greater when temperatures were cool compared with efficacy at warm temperatures. Although plants in these trials were in a greenhouse environment, fall temperatures ranged from 20 to 28°C, whereas in the spring trial, temperatures fluctuated from 15 to 25°C.

These data indicate that the Corsica, SD, infestation at present should be well controlled with *S*-metolachlor, dicamba, and glufosinate. However, thifensulfuron alone should be avoided. Indeed, cases of thifensulfuron resistance have been reported in Kansas, South Carolina, and Wisconsin (Heap, 2019). In addition, control with atrazine, glyphosate, and mesotrione was poor, and Palmer amaranth biotypes from Kansas, Texas, Nebraska, Missouri, Florida, Arkansas, Georgia, and Arizona have been reported to be resistant to at least one of these herbicides (Heap, 2019).

SUMMARY

Based on herbicide trials, plant growth, and swine import data from southern US states into South Dakota (R. Thaler, personal communication, 2019), the origin of the Palmer amaranth infestation is suspected to be from Missouri. Unfortunately, the final destination of the swine was unknown. Other Palmer amaranth infestations due to infested manure and subsequent spread may be present in South Dakota. News releases, surveys (Van De Stroet, 2018), and presentations at state annual extension meetings have been used to raise awareness of producers and the general public about the growth and possible control options for this new invader.

Palmer amaranth plants not well controlled or emerging after early control efforts in South Dakota soybean can result in high yield losses. Yield losses were greatest when densities were moderate (6–10 plants m^{-2}), rather than high (>18 plants m^{-2}). Yield losses from late-emerging Palmer amaranth were inconsistent and not explained by Palmer amaranth density or biomass. However, due to the tall nature of the plant, although yield loss may not occur, producers may choose to drive around, rather than combine through, infested areas, resulting in 100% loss in infested areas.

At the time this study was conducted, the South Dakota biotype was well controlled with *S*-metolachlor (PRE), and glufosinate and dicamba (POST) under greenhouse conditions when plants were small. However, resistance of Palmer amaranth biotypes to these herbicides has already been documented in other states (Heap, 2019). Herbicide programs that use multiple modes of action and rotation of control methods are recommended to minimize future problems with Palmer amaranth.

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REFERENCES

Benjamin, L.R., and R.C. Hardwick. 1986. Relative growth rate as a function of space per plant. Ann. Bot. 58:766–770. doi:10.1093/oxfordjournals.aob.a087255

Betts, L. 2017. Palmer explodes into Iowa. Corn and Soybean Digest. 20 January. http://www.cornandsoybeandigest.com/weeds/palmer-explodes-iowa (accessed 13 Aug. 2017).

Bravo, W., R.G. Leon, J.A. Ferrell, M.J. Mulvaney, and C.W. Wood. 2017. Differentiation of life-history traits among Palmer amaranth populations (*Amaranthus palmeri*) and its relation to cropping systems and glyphosate sensitivity. Weed Sci. 65:339–349. doi:10.1017/wsc.2017.14

Bussler, B.H., B.D. Maxwell, and K.J. Puetmann. 1995. Using plant volume to quantify interference in corn (*Zea mays)* neighborhoods. Weed Sci. 43:586–594. doi:10.1017/S0043174500081698

Cousens, R. 1985. A simple model relating yield loss to weed density. Ann. Appl. Biol. 107:239–252. doi:10.1111/j.1744-7348.1985.tb01567.x

Culpepper, A.S., T.M. Webster, L.M. Sosnoskie, and A.C. York. 2010. Glyphosate-resistant Palmer amaranth in the United States. In: V.K. Nandula, editor, Glyphosate resistance in crops and weeds: History, development, and management. John Wiley & Sons, New York. p. 195–212. doi:10.1002/9780470634394.ch11

Davis, A.S., B.J. Schutte, A.G. Hager, and B.G. Young. 2015. Palmer amaranth (*Amaranthus palmeri*) damage niche in Illinois soybean is seed limited. Weed Sci. 63:658–668. doi:10.1614/WS-D-14-00177.1

Farmer, J.A., E.B. Webb, R.A. Pierce, and K.W. Bradley. 2017. Evaluating the potential for weed seed dispersal based on waterfowl consumption and seed viability. Pest Manage. Sci. 73:2592–2603. doi:10.1002/ps.4710

Ferrell, J., and R. Leon. 2016. Control of Palmer amaranth in agronomic crops. Univ. of Florida IFAS Ext. Rep. SS-AGR-338. Univ. of Florida, Gainesville.

Godar, A.S., V.K. Varanisi, S. Nakka, P.V.V. Prasad, C.R. Thompson, and J. Mithila. 2015. Physiological and molecular mechanisms of differential sensitivity of Palmer amaranth (*Amaranthus palmeri*) to mesotrione at varying growth temperatures. PLoS One 10:e0126731. doi:10.1371/journal.pone.0126731

Guo, P., and K. Al-Khatib. 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. doi:10.1614/P2002-127

Heap, I. 2019. The international survey of herbicide resistant weeds. www.weedscience.org (accessed 28 Jan. 2019).

