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Palmer Amaranth in South Dakota: Growth, Herbicidal Control, and Soybean Yield Loss

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PALMER AMARANTH IN SOUTH DAKOTA: GROWTH, HERBICIDAL CONTROL, AND SOYBEAN YIELD LOSS

BY

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This thesis is approved as a creditable and independent investigation by a candidate for the Master of Science degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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TABLE OF CONTENTS

CHEMICAL NOMENCLATURE

Common Name	Chemical Name
atrazine	6-chloro-N-ethyl-N'-(1-methylethyl)-1,3,5-triazine-2,4-diamine
dicamba	3,6-dichloro-2-methoxybenzoic acid
glufosinate	2-amino-4-(hydroxymethylphosphinyl)butanoic acid
glyphosate	N-(phosphonomethyl)glycine
mesotrione	2-(4-mesyl-2-nitrobenzoyl)-3-hydroxycylohex-2-enone
S-metolachlor	2-chloro-N-(2-ethyl-6-methylphenyl)-N-[(2S)-1-methoxypropan-2-yl]acetamide
thifensulfuron	3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl] amino]sulfonyl]-2-thiophenecarboxylic acid

LIST OF TABLES

LIST OF FIGURES

Figure Page

ABSTRACT

PALMER AMARANTH IN SOUTH DAKOTA: GROWTH, HERBICIDAL CONTROL, AND SOYBEAN YIELD LOSS

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Palmer amaranth is a growing concern in the United States. Previously thought to only be able to occupy the southern United States, this plant can now be found throughout the northern states as well. Infestations of Palmer amaranth can now be found in South Dakota and is raising many concerns. Palmer amaranth is characterized by large growth and can be highly competitive with many important crops. Soybean is an important crop in South Dakota, as well as the rest of the world, and has not escaped the detrimental aspects of an infestation of Palmer amaranth. The objectives of this study were to determine the possible impacts Palmer amaranth South Dakota.

Surveys were given to applicators and producers from many counties in South Dakota to gauge public awareness of Palmer amaranth and determine other possible infestations of Palmer amaranth. These surveys were made available at commercial applicator recertification classes throughout South Dakota and the Soy 100 meeting in Brookings, SD.

Growth rates and plant volume and biomass of Palmer amaranth from several seed source locations and local ascensions of common waterhemp and redroot pigweed were examined and compared in eastern South Dakota. Growth studies were conducted near Aurora, SD over two years using three planting dates from mid-May to late-June.

Plant volume was measured every 10 to 20 days until harvest beginning in late-July. At harvest, plants were oven-dried and biomass was recorded.

Efficacy of several herbicide treatments were recorded on Palmer amaranth seedlings. Pre- and post-emergence treatments were conducted on Palmer amaranth planted in either sand or potting mix. Post-emergence treatments were applied at the three- to four-leaf stage. Visual ratings of plants were conducted 21 days after treatment.

Soybean yield loss due to Palmer amaranth was determined near Corsica, SD. Palmer amaranth in square meter plots were counted and harvested for biomass when soybeans reached R7 to R8. Plots containing two rows of soybeans were harvested several weeks later and yield loss was determined.

Survey results indicated that more needs to be done to provide information to the public based on respondents' ability to correctly identify Palmer amaranth, common waterhemp, and redroot pigweed seedlings and mature plants. Several respondents also indicated possible infestations of Palmer amaranth. Not all counties in South Dakota were represented by the study.

Palmer amaranth had greater growth and biomass than either common waterhemp or redroot pigweed. Final volume of Palmer amaranth was greater at lower densities. Growth rates between sampling dates varied among planting dates, which resulted in similarities in final volume among planting dates. Common waterhemp and redroot pigweed shared similar plant volumes and biomass, however, plants in 2015 were larger, possibly due to climatic differences between years.

Herbicides tested that offered the best control of Palmer amaranth was a pre-emergence application of S-metolachlor and a post-emergence application of either dicamba or glufosinate. Glyphosate only provided partial control and mesotrione provided variable control. Atrazine had the little control as a pre- or post-emergence treatment. Thifensulfuron had no control of Palmer amaranth.

Soybean yield loss in 2016 determined an incremental loss of 9% at one Palmer amaranth m^{-2}. Maximum yield loss of 45% was seen at 15 plants m^{-2}, however, yield losses at densities slightly lower and higher caused a 35% maximum yield loss prediction. Yield loss in 2017 was variable due to outside factors and a relationship between yield loss and Palmer amaranth density or biomass could not be determined.

Chapter 1: Introduction and Literature Review

Soybean [*Glycine max* (L.) Merr.] is an important crop for South Dakota as well as the United States. In 2016, about 118 billion kilograms of soybeans were produced on 33.5 million hectares (3,511 kg/ha) in the United States (USDA-NASS, 2017). Soybeans were produced on land with an average value of $10,102 per hectare (USDA-NASS, 2016). South Dakota farmers contributed 7 billion kilograms to total U.S. soybean production grown on 2.1 million ha (3,335 kg/ha) (USDA-NASS, 2017), which had an average value of $8,694 per hectare (USDA-NASS, 2016). About 60 percent of South Dakota soybean crop is exported overseas. Average soybean price was $0.33 kg^{-1}, making the South Dakota soybean crop worth about $2.3 billion. Yield reductions as low as five percent can therefore have a very detrimental impact to individual growers and the state's economy.

Weeds are a continuing threat to crop yield. The degree of yield loss depends on many environmental conditions such as rainfall, temperature, etc., but also the weed species present, its density, and timing of its interaction with the crop. Many crops have a critical weed-free period, which has been defined by Van Acker et al. (1993) as "an interval in the life cycle of the crop when it must be kept weed free to prevent yield loss". This period in soybeans can vary; Halford et al. (2001) estimated a weed-free period starting at V1 (first trifoliate leaf) or V2 until the crop reaches R1 growth stage (first full flower). Van Acker et al. (1993) reported a period ranging from soybean emergence to V4. The start of the critical weed-free period in soybeans can also be affected by soybean row width. Knezevic et al. (2003) reported that the critical time for weed removal to minimize yield loss was at V1, V2, and V3 for soybean row widths of 76-, 38-, and 19-

cm, respectively. South Dakota producers have experienced problems with amaranth species such as common waterhemp [*Amaranthus rudis* (Moq.) Sauer], redroot pigweed (*Amaranthus retroflexus* L.), and many others. Palmer amaranth (*Amaranthus palmeri* S. Watson) has also become problematic in South Dakota, first reported in 2014 (Johnson, 2014), and regionally in recent years.

Palmer amaranth is an annual plant with male and female flowers on separate plants (dioecious) (Franssen et al. 2001). Male Palmer amaranth plants are characterized by an inflorescence that is soft to the touch, whereas female inflorescence is characterized by sharp, stiff bracts and can also be found in the leaf axis (Figure 1.1). The plant can be quite plastic in physical appearance. Many biotypes contain a V-shaped chevron on the leaf that can range in color from pink to red, purple (Figure 1.2), and white (Figure 1.3), whereas others have no leaf mark (Figure 1.4). Leaf size and shape can also change among a population, while some may be narrow, others may be large and wide. There is evidence Palmer amaranth can hybridize with common waterhemp, which is also dioecious. When crossing Palmer amaranth and common waterhemp in a controlled setting, Franssen et al. (2001) produced 35 hybrids out of 22,000 seeds that were planted. Hybridized plants can exhibit characteristics of both species, causing greater difficulty in identification. Despite these differences, distinguishing features are the petiole, which is longer than a diamond-shaped leaf (Figure 1.5), a long terminal inflorescence (Figure 1.6), a rosette-like growth around the apical meristem (Figure 1.3 and Figure 1.4), and a lack of hair (Figure 1.7) (Legleiter and Johnson, 2013).

Figure 1.1. Inflorescence of a male (left) and female (right) Palmer amaranth plant.

Figure 1.2. A leaf of a Palmer amaranth plant with a purple chevron.

Figure 1.3. A Palmer amaranth plant displaying a rosette-like leaf arrangement with white chevrons.

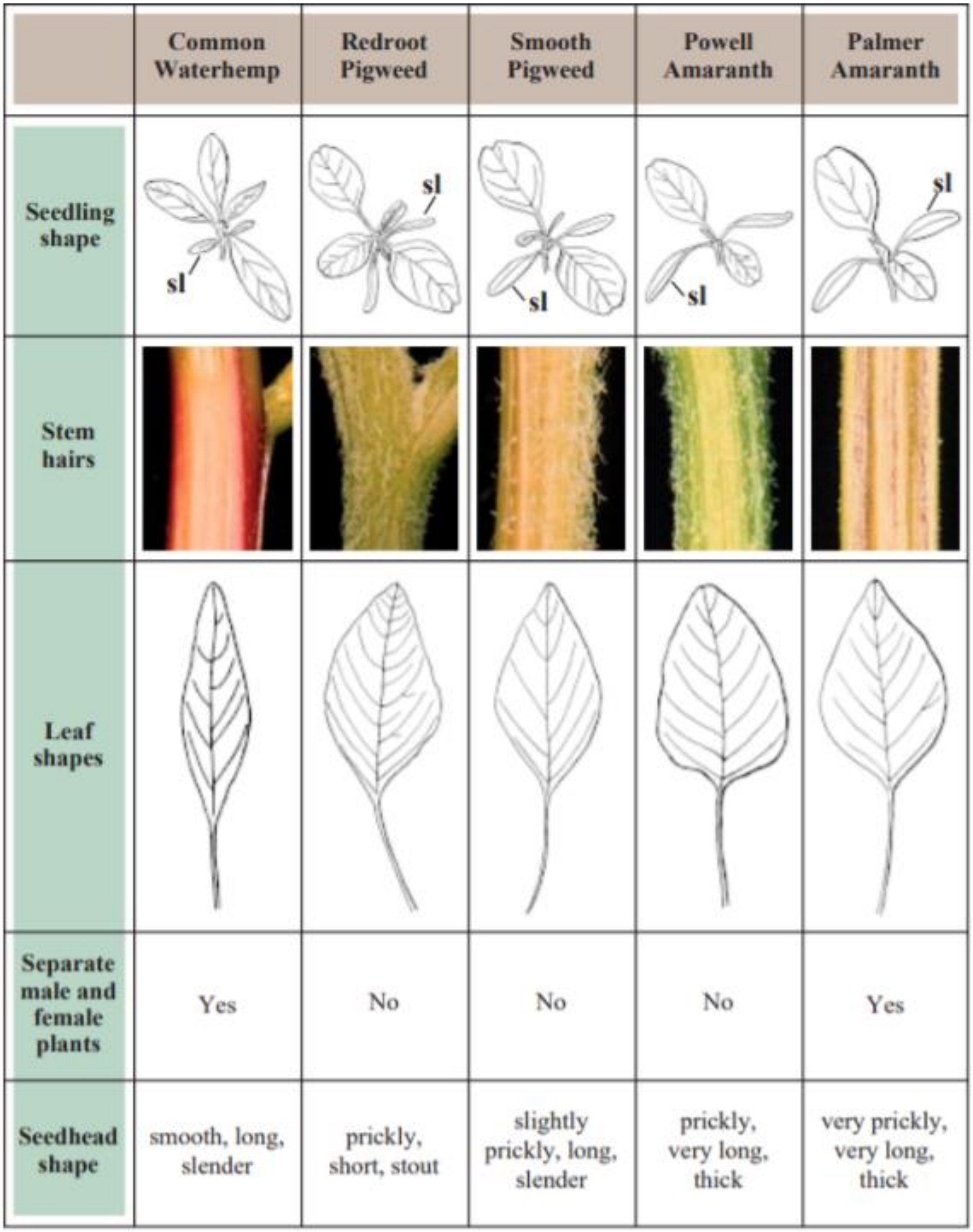
Figure 1.4. A Palmer amaranth plant displaying a rosette-like leaf arrangement with no chevrons.

Figure 1.5. A diamond-shaped Palmer amaranth leaf attached to an even longer petiole.

Figure 1.6. The long inflorescence of a male (left) and female (right) Palmer amaranth plant.

Figure 1.7. The hairless stem of a male (left) and female (right) Palmer amaranth plant.

Redroot pigweed plants have both male and female flowers (monoecious) on an individual plant and inflorescence is often short and compacted (Pratt et al., 1999). A hairy stem and leaves are common characteristics of redroot pigweed as well. Common waterhemp is similar to Palmer amaranth in regard to a smooth stem and leaves and that it is also dioecious. Characteristics of common waterhemp that distinguish it from Palmer amaranth is a shorter petiole attached to a linear-shaped leaf. Figure 1.8 from Pratt et al. (1999) illustrates these differences between common amaranth species.



	Common Waterhemp	Redroot Pigweed	Smooth Pigweed	Powell Amaranth	Palmer Amaranth
Seedling shape					
Stem hairs					
Leaf shapes					
Separate male and female plants	Yes	No	No	No	Yes
Seedhead shape	smooth, long, slender	prickly, short, stout	slightly prickly, long, slender	prickly, very long, thick	very prickly, very long, thick

Figure 1.8. Distinguishing characteristics of several common amaranth species (Pratt et al., 1999).

Native to northwestern Mexico and the drier regions of the southwestern United States, Palmer amaranth began its spread northeastward during the late 1800's (Sauer, 1957). Palmer amaranth reports in Virginia, Oklahoma, South Carolina, and as far north as Michigan (Culpepper et al., 2010) were evidence of its expansion. It was not until the past twenty-five years that Palmer amaranth has been a weed of major concern. A survey by Webster and Nichols (2012) reported that nine out of the ten states surveyed in the southern United States ranked Palmer amaranth as the most troublesome cotton weed in 2009 whereas in 1995 this weed was ranked lower as troublesome. Palmer amaranth has been documented in South Dakota and as far north as several counties in Michigan. It has been speculated that these infestations came from diverse sources including seed contamination in cottonseed meal used for dairy fodder (Sprague, 2014) and pollinator seed mix in Iowa and Minnesota (Betts, 2017), waterfowl (Bradley, 2016), or the spread of animal manure such as in South Dakota (Corsica). The Weed Science Society of America (WSSA) recently ranked Palmer amaranth as the most troublesome and difficult to control weed in 12 categories of broadleaf crops, fruits and vegetables (Van Wychen, 2016).

Ward et al. (2013) reviewed the taxonomy and life history attributes of Palmer amaranth. Their review of the literature suggested that Palmer amaranth has negative agricultural impacts and is resistant to many herbicides such as acetolactate synthase (ALS) inhibitors, dinitroanilines (microtubule inhibitors), triazines (photosynthesis inhibitors), glyphosate (EPSP inhibitor), and 4-Hydroxyphenylpyruvate dioxygenase (HPPD) inhibitors. It was also noted that some biotypes of Palmer amaranth have become resistant to multiple modes of herbicide action. The assumption was made that due to

Palmer amaranth being adapted to desert conditions, it would be at a competitive disadvantage to other *Amaranthus* species in higher latitudes and/or cooler environments. However, this seems to be partly untrue as Davis et al. (2015) reported that in Illinois, Palmer amaranth can grow very well in northern locations and that only the lack of seed is contributing to its scarcity. They have shown that while Palmer amaranth can grow well under cooler conditions, its high growth rate can be diminished and become comparable to, or less than, common waterhemp and/or redroot pigweed.

Guo and Al-Khatib (2003) studied the germination and growth of redroot pigweed, Palmer amaranth, and common waterhemp in a greenhouse under different temperatures. All species were shown to germinate and thrive more readily in warmer conditions. Peak germination for Palmer amaranth and redroot pigweed, which was 35/30 ºC (day/night cycle), was 10 ºC higher than common waterhemp. Heat stress on all three species was analyzed and Palmer amaranth was more adapted to higher temperatures. For example, plant death for redroot pigweed, common waterhemp, and Palmer amaranth occurred at 8, 9, and 25 days later, respectively, after initiation of a 45/40 ºC cycle. Biomass of Palmer amaranth was less than redroot pigweed and common waterhemp at 15/10 ºC yet larger than both at 25/20 ºC and 35/30 ºC. Out of the three species, Palmer amaranth had the largest root volume at 35/30 ºC and the smallest at 15/10 ºC.

Another study in a laboratory examined several *Amaranthus* species' germination response to different temperatures (5, 10, 15, 20, 25, 30, and 35 °C constants or ±40% of constants with diurnal alternation) and reported similar results. Steckel et al. (2004) found that, apart from prostrate pigweed (*Amaranthus albus* L.), optimal germination of eight other amaranth species occurred when temperature was greater than 20 ºC. Palmer amaranth at an alternating (± 40% of the constant) temperature with a mean of 30º C achieved 100% germination on the first day.

Palmer amaranth, like other annual weeds, relies on a seed bank to establish plants during the next growing cycle. In a study near Shafter, California, by Keeley et al. (1987), a single Palmer amaranth plant that emerged early [March (~18 ºC soil temp.) through June (~30 ºC soil temp.)] produced between 200,000 and 600,000 seeds whereas late emerging plants [July (~31.5 ºC soil temp.) through September (~28 ºC soil temp.)] produced 115 to 80,000 seeds. At soybean maturity, Palmer amaranth sampled in Arkansas, Tennessee, Illinois, Missouri, and Nebraska retained 95 to 100% of its seed (Schwartz et al. 2016). Due to high retention rates, this can allow for seed bank control during harvest if seeds can be destroyed. Seeds that do fall to the soil surface can germinate the following year. However, once the seed contacts with the soil surface, seed viability can start to decrease. A seed viability at different burial depths study by Sosnoskie et al. (2013) reported at 1-cm depth, seed viability decreased to 65 and 9% after six and 36 months, respectively, and to 78 and 22% germination at 40-cm at the same timings from an initial seed population viability of ≥ 96%.

Horak and Loughin (2000) compared height, plant volume, and leaf area of Palmer amaranth, common waterhemp, redroot pigweed, and prostrate pigweed in a field study near Manhattan, Kansas. Palmer amaranth generally exceeded the other species in each attribute (plant volume, dry weight, and leaf area). Additionally, the rate of height increase of Palmer amaranth was 24 to 62% greater than other *Amaranthus* species per growing degree day (base temperature of 10 ºC). The growth and development of Palmer amaranth most closely resembled that of common waterhemp, and the authors suggested that it may share similar habitat preferences with that species.

Davis et al. (2015) determined that Palmer amaranth growth and development is heat driven. The rate that growing degree days base 10 ºC accumulates affects both growth (plant volume and height) and percent flower initiation, which were positively associated with accumulated thermal time. In this study, Palmer amaranth was transplanted in soybean fields concurrent with soybean planting and removed soon after Palmer amaranth flowering was initiated (maximum five weeks interference) when soybeans were at the R1 to R3 growth state. Soybean yield loss ranged from 2 to 30% when Palmer amaranth density was 8 plants m^{-2}. The northern Illinois location (41.8 °N in 2011 and 2012) had yield losses of 0 to 10% whereas the southern (37.4 °N and 37.7 °N in 2011 and 2012, respectively) and central locations (40.0 °N in 2011 and 2012) had yield losses ranging from 3 to 30% at the same density. This study used soybean varieties with maturities of 4.4, 3.5, and 3.1 for the southern, central, and northern locations, respectively. Corsica, South Dakota (43.4 °N) is most comparable to the northern Illinois location. Relative maturity used in South Dakota ranges from 1 to 2.5 from north to south with variations east to west (Mourtzinis and Conley, 2017).

Bensch et al. (2003) conducted field studies in 1997 and 1998 in Manhattan and Topeka, Kansas to compare redroot pigweed, Palmer amaranth, and common waterhemp and their effects on soybean yield. *Amaranthus* species were introduced at seven weed densities at soybean planting and approximately two weeks later at the soybean cotyledon stage. Soybeans were indeterminate with a Group 3 maturity rating. Greatest soybean yield loss occurred when weeds were planted at soybean planting with the highest tested weed density of eight plants m^{-1} of row (10.5 plants m^{-2}). Yield losses were about 79, 56, and 38% for Palmer amaranth, common waterhemp, and redroot pigweed, respectively, at Topeka, Kansas in 1998 (May 28 planting date). Yield loss by species was variable between site-years, although Palmer amaranth caused consistently higher soybean yield loss. Significant yield loss due to any weed presence was not seen for the second planting. Predicted dry weight biomass was 341 and 86 g m^{-2} for Palmer amaranth, 144 and 123 g m^{-2} for common waterhemp, and 56 and 14 g m^{-2} for redroot pigweed at Topeka and Manhattan, respectively. It was thought that better soil and fertility conditions was the main cause of greater biomass in Topeka compared to Manhattan.

A study by Klingaman and Oliver (1994) in Fayetteville, Arkansas examined the effect of Palmer amaranth interference on soybean growth and yield. Palmer amaranth seeds and soybeans (Forrest, Group 5) were planted on the same day (June 11, 1990 and May 24, 1991). Densities of Palmer amaranth were thinned to 0.33, 0.67, 1, 2, 3.33, and 10 plants m^{-1} of row, which is equal to plants m^{-2} based on soybean row width. Twelve weeks after emergence soybean canopy width was reduced by 6% at 0.33 plants m^{-1} of row up to 55% when competing with Palmer amaranth at 10 plants m^{-1} of row. Emergence timings of soybeans and Palmer amaranth were not reported. Soybean yield loss was greater as Palmer amaranth density increased. Palmer amaranth density at 0.33 plants m^{-1} of row had a soybean yield reduction of 17% and increased linearly with increasing Palmer amaranth density. However, lower soybean yield loss per Palmer amaranth plant was observed when weed density reached between 2 and 3.33 plants m^{-1} of row, which suggests that intraspecific interference among Palmer amaranth plants occurred.

To determine the distance of influence of certain weeds on soybeans, Monks and Oliver (1988) planted Palmer amaranth and other weeds [common cocklebur (*Xanthium strumarium* L.), johnsongrass (*Sorghum halepense* (L.) Pers.), sicklepod (*Cassia obtusifolia* L.), and tall morningglory (*Ipomoea purpurea* (L.) Roth.)] into soybean rows. Along with common cocklebur, Palmer amaranth reduced soybean biomass during the growing season. A negative impact on all weeds when competing with soybeans was also observed. Soybean competition reduced biomass of all weeds by 90 to 97% after 16 weeks. Palmer amaranth competition reduced soybean biomass if Palmer amaranth was within 50-cm of soybeans, however yield was affected if Palmer amaranth was 25-cm or closer to soybeans.

Chandi et al. (2012) examined several biotypes of Palmer amaranth and compared their levels of interference in soybeans. Palmer amaranth density of 0.37 plant m^{-2} reduced soybean yield by 21% overall. Biotypes were separated by susceptibility or resistance to glyphosate. It was found that there was a higher negative response of soybean fresh weight, dry weight, and yield from glyphosate susceptible Palmer amaranth than biotypes with glyphosate resistance. An indication of a competitive disadvantage was associated with glyphosate resistance, however Chandi et al. (2012) concluded that more Palmer amaranth biotype testing was needed to determine true fitness cost to glyphosate resistance.

Jha and Norsworthy (2009) analyzed how tillage and soybean canopy influenced the emergence of Palmer amaranth from a natural seed bank in field experiments near Pendleton, South Carolina. Emergence of Palmer amaranth began in late April to early May and extended until late August to mid-October, which coincided with a mean soil temperature ≥ 25 ºC one week before first emergence. Peak emergence periods were seen from mid-May to mid-July, which were largely impacted by rainfall events. Variations in precipitation, soil temperature, and soybean canopy cover seemed to have the most effect on Palmer amaranth emergence. Spring tillage (disk harrow in late April followed by (fb) rotary tiller before planting in 2004 and 2005) did not have a major impact on emergence. Group 6 soybeans were planted on May 21, 2004 and May 13, 2005, whereas Group 5 was planted on April 12, 2006. Increased canopy cover (percent light interception measured by photosynthetically active radiation) reduced Palmer amaranth emergence by 73 to 76% in no-till compared to plots without any soybean cover. This reduction in Palmer amaranth emergence was reported on July 9, 2004 (32 days after soybean emergence) when soybean canopy reached 75% light interception. The same reduction in emergence was reported on June 30, 2006 (33 days after soybean emergence) when soybean canopy reached 81% light interception. However, in 2005, soybean canopy at 75% interception had no influence on Palmer amaranth emergence. Soybean development during which a canopy effect was reported was not given but may have been V4 to V6 based on days required per growth stage. Considering total emergence of Palmer amaranth, > 90% occurred before soybean canopy closure. It was concluded that the peak emergence periods, from early May to mid-July, posed the highest threat to soybeans for two reasons. One, this time frame coincides with the critical weed free period for soybeans [from V1 to V4 or to R1 depending on tillage and soybean row width (Van Acker et al., 1993; Halford et al., 2001; Knezevic et al., 2003)] and yield losses ≥2.5% may occur depending on weed density. The second reason is that Palmer amaranth growth is not hampered by a soybean canopy, which may result in longer, more robust Palmer amaranth plants.

Bell et al. (2015a) studied Palmer amaranth emergence in soybean plots in Arkansas. Treatments included different seeding rates of drilled glufosinate-resistant Group 4 soybeans (Halomax 494) and the presence of a pre-emergence herbicide application of flumioxazin (82 g ai ha^{-1}), a protoporphyrinogen oxidase (PPO) inhibitor, plus pyroxasulfone (104 g ai ha^{-1}), a long-chain fatty acid inhibitor. They found that increasing the seeding rates of soybeans negatively impacted the emergence rates of Palmer amaranth compared to plots without soybeans. The use of pre-emergence herbicide did not increase yields among different soybean seeding rates. However, the application of pre-emergence residual herbicides reduced Palmer amaranth emergence compared to treatments with no pre-emergence herbicide. It was also concluded than emergence of Palmer amaranth was dependent on soil temperature fluctuations (large fluctuations caused higher emergence rates), also reported by Jha and Norsworthy (2009), which was influenced by soybean density.

A study of the effect of row spacing, seeding rate, and herbicide program in glufosinate-resistant soybeans on Palmer amaranth by Bell et al. (2015b) reported that Palmer amaranth control was 99 to 100% for both study years when a pre-emergence application of S-metolachlor (1,545 g ai ha^{-1}) plus metribuzin (368 g ai ha^{-1}) was used 21 days after soybean planting (DAP). Control ratings of Palmer amaranth plants 42 DAP when the pre-emergence application was used were greater than 88% in both years. Palmer amaranth control was 15 to 79% lower when only a post-emergence herbicide program was used [glufosinate (595 g ai ha^{-1}) and S-metolachlor (1,217 g ai ha^{-1}) plus fomesafen (266 g ai ha^{-1}) 21 DAP fb glufosinate (738 g ai ha^{-1}) plus acetochlor (1,260 g ai ha^{-1})]. It was concluded that an herbicide program involving a pre-emergence herbicide was best for soybean yield and economic returns. Herbicide programs also influenced Palmer control, density, and seed production more heavily than soybean row spacing and seeding rate.