Horak, M.J., and D.E. Peterson. 1995. Biotypes of Palmer amaranth (*Amaranthus palmeri*) and common waterhemp (*Amaranthus rudis*) are resistant to imazethapyr and thifensulfuron. Weed Technol. 9:192–195. doi:10.1017/S0890037X00023174

Hunt, R. 1990. Relative growth rates In: Basic growth analysis. Springer, Dordrecht, the Netherlands. p. 25–34. doi:10.1007/978-94-010-9117-6_3

Keeley, P.E., C.H. Carter, and R.J. Thullen. 1987. Influence of planting date on growth of Palmer amaranth (*Amaranthus palmeri*). Weed Sci. 35:199–204. doi:10.1017/S0043174500079054

Klingaman, T.E., and L.R. Oliver. 1994. Palmer amaranth (*Amaranthus palmeri*) interference in soybeans (*Glycine max*). Weed Sci. 42:523–527. doi:10.1017/S0043174500076888

Korres, N.E., and J.K. Norsworthy. 2017. Palmer amaranth (*Amaranthus palmeri*) demographic and biological response characteristics in wide-row soybean. Weed Sci. 65:491–503. doi:10.1017/wsc.2017.12

Minnesota Department of Agriculture. 2019. Palmer amaranth in Minnesota. Minnesota Department of Agriculture, St. Paul, MN. https://www.mda.state.mn.us/plants-insects/palmer-amaranth-minnesota (accessed 14 Feb. 2019).

Morgan, G.D., P.A. Baumann, and J.M. Chandler. 2001. Competitive impact of Palmer amaranth (*Amaranthus palmeri*) on cotton (*Gossypium hirsutum*) development and yield. Weed Technol. 15:408–412. doi:10.1614/0890-037X(2001)015[0408:CIOPAA]2.0.CO;2

NDSU Agriculture Communication. 2018. Palmer amaranth confirmed in more N.D. counties. North Dakota State University, Fargo, ND. https://www.ag.ndsu.edu/news/newsreleases/2018/oct-22-2018/palmer-amaranth-confirmed-in-more-n-d-counties (accessed 14 Feb. 2019).

Norsworthy, J.K., B.W. Schrage, T.L. Barber, and L.M. Schwartz. 2016. Emergence date influences growth and fecundity of Palmer amaranth in cotton. J. Cotton Sci. 20:263–270.

Rowland, M.W., D.S. Murray, and L.M. Verhalen. 1999. Full-season Palmer amaranth (*Amaranthus palmeri*) interference with cotton (*Gossypium hirsutum*). Weed Sci. 47:305–309. doi:10.1017/S0043174500091815

Sauer, J. 1957. Recent migration and evolution of the dioecious amaranths. Evolution 11:11–31. doi:10.1111/j.1558-5646.1957.tb02872.x

Schwartz-Lazaro, L.M., J.K. Norsworthy, R.C. Scott, and L.T. Barber. 2017. Resistance of two Arkansas Palmer amaranth populations to multiple herbicide sites of action. Crop Prot. 96:158–163. doi:10.1016/j.cropro.2017.02.022

Shaner, D.L., editor. 2014. Herbicide handbook. 10th ed. WSSA, Westminster, CO.

South Dakota Animal Industry Board. 2016. Imports. South Dakota Animal Industry Board, Pierre, SD. https://aib.sd.gov/imports.html (accessed 28 Jan. 2019).

Sprague, C. 2014. Palmer amaranth: Managing this new weed problem. Progressive Forage. 1 May. http://www.Progressiveforage.com/forage-production/management/palmer-amaranth-managing-this-new-weed-problem (accessed 8 Apr. 2016).

US Census Bureau. 2018. State imports for South Dakota. US Census Bureau, Washington, DC. https://www.census.gov/foreign-trade/statistics/state/data/imports/sd.html (accessed 28 Jan. 2019).

Uscanga-Mortera, E., S.A. Clay, F. Forcella, and J. Gunsolus. 2007. Common waterhemp growth and fecundity as influenced by emergence date and competing crop. Agron. J. 99:1265–1270. doi:10.2134/agronj2007.0029

Van Acker, R.C., C.J. Swanton, and S.F. Weise. 1993. The critical period of weed control in soybean [*Glycine max* (L.) Merr.]. Weed Sci. 41:194–200. doi:10.1017/S0043174500076050

Van De Stroet, B.M. 2018. Palmer amaranth in South Dakota: Growth, herbicidal control and soybean yield loss. MS thesis. South Dakota State University, Brookings, SD.

Van Wychen, L. 2016. Survey of the most common and troublesome weeds in broadleaf crops, fruits and vegetables in the United States and Canada. WSSA National Weed Survey Dataset. WSSA, Westminster, CO. http://wssa.net/wp-content/uploads/2016_Weed_Survey_Final1.xlsx (accessed 29 Oct. 2017).

Ward, S.M., T.M. Webster, and L.E. Steckel. 2013. Palmer amaranth (*Amaranthus palmeri*): A review. Weed Technol. 27:12–27. doi:10.1614/WT-D-12-00113.1

Webster, T.M., and R.L. Nichols. 2012. Changes in the prevalence of weed species in the major agronomic crops of the southern United States: 1994/1995 to 2008/2009. Weed Sci. 60:145–157. doi:10.1614/WS-D-11-00092.1

Wright, S.R., H.D. Coble, C.D. Raper, Jr., and T.W. Rufty, Jr. 1999. Comparative responses of soybean (*Glycine max*), sicklepod (*Senna obtusifolia*), and Palmer amaranth (*Amaranthus palmeri*) to root zone and aerial temperatures. Weed Sci. 47:167–174. doi:10.1017/S004317450009158X