Norsworthy et al. (2016) performed a field experiment to determine the impact of in-crop herbicide programs and post-harvest fall management of soybean residue spreading or soil incorporation, a rye cover crop, windrowing of residue with/without burning, or residue removal at harvest on Palmer amaranth density and seed production. The most effective post-harvest program to control Palmer amaranth consisted of either residue collection and removal, rye cover crop, or crop residue incorporation. Seed production of Palmer amaranth was not affected by fall residue management. Herbicide programs included glyphosate (870 g ha^{-1}) at V2 fb glyphosate (870 g ha^{-1}) at V7 or a pre-emergence application of flumioxazin (71 g ai ha^{-1}) fb S-metolachlor (1,215 g ai ha^{-1}) plus fomesafen (266 g ai ha^{-1}) at V2 with either glyphosate (870 g ha^{-1}) or glufosinate (594 g ai ha^{-1}) at V2 and V7. Palmer amaranth density and seed production was reduced when a pre-emergence herbicide was applied. Residual herbicide used was a premix of S-metolachlor (1,215 g ai ha^{-1}) and fomesafen (266 g ai ha^{-1}). Glufosinate (594 g ai ha^{-1}) plus the residual herbicide was much more effective than when glyphosate (870 g ha^{-1}) was added to the residual herbicide application. Although a pre-emergence only application was not tested, it was concluded that a combination of a pre- plus post-emergence residual herbicide program with either a rye cover crop, chaff removal, or seed incorporation were the best strategies in lessening Palmer amaranth density and seed population.

Palmer amaranth has spread to the northern states in the United States despite its origination from a dry, arid climate. Once this species becomes established total removal is difficult (Culpepper et al., 2010; Sprague, 2014). Management techniques have been developed to help limit the further infestation of Palmer amaranth (Norsworthy et al., 2016). These can include cover crops, residue soil incorporation, removal and/or destruction of Palmer amaranth plants before seed shatter, and herbicide programs that utilize multiple modes of action. No management strategy has been completely effective, as evidenced by the slow but continued spread of Palmer amaranth. Seed destruction efficiency is not always 100%, especially due to the number and small seed size of Palmer amaranth. A period between cover crop termination and crop establishment can allow for Palmer amaranth to germinate and become competitive, and large variations in Palmer amaranth biology allow for selection of herbicide resistance biotypes in just a few years of application. Spread can also be facilitated through natural means (animals, wind, etc.) or mechanical movement, such as custom harvesters, contaminated seed mixes, or animal feed. The objectives of this research were to: 1) examine the potential for Palmer amaranth to grow in eastern South Dakota and compare its growth to common waterhemp and redroot pigweed, 2) determine Palmer amaranth competitiveness of an infestation near Corsica, South Dakota with soybeans, and 3) determine the effectiveness of certain herbicides on plants from seeds of the previously mentioned infestation.

CHAPTER 2. MATERIALS AND METHODS

2016 Survey

The Palmer amaranth survey was written (see pages 20 and 21 for survey) and conducted in 2016. Surveys were printed and handed out at commercial and private applicator certification renewal sessions around the state and the annual Soy 100 meeting in Brookings, South Dakota. Completed surveys were accumulated at the end of each session or meeting and data for each question entered into an Excel spreadsheet. These sessions were chosen to represent those individuals who had the most contact with weeds in fields and were tasked with controlling those weeds. The purpose of the survey was to investigate where surveyed individuals were located, the level of concern for Palmer amaranth, locations of possible Palmer amaranth infestations, and the ability of individuals to correctly identify and differentiate between Palmer amaranth, common waterhemp, and redroot pigweed.

Images of seedling and mature plants were used on the survey. Participants were to match the images to the correct species (Palmer amaranth, common waterhemp, or redroot pigweed). The images shown in the survey were chosen to 1) inform individuals as to how closely *Amaranthus* species can resemble each other and 2) highlight certain characteristics of each species most commonly used for identification. Images of Palmer amaranth showed elongated petioles, rosette-like growth, an absence of hair, and a diamond- to egg-shaped leaf. Common waterhemp images highlighted a lack of hair, long petioles, and lanceolate and glossy leaves. Redroot pigweed images described a rough and hairy appearance, oval-shaped leaves, medium to long petioles, and a compact inflorescence.

Palmer Amaranth Survey

South Dakota State University

1. **Which county do you perform the majority of your duties? ________________**

2. **Have you previously heard about Palmer amaranth?** **YES** **NO**

   (If yes where did you receive the information from?) ______________________

3. **Do you suspect you have Palmer amaranth in your area?** **YES** **NO**

4. **Please circle the correct name of the plant shown in each box.**

A. Palmer amaranth
B. Redroot pigweed
C. Common waterhemp

A. Palmer amaranth
B. Redroot pigweed
C. Common waterhemp

A. Palmer amaranth
B. Redroot pigweed
C. Common waterhemp

5. Please circle the name of the plant shown in each box.

A. Palmer amaranth
B. Redroot pigweed
C. Common waterhemp

A. Palmer amaranth
B. Redroot pigweed
C. Common waterhemp

A. Palmer amaranth
B. Redroot pigweed
C. Common waterhemp

Correct Answers (left, right, bottom):

4. Redroot pigweed; Palmer amaranth; Common waterhemp

5. Redroot pigweed; Palmer amaranth; Common waterhemp

planting, plants were transplanted into plots at Aurora, SD. Growth stage at time of transplanting varied from 1- to 2-leaf and 3-cm tall (early planting) to 3- to 4-leaf and 4- to 5-cm tall (late planting) (Table 2.1). At transplanting in 2015, 12 Palmer plants were placed equidistant apart in each 1-m^2 plot for all three planting dates. Seedling survival was affected after transplanting, especially the first planting date, resulting in plots that varied in final density from 4 to 12 plants m^{-2} (Table 2.2). In addition, one Palmer amaranth was planted with no competition in a plot at the second and third planting dates (density = one plant m^{-2}). Due to limited germination and plant survival, only one redroot pigweed was planted per plot, replicated 5 times, at the second planting date. Common waterhemp seeds did not germinate in the greenhouse, so seedlings, which germinated from a natural infestation, were followed starting at the third planting date. Common waterhemp plants were thinned to a density of 1 plant m^{-2}.

The 2016 dates of greenhouse planting and transplanting were similar to 2015. Two final densities were used per plot. Final Palmer amaranth densities were one plant m^{-2} and four plants m^{-2} which were thinned from four plants m^{-2} and 12 plants m^{-2}, respectively, five weeks after each respective transplanting date when plants were fully established. Both final densities were replicated four times. Similar germination and establishment problems for redroot pigweed and common waterhemp seeds persisted despite water soaking and scarification. Naturally germinated seedlings were used for these two species during the first (early) and third (late) planting dates (May 25 and June 24, respectively) and densities were thinned to one and four plants m^{-2} at the same time as the Palmer plots.

In a second trial, comparison of Palmer amaranth seed growth among plants from diverse geographic ascensions was conducted in 2016. Palmer amaranth seeds used were harvested from Urbana, IL (40° N, 88° W), Jenkins, GA (32° N, 82° W), Manhattan, KS (39° N, 96° W), Columbia, MO (39° N, 92° W), Fayetteville, AR (36° N, 94° W), and Las Cruces, NM (32° N, 106° W) and were obtained from A. Davis (USDA-ARS, Champaign, IL), and seed used from the Corsica, SD (43° N, 98° W) ascension were harvested in fall 2015. Plants were transplanted into plots on June 10, 2016, the second transplant date of the timing study. Planting density was six plants m^{-2} and thinned to two plants m^{-2} five weeks after transplanting.

Table 2.1. Dates of planting and transplanting for Palmer amaranth studies near Aurora, SD.

Planting Group	--------------2015--------------		Growth Stage	--------------2016--------------	
	Plant	Transplant		Plant	Transplant
1	7-May	22-May	1- to 2-leaf	10-May	25-May
2	26-May	10-Jun	2- to 3-leaf	25-May*	10-Jun
3	11-Jun	24-Jun	3- to 4-leaf	10-Jun	24-Jun

* Palmer amaranth planting for geographical location study

Table 2.2. Final Palmer amaranth densities in 2015 of each plot for their respective transplant date.

	------------------Palmer amaranth final density m^{-2}------------------					
Transplant date	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	Plot 6*
22-May	9	12	10	4	-	-
10-Jun	12	11	10	12	12	1
24-Jun	12	12	12	12	12	1

* Initial Palmer amaranth density of one plant m^{-2}

Height and diameter (widest point of plant) for all plants were measured about every 10 to 20 days. Data were used to determine plant volume and plant size. Male Palmer plants were covered with pollination bags in 2015 as flowering was initiated to reduce pollen flow to female plants. Two male and female plants from each plot were cut at the soil level, placed in bags, and oven dried at 60 ºC until constant weight on August 1st. The amount of time in the field varied from 72 days (first planting, May 22) to 40 days (third planting, June 24). Dry weight was recorded and dry weight per plant was calculated. All other plants were harvested on the same date and destroyed. In 2016, harvest occurred from July 25th to August 21st. Palmer amaranth plants were harvested shortly after sufficient inflorescence emergence to indicate plant gender. Common waterhemp and redroot pigweed plants that had early emergence (first planting date, May 25) were harvested July 25th and late emerging plants (third planting date, June 24) were harvested when the last Palmer amaranth plants were harvested (August 21st). All plants in every plot were harvested and oven dried for dry weight in 2016.

Statistical analysis was done using RStudio (version 3.2.2). Analysis of variance (ANOVA) was used to determine significant differences among treatments. Means were separated using Fisher's least significant difference at the 95% confidence level. Studies by years were analyzed separately due to differences in experimental setup. Plant volume (V) was calculated using the formula $V=3.14*r^2*h$, where r is the radius of the plant obtained from plant diameter and h is the height of the plant from soil surface to the tallest point of the plant, including the terminal inflorescence when present. Analysis was not applied to solitary Palmer in 2015 due to only one replication of each.

Greenhouse herbicide study

Trials were conducted in the greenhouse with seed taken from an infestation near Corsica, SD using herbicides with different modes and sites of action on Palmer amaranth. Palmer seeds were collected from plants in fall 2016 and were planted in either potting mix and or sand in spring and fall 2017.

In the spring trial, seeds were planted into greenhouse potting mix in greenhouse pots (10-cm wide by 10-cm deep). Plants for post-emergence treatments were grown to the three- to four-leaf stage with heights ranging from 3- to 10-cm (23 days after planting). Pots designated for pre-emergence treatment were filled with either potting mix or sand and subjected to herbicide application (Table 2.3) shortly after seeds were planted. There were 10 replications (pots) per herbicide treatment with the exception of the thifensulfuron treatment, which had eight replications. Plants were not thinned after emergence and all pots had similar stands of 20 to 25 plants per pot. The fall trial had slight changes to the methodology. In post-emergence treatments, plants were grown to the three- to four-leaf stage (22 days after planting) but split into 5 replications of plants with heights of 5- to 10-cm and 10- to 20-cm due to variability in plant height despite similar growth stage (three to four true leaves). Plant density was thinned to 15 to 20 plants per pot. Post-emergence herbicide applications are typically performed at or prior to this growth stage to obtain optimum control.

Plants were treated with rates of herbicides plus other additives as suggested by each herbicide label (Table 2.3). Treatment cost of each were calculated based on the 2017 Pest Management guide for South Dakota. Atrazine and S-metolachlor were applied over Palmer amaranth plants in sand and potting mix at the pre-emergence timing to simulate different soil types. Once control ratings were established 21 days after application for the atrazine pre-emergence treatment in the potting mix, five pots were sprayed with a post-emergence atrazine treatment.

Treatments were applied using a spray booth (EDA.inc, Folsom, CA). Rate of application was 225 L ha^{-1} rate at 197 kPa with a single flat fan nozzle (TeeJet 8001), which is rated at 0.38 L min^{-1} at 276 kPa. The shelf holding the pots was moved to allow for 76 cm between the nozzle and application target (top of Palmer amaranth or soil). The nozzle moved by a chain and speed was set to 1.6 kph.

All treatments in both trials were given control ratings from 0- to 100% (no injury to complete death of plants) 21 days after application. Ratings were averaged for each treatment among the replications. Once ratings were given, the sand and potting mix used were subjected to autoclaving to sterilize any non-germinated Palmer amaranth seeds.

Table 2.3. Palmer amaranth herbicide treatments, application timing (pre-emerge or post-emerge), soil type, rates, and treatment cost.

Application Timing	Soil Type	--------------Herbicide--------------		Rate	Treatment Cost[a]
		---Common---	------Trade------	-g ai ha^{-1}-	--$ ha^{-1}--
Check	Sand		Check		
	Potting Mix				
Pre	Sand	Atrazine	Atrazine 4L		
	Potting Mix			2242.8	$18.28
Pre	Sand	S-metolachlor	Dual II Magnum		
	Potting Mix			2141.8	$40.76
Post	Potting Mix	Atrazine	Atrazine 4L	2242.8	$47.30
			COC[b]	2.3 L	
			NPD[c]	0.4 L	
Post	Potting Mix	Mesotrione	Callisto	105.1	$119.47
			COC	2.3 L	
			AMS[d] + NIS[e]	5.6 L	
			NPD	0.4 L	
Post	Potting Mix	Dicamba	Clarity	560.7*	$33.59
			COC	0.6 L	
			AMS + NIS	2.8 L	
			NPD	0.4 L	
Post	Potting Mix	Thifensulfuron	Harmony SG	280.4	$33.10
			AMS + NIS	2.8 L	
			NPD	0.4 L	
Post	Potting Mix	Glufosinate	Liberty	738.0	$65.08
			AMS + NIS	11.2 L	
			NPD	0.4 L	
Post	Potting Mix	Glyphosate	Roundup[f]	1261.6*	$23.54
			AMS + NIS	5.6 L	
			NPD	0.4 L	

[a]Treatment cost includes herbicide cost and adjuvant cost based on 2017 average cost in South Dakota

[b]COC is crop oil concentrate

[c]NPD is non-polymer deposition adjuvant

[d]AMS is ammonium sulfate

[e]NIS is non-ionic surfactant

[f]Roundup Weathermax

* Dicamba and Glyphosate rates are shown in g ae ha^{-1}

Soybean yield study

The soybean yield study was established near Corsica (southeast, SD, 43° 22'N, 98° 24'W, elev. 479.2m) in 2016 and 2017. The effect of Palmer amaranth density on soybean yield was examined. The experimental design was a completely randomized design (CRD) with three density ranges and a control (zero Palmer amaranth) with four to five replications in each range. Plots were placed within patches of Palmer amaranth to acquire densities which fell in the desired ranges. Check plots were placed near density plots to more closely compare weedy with weed-free yields. Palmer amaranth plot densities are reported in Table 2.5 for 2016 and 2017. Individual plot size was 1- by 1-m, containing two rows of soybeans at 0.8-m spacing. The soil was a Eakin-Ethan complex (fine-silty, mixed, superactive, mesic typic Argiustolls-fine-loamy, mixed, superactive, mesic typic Calciustolls) with a pH of 6.7, 95-g sand, 675-g silt, and 230-g clay kg^{-1} soil, and an organic matter content of 30-g kg^{-1} soil.

Palmer amaranth near Corsica, SD was a relatively new infestation discovered in 2015, possibly from a Texas swine manure application. The field where the study was conducted was subject to conventional tillage and free of any weeds other than Palmer amaranth. Palmer was introduced into the field through the spreading of manure which had come from a truck washout station located nearby. Some trucks that had used the station were known to have been carrying swine and other livestock from southern states.

Palmer plants were counted and harvested from each plot when peak biomass was reached (September 16th, 2016 and September 7th, 2017) and dried. Removal of Palmer coincided with the R7-R8 soybean stages of development. Soybean plants were removed from plots at physiological maturity on October 4th (2016) and October 9th (2017). Grain was collected by threshing plants using a Massey Ferguson 8 plot combine. Grain was weighed and yield was calculated for each plot. Soybean yield loss was calculated using the rectangular hyperbolic yield-loss function (Cousens, 1985):

$$YL = (I*D) / \left(1 + (I*D) / A\right)$$

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.

Table 2.4. Description of soybean study with Palmer amaranth density range, number of plots, and density of each plot in 2016 and 2017.

Density Range	----------------2016----------------		------------------2017------------------	
--plants m^{-2}--	Num. Plots	Densities	Num. Plots	Densities
0	4	0	4	0
1-5	4	1, 1, 3, 5	5	1, 1, 3, 3, 5
6-10	5	6, 7, 7, 7, 9	5	6, 7, 8, 9, 9
>10	4	15, 19, 20, 27	6	12, 13, 15, 18, 22, 23

CHAPTER 3. RESULTS AND DISCUSSION

2016 Survey

Results from surveys were compiled from individuals at commercial and private applicator training sessions and the annual Soy 100 meeting in the spring of 2016. About 250 surveys were completed from around the state. The pictures shown in the survey were chosen to 1) inform individuals as to how closely *Amaranthus* species can resemble each other and 2) highlight certain characteristics of each species most commonly used for identification. Participants correctly recognized mature plants of redroot pigweed, and Palmer amaranth about 70% of the time. There was more difficulty with common waterhemp (68% correct) with the plant most often confused with Palmer amaranth. Seedling plants were not as readily correctly identified. Forty percent of the participants correctly identified redroot pigweed, with an even split between answering waterhemp or Palmer amaranth. Palmer amaranth seedlings were correctly identified 60% of the time, with most incorrect answers being waterhemp. Common waterhemp seedlings were only correctly identified 29% of the time with 59% of the respondents identifying the plant as redroot pigweed.

The results indicate that more and better information, especially on seedling identification, is needed to have producers and professionals recognize these three species. Early identification with appropriate control is often less costly and most effective. In addition, many of the common waterhemp infestations in South Dakota are herbicide resistant (glyphosate, ALS, or both), and if confused with redroot pigweed, the action steps may not provide acceptable results, which at this time is not.

Respondents were also asked, 1) if they had heard information about Palmer amaranth and if yes, the sources of information; and 2) if they know of Palmer infestations in their county of work. Of the respondents, nearly 80% said they have heard about Palmer amaranth. This indicates that producers are getting information about this weed before widespread distribution.

As of 2017, there have been at least nine confirmed infestations in South Dakota including Bennett, Brule, Buffalo, Douglas, Gregory, Hughes, Lyman, Potter, and Sully county shown in Figure 3.1 (Shaffer and Clay, 2017). Based on survey results, respondents from 26 different SD counties said yes, Palmer amaranth is present in their area. However, when matching up responses that were correct for seedling as well as mature plant identification and then matching to 'yes in my county', only 17 counties were then highlighted. This indicates that there is confusion about the plant identification but, even with 17 counties, there are potentially many unmapped areas of infestation. Counties that had correct seedling AND mature plant ID and said, yes there is an infestation, included: Beadle, Bon Homme, Brookings, Brown, Codington, Davison, Day, Grant, Hamlin, Hutchinson, Lake, McCook, Minnehaha, Moody, Spink, Union, and Yankton (Figure 3.2). Respondents from 11 counties (Figure 3.3) correctly identified either the seedling OR mature plant. However, these respondents also said there was an infestation of palmer amaranth in their county. Only two of these counites have confirmed infestations and the other counties have no confirmed infestations that have been identified at this time. Respondents from five counties (Figure 3.4) had incorrect identification but said yes to an infestation of Palmer amaranth. Maps of compiled survey data courtesy of John Green using ESRI ArcGIS ArcMap 10.5.

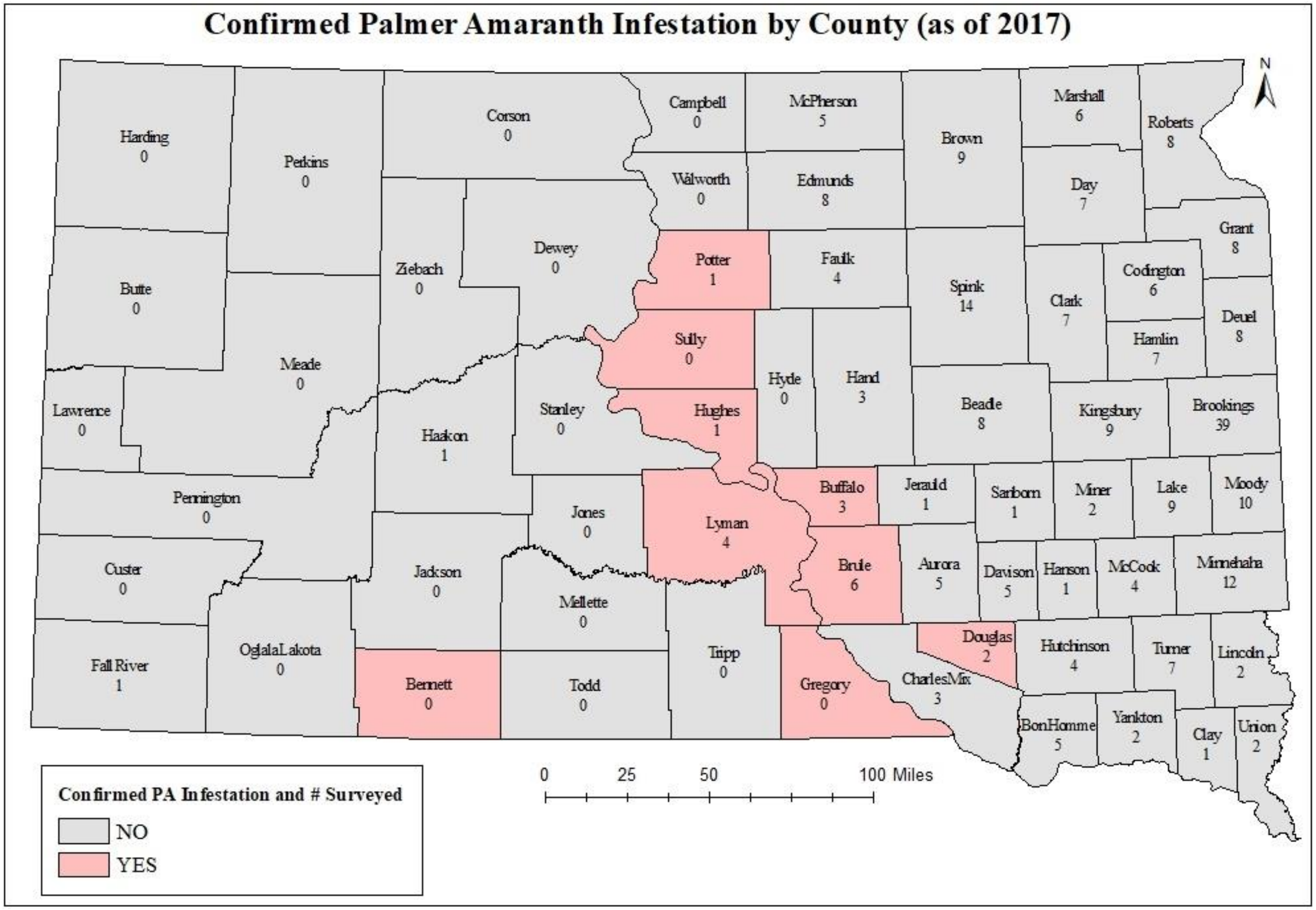


Figure 3.1. Counties in South Dakota with confirmed infestations of Palmer amaranth (Schaffer and Clay, 2017) and the number of survey respondents.

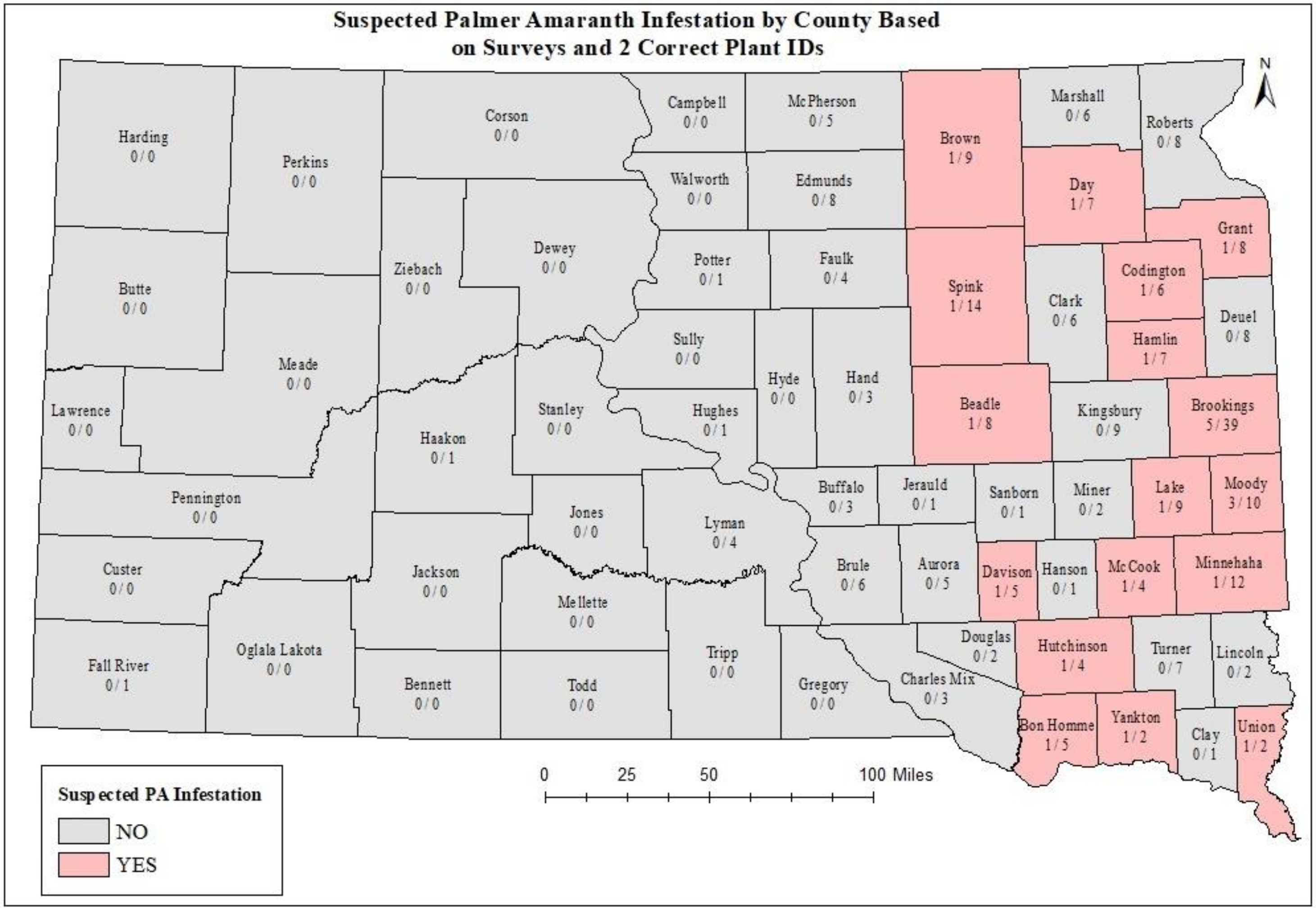


Figure 3.2. Counties that indicated a Palmer amaranth infestation and correctly identified both the Palmer amaranth seedling and mature plant and number of respondents with two correct plant ID and said yes to an infestation out of total survey respondents.

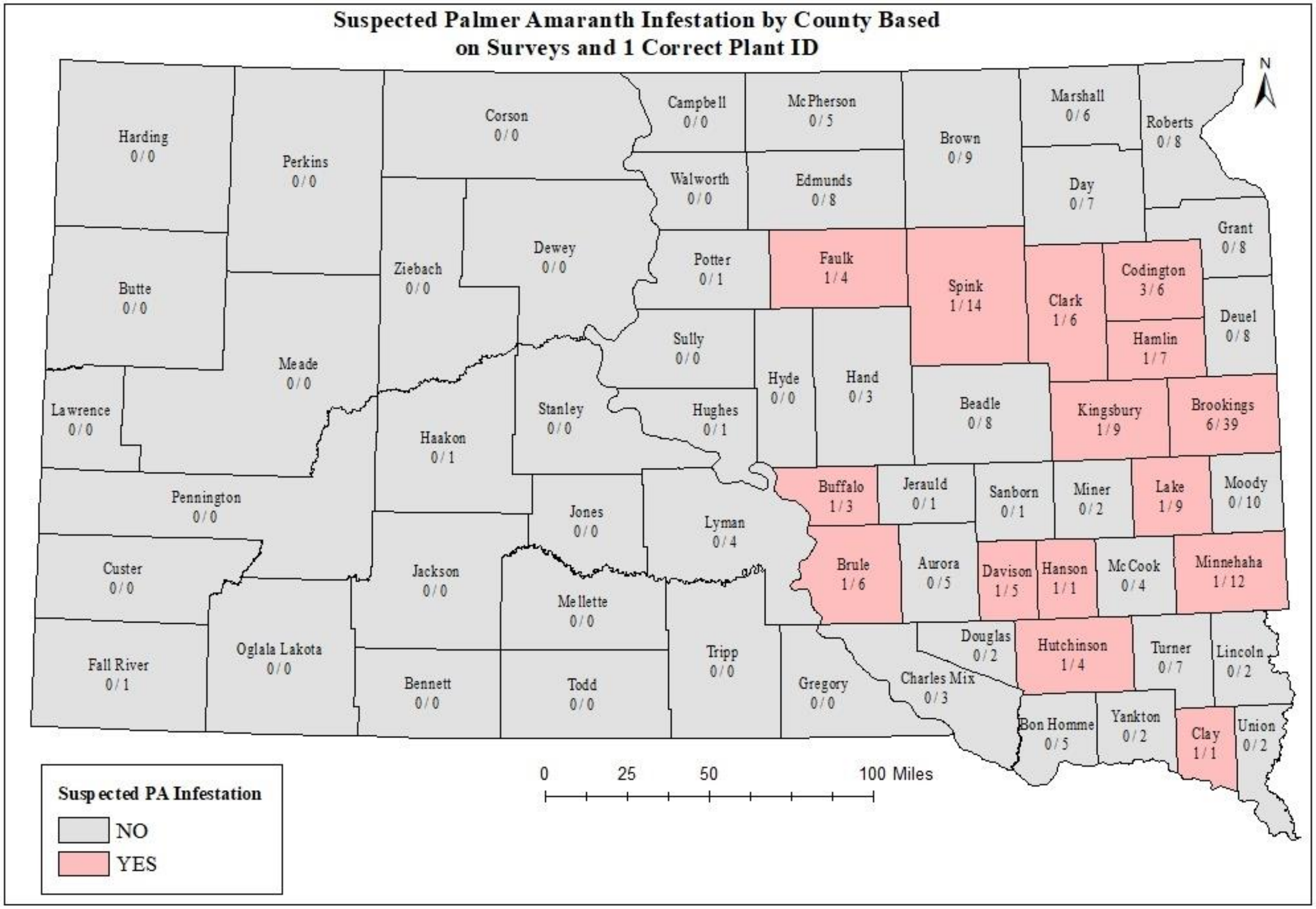


Figure 3.3. Counties that indicated a Palmer amaranth infestation and correctly identified the Palmer amaranth seedling or mature plant and number of respondents with one correct plant ID and said yes to an infestation out of total survey respondents.

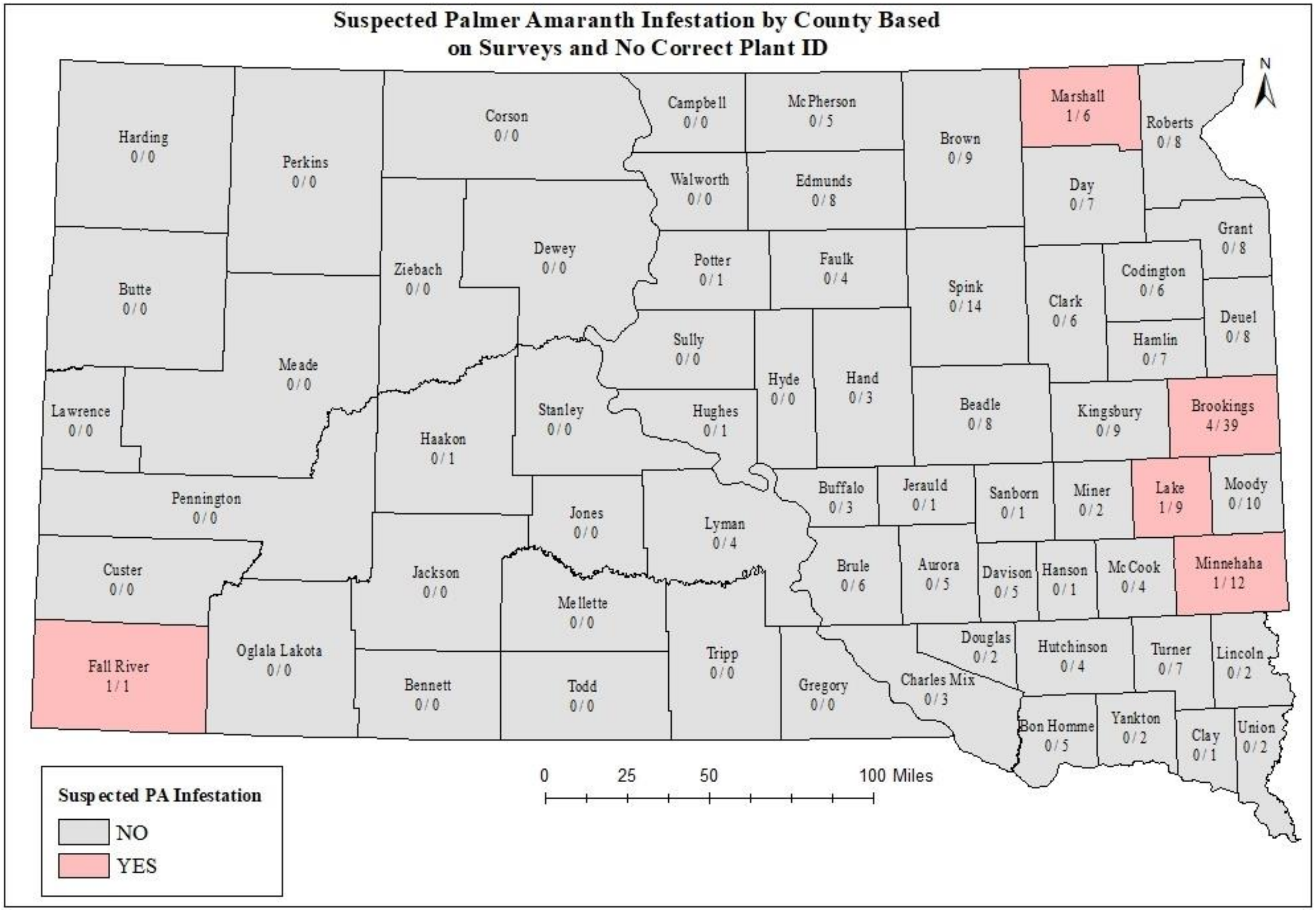


Figure 3.4. Counties that indicated a Palmer amaranth infestation but did not correctly identify either Palmer amaranth seedling or mature plant and number of respondents with no correct plant ID and said yes to an infestation out of total survey respondents.

Throughout the survey process, several issues presented themselves. Occasionally, surveys collected were incomplete, which limited the data source of this study. Most frequently, many individuals chose not to participate in the survey, which may have resulted in an underrepresentation of several counties or regions in South Dakota. Follow-up surveys may need to be more in-depth, such as including plants of each species that are more easily distinguishable from each other as well as including plants similar in appearance. Another change would be in the form of how the survey was presented. Applications on phones can now provide a quick-poll of individuals in a room. A survey in the form of a PowerPoint presentation may generate more participation and better data.

Climatic data

Temperature, growing degree days (GDD based on 10 °C starting in May), and precipitation data for Brookings (closest reporting weather station to Aurora location) were used for the comparison studies. Average weekly temperatures for the 2015 and 2016 growing seasons (May-September) are presented in Figure 3.5 and were similar to the 30-year (1981-2010) average in 2015 and about 10% warmer in 2016 from early June to mid-August. Table 3.1 shows accumulated growing degree days were four and 117 greater for 2015 and 2016, respectively, from normal in Brookings, SD. Weekly accumulated growing degree days in Brookings are reported in Figure 3.6 and shows that the 2016 departure from normal started in early June. Precipitation was normal in 2015 and 21.7 cm below normal in 2016. Monthly precipitation data in Brookings in Table 3.2 and weekly accumulated precipitation data in Figure 3.7 illustrates a large range in precipitation accumulation throughout 2015 followed by a lower and narrower range in 2016.

Parkston (closest reporting weather station to Corsica location) was used for temperature, growing degree day (base 10 °C), and precipitation data for the soybean yield study. Figure 3.8 shows temperatures for 2016 were similar to slightly warmer than the 30-year average. The 2017 temperatures were comparable to 2016 but slightly cooler from late July to late August. Accumulated growing degree days (base 10 °C) in 2016 were 203 days greater than the average whereas 2017 was 77 growing degree days higher than the average (Table 3.3). Growing season (May-October) precipitation totaled about 44 cm in 2016 and 40 cm in 2017, which was close to the 30-year average (Table 3.4).

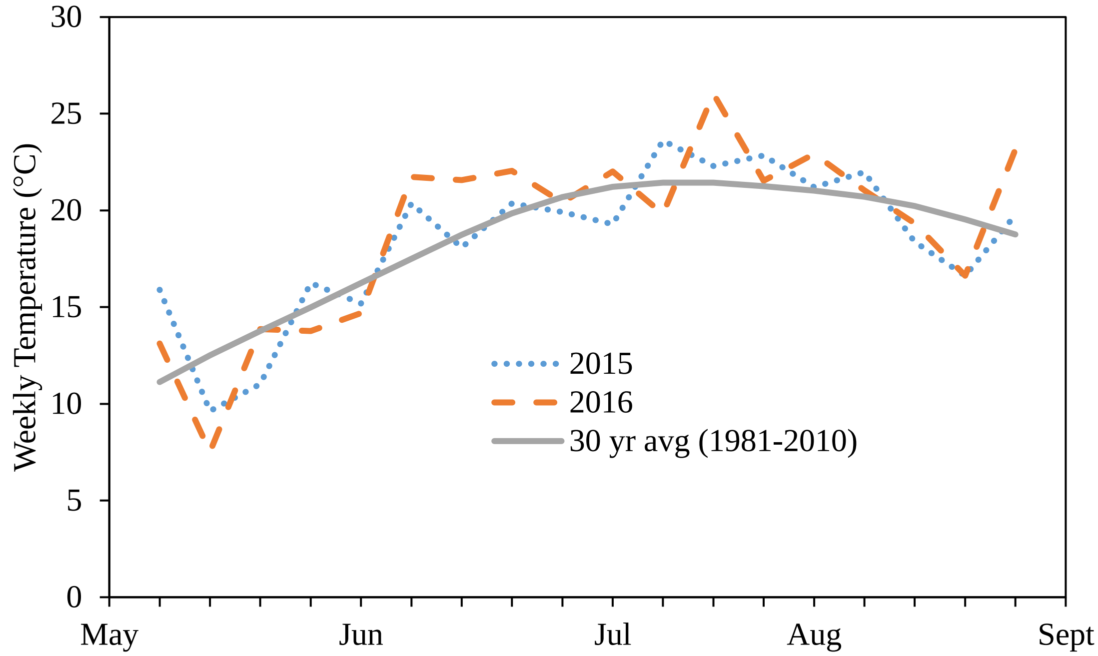


Figure 3.5. Weekly average temperatures at Brookings, 2015, 2016, and 30-year (1981-2010) average.

Table 3.1. Accumulated growing degrees (base 10 °C) for Brookings by month and departure from the 30-year (1981-2010) average for 2015 and 2016.

Month	2015	2016	30-Year Average (1981-2010)	2015 Departure From Average	2016 Departure From Average
	--------------------------------(Base 10°C)--------------------------------				
May	145	158	151	-5	8
June	286	324	262	24	62
July	352	383	351	1	32
August	298	329	314	-16	15
Total	1081	1194	1077	4	117

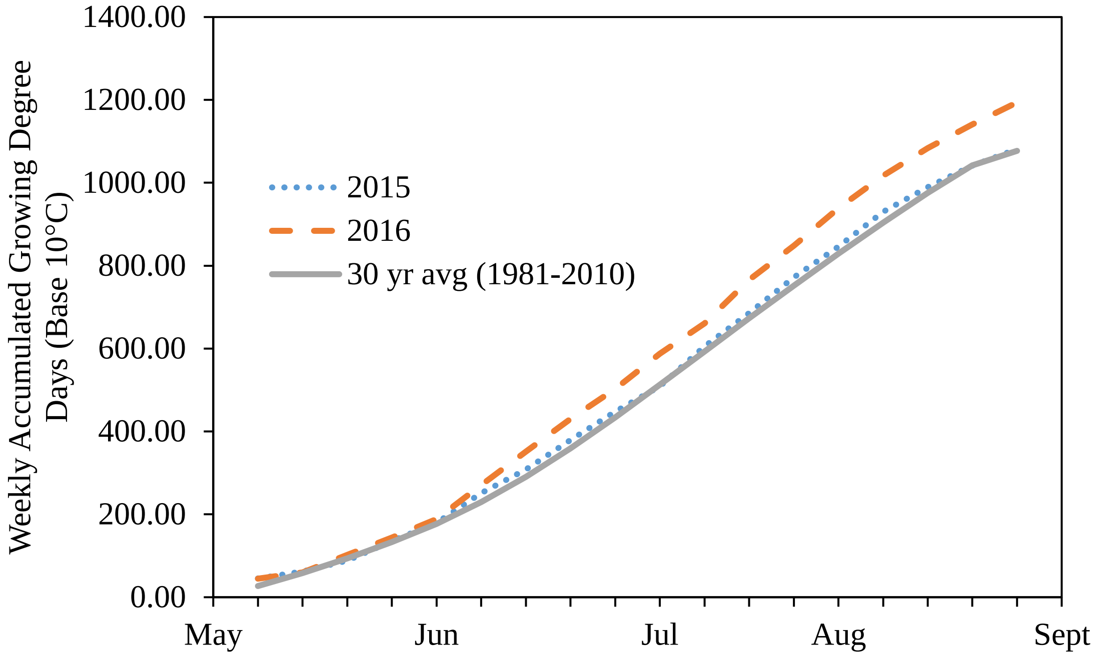


Figure 3.6. Weekly accumulated growing degree days at Brookings in 2015, 2016, and the 30-year (1981-2010) average.

Table 3.2. Precipitation data (in cm) for Brookings by month and departure from the 30-year (1981-2010) average for 2015 and 2016.

Month	2015	2016	30-Year Average (1981-2010)	2015 Departure From Average	2016 Departure From Average
	-------------	-------------	------cm------	-------------	-------------
May	11.2	1.9	7.5	3.6	-5.7
June	5.4	3.4	10.9	-5.5	-7.5
July	9.4	4.9	8.3	1.1	-3.3
August	16.1	2.6	7.8	8.3	-5.2
Total	42.0	12.8	34.5	7.5	-21.7

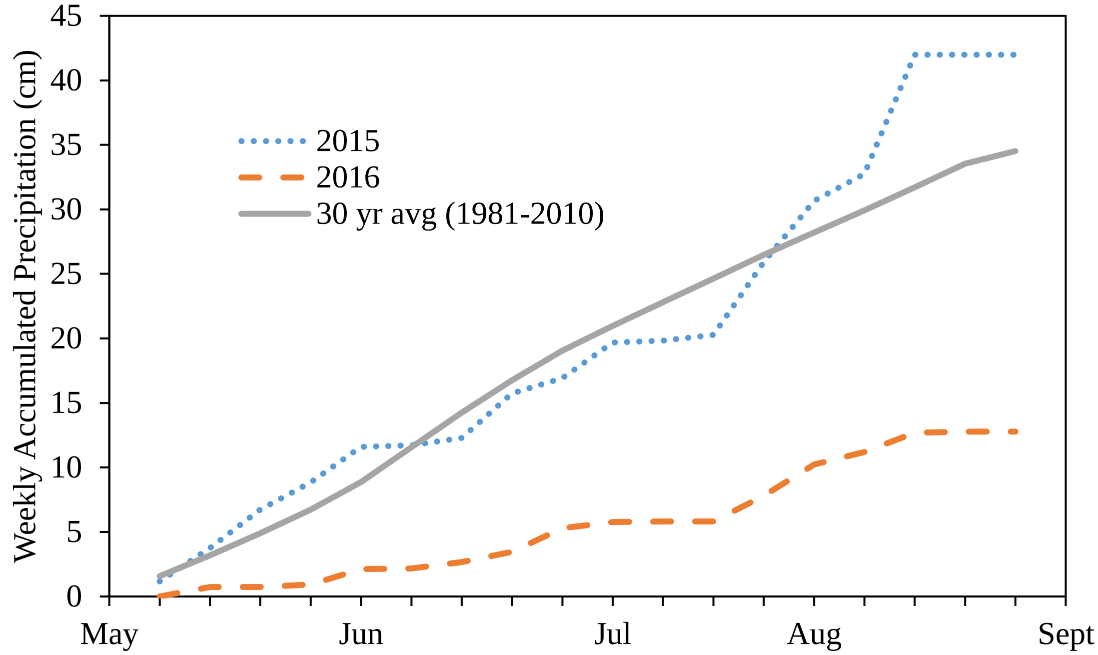


Figure 3.7. Weekly accumulated precipitation (in cm) at Brookings in 2015, 2016, and the 30-year (1981-2010) average.

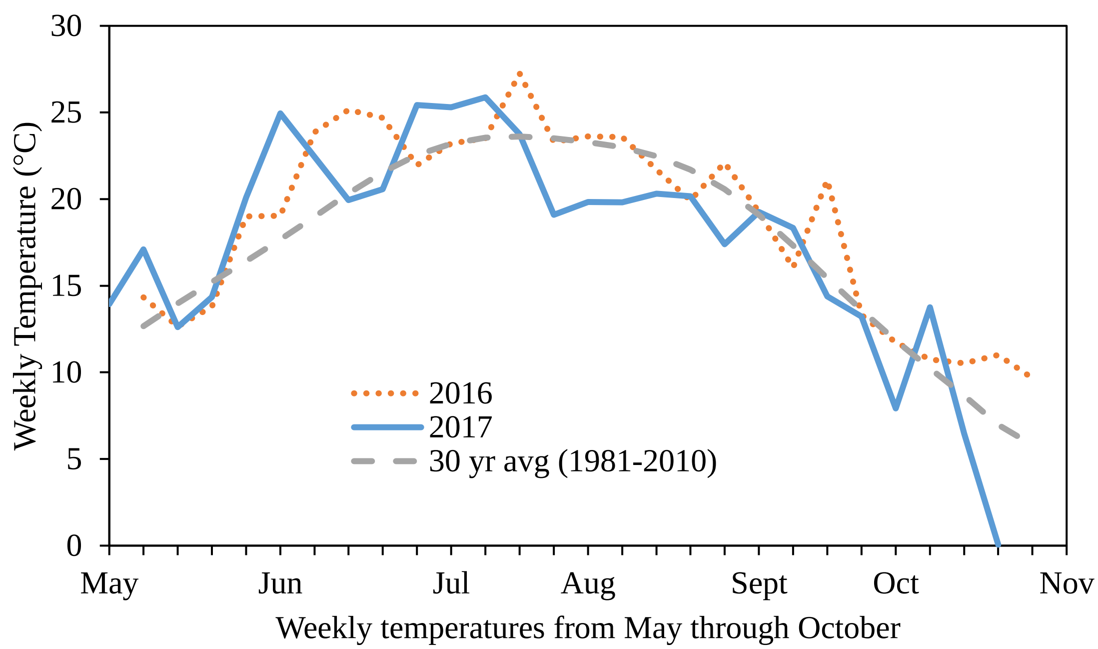


Figure 3.8. Weekly average temperatures at Parkston, 2016, 2017, and the 30-year (1981-2010) average.

Table 3.3. Accumulated growing degrees (base 10°C) for Parkston by month and departure from the 30-year (1981-2010) average for 2016 and 2017.

Month	2016	2017	30-Year Average (1981-2010)	2016 Departure From Average	2017 Departure From Average
	----------------------------(Base 10°C)----------------------------				
May	204	179	178	26	1
June	401	361	310	91	51
July	431	466	416	15	50
August	388	310	383	5	-73
September	266	256	225	41	31
October	126	118	101	26	17
Total	1816	1689	1613	203	77

Table 3.4. Precipitation data (in cm) for Parkston by month and departure from the 30-year (1981-2010) average for 2016 and 2017.

Month	2016	2017	30-Year Average (1981-2010)	2016 Departure From Average	2017 Departure From Average
	-------------------------------------cm-------------------------------------				
May	12.4	7.8	8.1	4.3	-0.3
June	3.1	5.2	10.4	-7.3	-5.2
July	5.5	3.8	6.8	-1.3	-3.0
August	8.3	10.6	6.1	2.2	4.4
September	9.1	6.8	6.4	2.7	0.4
October	5.5	6.0	4.6	1.0	1.5
Total	43.9	40.2	42.4	1.5	-2.3

Amaranthus comparison studies (Aurora 2015)

At Aurora, final Palmer amaranth densities in the comparison plots varied from 4 to 12 plants m^{-2}. Plant volume analysis of variance among densities within each planting were similar ($p>0.05$). Therefore, data were combined by planting date and data across planting dates were tested against each other for differences in biomass and volume. Solitary Palmer amaranth plants in 2015 (planting date two and three) were not included in the overall comparisons due to lack of replication, however, the data collected for these plants are reported (Figures 3.9, 3.10, and 3.11). Common waterhemp and redroot pigweed were grown at a density of one plant m^{-2} and replicated. Comparisons were made among species, however, due to the differences in densities, these comparisons are inexact.

In 2015, Palmer amaranth growth was slow, as measured by calculated volume, until late-June. Of the plants that experienced competition, plants in planting date one had the largest volume compared with plants in cohort two and three. Growth rates, expressed as m^3 day^{-1} between sampling dates, peaked about July 23rd and slowed for cohorts one and two, whereas plants in cohort three continued to have high growth rates (Figure 3.9). Inflorescence emergence of 50% of all Palmer, regardless of planting date, was around July 15th. Similar inflorescence timing in 2016 indicates Palmer amaranth is influenced by decreasing daylength, which suggests Palmer amaranth is a short-day plant. This agrees with findings by Keely et al. (1987). The volume of Palmer amaranth at each sampling date among planting dates in 2015 is reported in Table 3.5. The plants in the earliest planting were the largest throughout the growing season and had a final volume of 0.97 m^3 compared to the later plantings that averaged 0.26 m^3. A comparison of the gender of Palmer amaranth did not show any differences in final plant volume when compared within a planting date. Male plants made up 52% of the population in 2015.

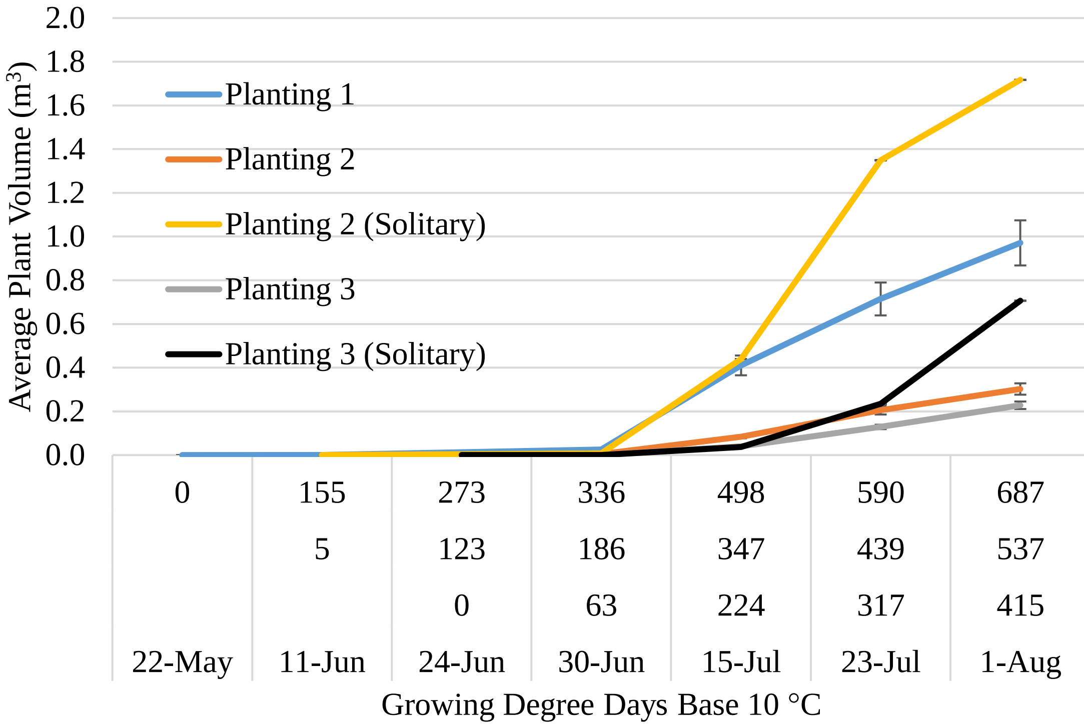


Figure 3.9. Average plant volume of Palmer amaranth for each planting (1=May 22, 2=June 10, 3=June 24) and respective accumulated growing degree days with and without competition in 2015.

Table 3.5. Comparison of Palmer amaranth volume among planting dates in 2015.

Date of Plant/Transplant		22-May	11-Jun	30-Jun	15-Jul	23-Jul	1-Aug
		------------------------Corn Growth Stage†------------------------					
		V2	V4	V6	V12	R1	R2
		----------------------------Volume (m^3)----------------------------					
7-May	22-May	<0.0001	0.0005 a*	0.0251 a	0.41 a	0.71 a	0.97 a
26-May	10-Jun	--	0.0001 b	0.0041 b	0.08 b	0.21 b	0.30 b
11-Jun	24-Jun	--	--	0.0005 c	0.04 b	0.13 b	0.23 b

* Means followed by the same letter are significantly different at P<0.05
†Corn growth stage is approximated and may vary over years, production environments, and locations

The growth rates among Palmer amaranth with and without intraspecific competition and redroot pigweed without competition at planting date two (June 10) were compared (Figure 3.10). Intraspecific competition lessened growth rate (m^3 day^{-1}) and final Palmer amaranth volume by 76% compared to the solitary Palmer amaranth plant. Palmer amaranth grown in intraspecific competition had plant volumes similar to redroot pigweed that was grown as a single plant. Redroot pigweed grown at one plant m^{-2} maintained faster growth and had greater volume (40%) compared to Palmer amaranth plants grown with competition. Redroot pigweed grown without competition had a total volume that was 67% less than that of the solitary Palmer amaranth plant, which had a final volume of 1.72 m^3.

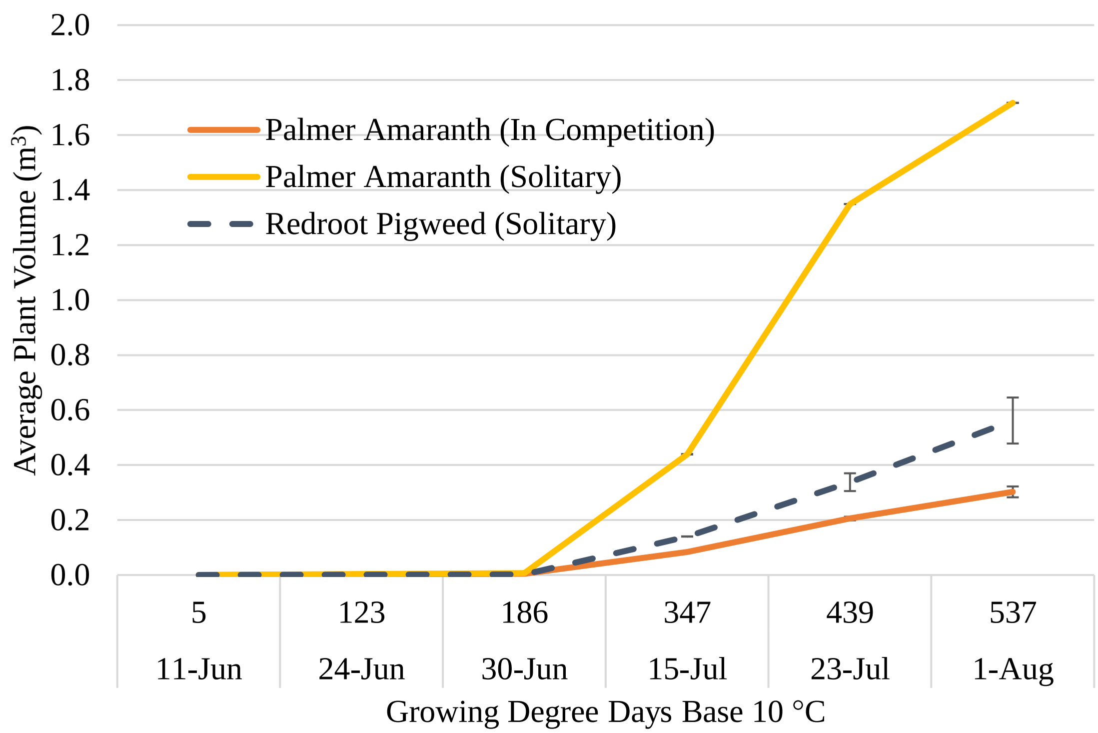


Figure 3.10. Growth rates of Palmer amaranth with and without intraspecific competition and redroot pigweed grown alone planted in the field on June 10, 2015.

Growth rates for planting date three (June 24, 2015) was very slow at the end of June (one week in the field) and did not increase until the end of July. It appears that growth rates increase dramatically when GDD reaches about 300 for each cohort. The growth rate for each cohort continued to increase throughout the growing season. Cohort one had 20% more GDD and 40% more GDD than cohort three, however the growth rates were three times greater than cohort two and almost five times greater than cohort three by August 1st. Common waterhemp without competition, which emerged at planting date three, had a similar final volume to Palmer amaranth with competition, 0.23 m^3 and 0.25 m^3, respectively. At harvest, the solitary Palmer amaranth plant was about 2.8 times larger than either Palmer amaranth with intraspecific competition at planting date three or solitary common waterhemp that emerged at planting date three (Figure 3.11).

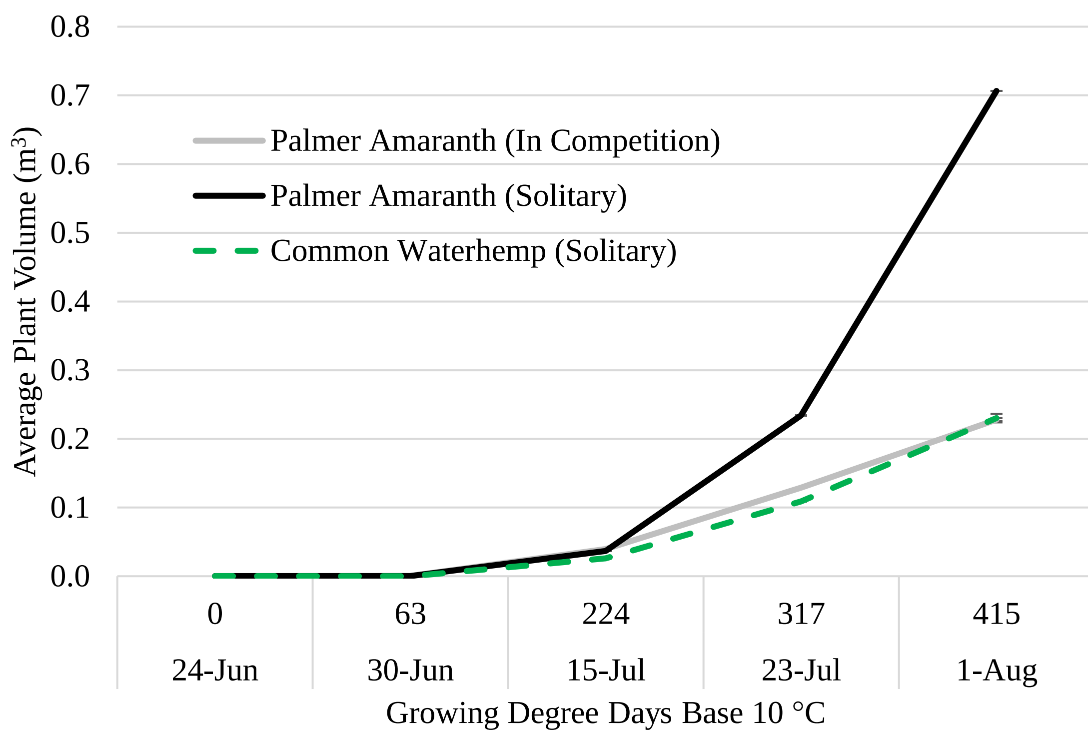


Figure 3.11. Growth rate comparison of Palmer amaranth with and without competition and common waterhemp for planting date three in 2015.

Biomass of each species by planting date is shown in Figure 3.12. A solitary female Palmer amaranth plant at planting date two (June 10, 2015) had the greatest biomass of 414.5 grams of dry matter, whereas the solitary male plant from planting date three was reduced by 83% (June 24, 2015). Lack of replication for the two solitary Palmer amaranth plants prevented further analysis. Palmer amaranth from planting date one had greater than three times more biomass (217.3 g $plant^{-1}$) than Palmer amaranth plants with intraspecific competition from planting date two and three (average of 72.9 and 52.2 g $plant^{-1}$, respectively). Biomass was similar between Palmer amaranth plants with intraspecific competition at planting date two and three. Solitary redroot pigweed and common waterhemp had similar biomass, although redroot pigweed had a longer growth period. Palmer amaranth grown in intraspecific competiton from planting date two and three were similar in biomass to the redroot pigweed and common waterhemp, although these were solitary plants, which was further supported by a t-test.

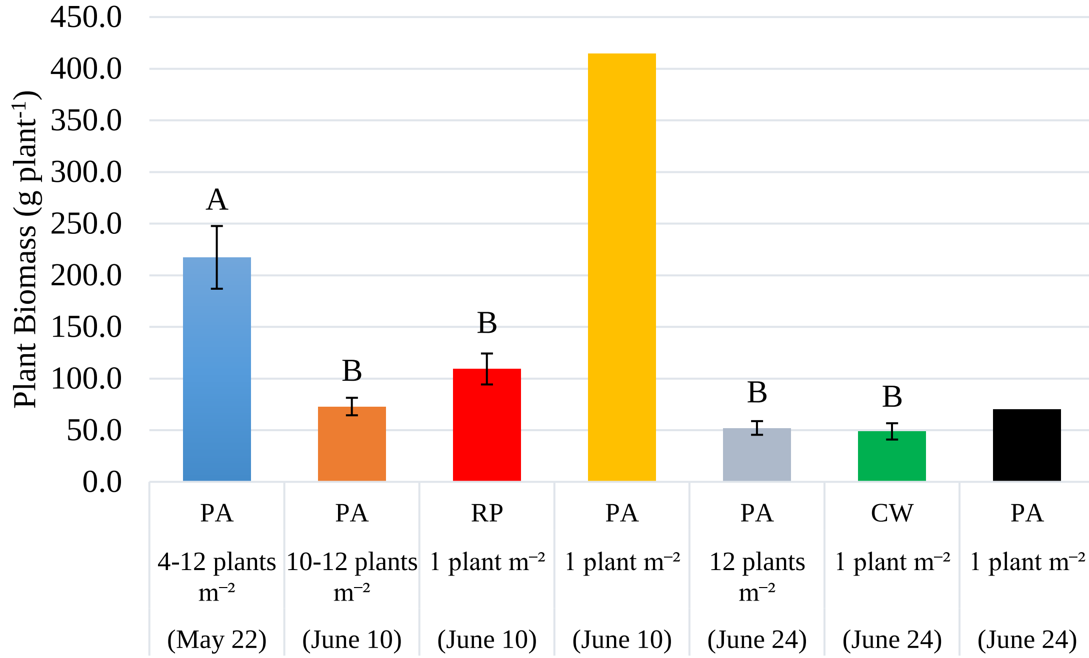


Figure 3.12. Biomass (g plant^{-1}) of Palmer amaranth (PA), redroot pigweed (RP), and common waterhemp (CW) for each planting date in 2015.

Amaranthus comparison studies (Aurora 2016)

The 2016 study data more accurately compares growth volumes among species due to similar densities for intraspecific competition. Plant harvest took place from July 25th to August 21st when Palmer amaranth plants had sufficient inflorescence growth to indicate gender. Due to this, Fisher's LSD becomes greater at later sampling dates from decreasing data points (plant measurements) during this time. Results of redroot pigweed and common waterhemp growth and plant volume (one and four plants m^{-2}) are reported and compared with Palmer amaranth planting date one (May 25, 2016) or three (June 24, 2016). Natural emergence timing for these two amaranth species coincided with these planting dates.

Growth rates of Palmer amaranth among planting dates and densities are reported on Figure 3.13. Male plants accounted for 47% of the Palmer amaranth population in 2016, and there was no gender influence on plant growth or biomass. Plant volume at each sampling date for planting date one (May 25, 2016) indicates that the growth of Palmer amaranth at both densities exceeded those of common waterhemp and redroot pigweed by July 16th (Table 3.6). During the same time, Palmer amaranth at one plant m^{-2} was three times larger than Palmer amaranth at four plants m^{-2} and was two times larger on August 2nd. Palmer amaranth at one plant m^{-2} between August 2nd and August 21st increased in volume by 472% to a final volume of 9.57 m^3 (Figure 3.14 and Table 3.6). Palmer amaranth grown at four plants m^{-2} in the same period increased in volume by 362% to a final volume of 3.29 m^3. Redroot pigweed, in contrast, had final volumes of 0.29 m^3 when planted at four plants m^{-2} and 0.13 m^3 when at a single plant m^{-2}. The high density common waterhemp had a final volume of 0.13 m^3, which was similar in volume to the solitary plants (0.04 m^3). These volumes were measured on July 25th. Both common waterhemp and redroot pigweed at planting date one were fully flowered by July 25th and were harvested along with several Palmer amaranth plants which had also initiated an inflorescence.

Planting date two cohort of Palmer amaranth had similar growth patterns between densities of one and four plants m^{-2} (Table 3.7). Plots with two plants m^{-2} had the greatest volume until the final sampling date, when all densities had similar volumes. Between August 2nd and August 21st Palmer amaranth at one, two, and four plants m^{-2} gained six, four, and three times more volume, respectively. Palmer amaranth at two plants m^{-2} had more growth by August 2nd than the one or four plants m^{-2} densities. At the August 21st harvest, two plants m^{-2} had the higher final volume of 5.62 m^3 (Table 3.7). After August 2nd, Palmer amaranth plots with an initial density of two plants m^{-2} had three plots with one plant m^{-2} and one with two plants m^{-2} whereas Palmer amaranth at an initial density of one plant m^{-2} had one plot harvested on July 25th, one on August 2nd, and two plots were harvested August 21st (due to lack of inflorescence). Palmer amaranth at four plants m^{-2} density had the lowest final volume of 2.56 m^3. Due to harvest upon inflorescence initiation, Palmer amaranth plots with an initial density of four plants m^{-2} was made up of three plots after August 2nd; one plot with two plants, one plot with three plants, and one with four plants.

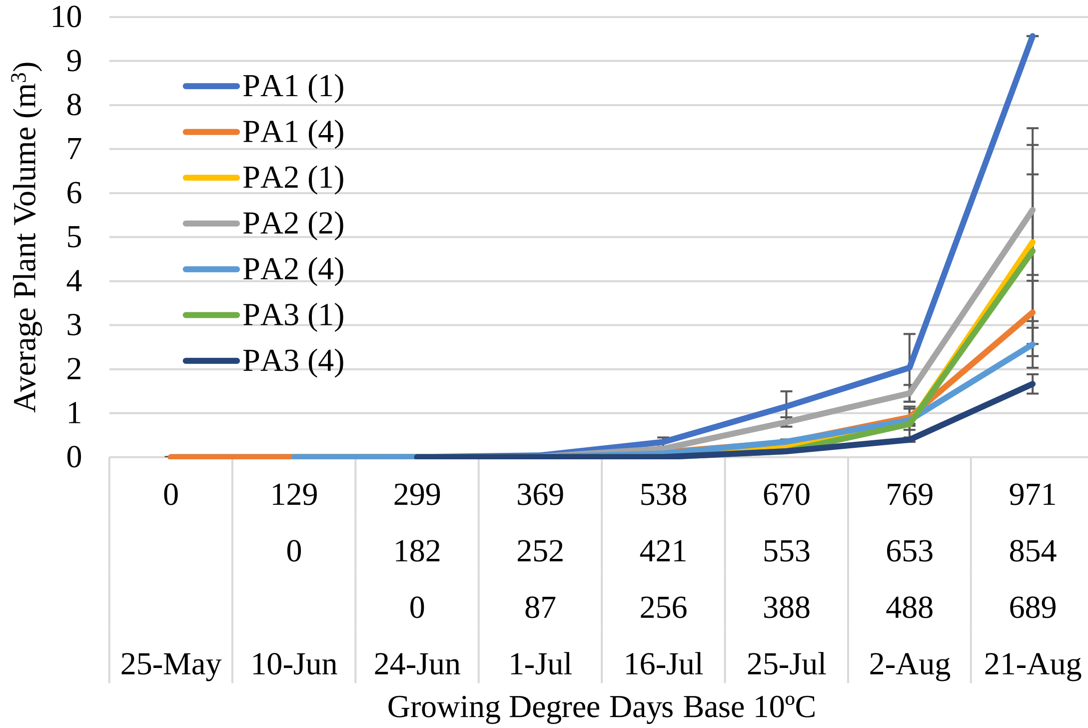


Figure 3.13. Growth rates of Palmer amaranth (PA) at each planting date (PA1=May 25, PA2=June 10, PA3=June 24) and initial density [(1), (2), or (4) plants m^{-2}] of each in 2016.

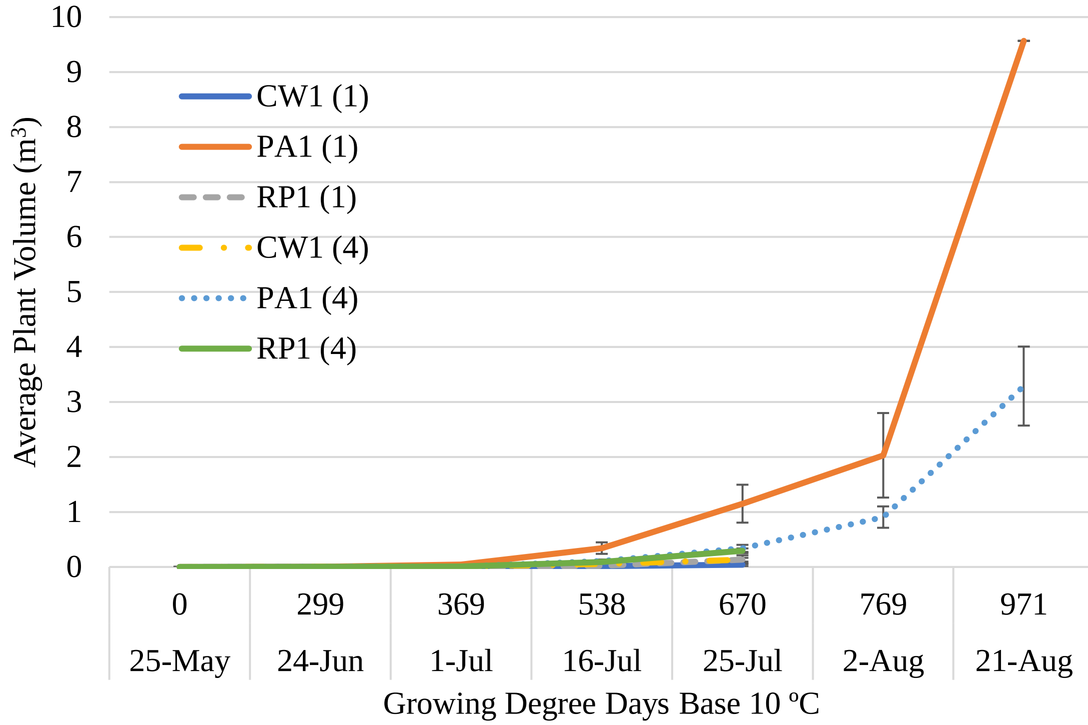


Figure 3.14. Growth rates of Palmer amaranth (PA1), common waterhemp (CW1), and redroot pigweed (RP1) from planting one (May 25) at each initial density [(1) or (4) plants m^{-2}] in 2016.

Table 3.6. Average plant volume comparison of Palmer amaranth, common waterhemp, and redroot pigweed at different densities from planting date one (May 25) in 2016.

Species	Density (plants m^{-2})	Growing Degree Days Base 10°C 299 24-Jun	369 1-Jul	538 16-Jul	670 25-Jul	769 2-Aug	971 21-Aug
		Volume (m^3 $plant^{-1}$)					
Palmer amaranth	1	0.0037 a*	0.0418 a	0.34 a	1.15 a	2.03 a	9.57 a
Common waterhemp	1	0.0012 bc	0.0021 b	0.01 c	0.04 c	--†	--
Redroot pigweed	1	0.0029 ab	0.0034 b	0.02 bc	0.13 c	--	--
Palmer amaranth	4	0.0006 c	0.0076 b	0.11 b	0.34 b	0.91 b	3.29 b
Common waterhemp	4	0.0033 a	0.0086 b	0.06 bc	0.13 c	--	--
Redroot pigweed	4	0.0036 a	0.0113 b	0.09 bc	0.29 bc	--	--

* Means followed by different letters are significantly different at $P<0.05$ in each column

† All plants were previously harvested

Table 3.7. Average plant volume comparison of Palmer amaranth at different densities for planting date two (June 10) in 2016.

Density (plants m^{-2})	---------------------Growing Degree Days Base 10°C---------------------					
	182	252	421	553	653	854
	24-Jun	1-Jul	16-Jul	25-Jul	2-Aug	21-Aug
	----------------------------Volume (m^3 $plant^{-1}$)----------------------------					
1	0.0002 a*	0.0022 b	0.06 b	0.27 b	0.75 b	4.89 a
2	0.0003 a	0.0086 a	0.19 a	0.80 a	1.45 a	5.62 a
4	0.0003 a	0.0033 b	0.07 b	0.35 b	0.84 b	2.56 a

*Means followed by different letters are significantly different at P<0.05 in each column

In planting date three (June 24), growth rates increased in late July for Palmer amaranth at both densities (Figure 3.15). Highest growth rates were observed after August 2nd when Palmer at one plant m^{-2} increased in volume by 567% to a final volume of 4.30 m^3 and Palmer at four plants m^{-2} increased in volume by 424% to 1.57 m^3 (Table 3.8). No Palmer amaranth was harvested before August 21st at the low density (one plant m^{-2}). Palmer amaranth plots after August 2nd with an initial density of four plants m^{-2} had final densities of two (one plot), three (one plot), and four (two plots) plants m^{-2}. Common waterhemp and redroot pigweed growth rates were significantly less than that of Palmer over both densities. Growth of common waterhemp and redroot pigweed did not accelerate until early August. Common waterhemp final volume was similar for both densities and higher than redroot pigweed. Redroot pigweed had a 25% difference in final volume between one and four plants m^{-2}.

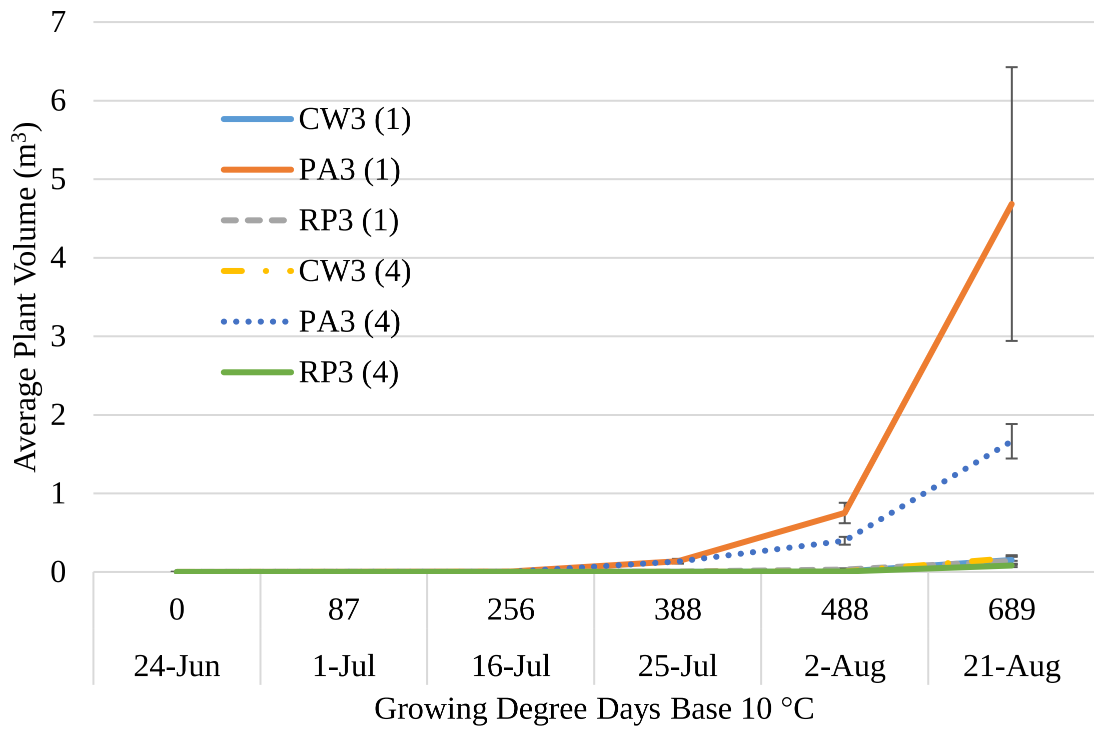


Figure 3.15. Growth rates of Palmer amaranth (PA3), common waterhemp (CW3), and redroot pigweed (RP3) for planting date three (June 24, 2016) at each initial density [(1) or (4) plants m^{-2}] in 2016.

Table 3.8. Average plant volume comparison of Palmer amaranth, common waterhemp, and redroot pigweed at different densities at planting date three (June 24) in 2016.

		Growing Degree Days Base 10°C					
	Density	0	87	256	388	488	689
Species	(plants m^{-2})	24-Jun	1-Jul	16-Jul	25-Jul	2-Aug	21-Aug
		Volume (m^3 $plant^{-1}$)					
Palmer amaranth	1	6.28E-06 a*	3.40E-05 a	6.14E-03 a	0.14 a	0.75 a	4.68 a
Common waterhemp	1	--†	--	--	<0.01 b	<0.01 c	0.15 c
Redroot pigweed	1	--	--	--	<0.01 b	0.03 c	0.14 c
Palmer amaranth	4	6.28E-06 a	4.21E-05 a	4.02E-03 a	0.13 a	0.40 b	1.66 b
Common waterhemp	4	--	--	--	<0.01 b	<0.01 c	0.18 c
Redroot pigweed	4	--	--	--	<0.01 b	<0.01 c	0.08 c

*Means followed by different letters are significantly different at P<0.05

†Plots of common waterhemp and redroot pigweed were July 25 to ensure measurement of proper species

Comparing all plantings and densities of Palmer amaranth, planting date one at one plant m^{-2} had the greatest volume per plant of 9.57 m^3 (Table 3.9) whereas planting date three at four plants m^{-2} had the lowest volume per plant of 1.66 m^3. Later planting had a negative effect on final volume across like densities. Plantings at dates two and three at one plant m^{-2} had the closest final volumes of 4.89 m^3 and 4.68 m^3, respectively. Density had a negative impact on volume in plantings one and three, however, at planting date two the highest volume was 5.62 m^3 per plant for two plants m^{-2} was similar to 4.89 m^3 per plant at one plant m^{-2}. Growth rates started differentiating in early July with the largest differences observed by August 2. Uscanga Mortera (2004) reported that common waterhemp and redroot pigweed plant growth was reduced due to later planting dates.

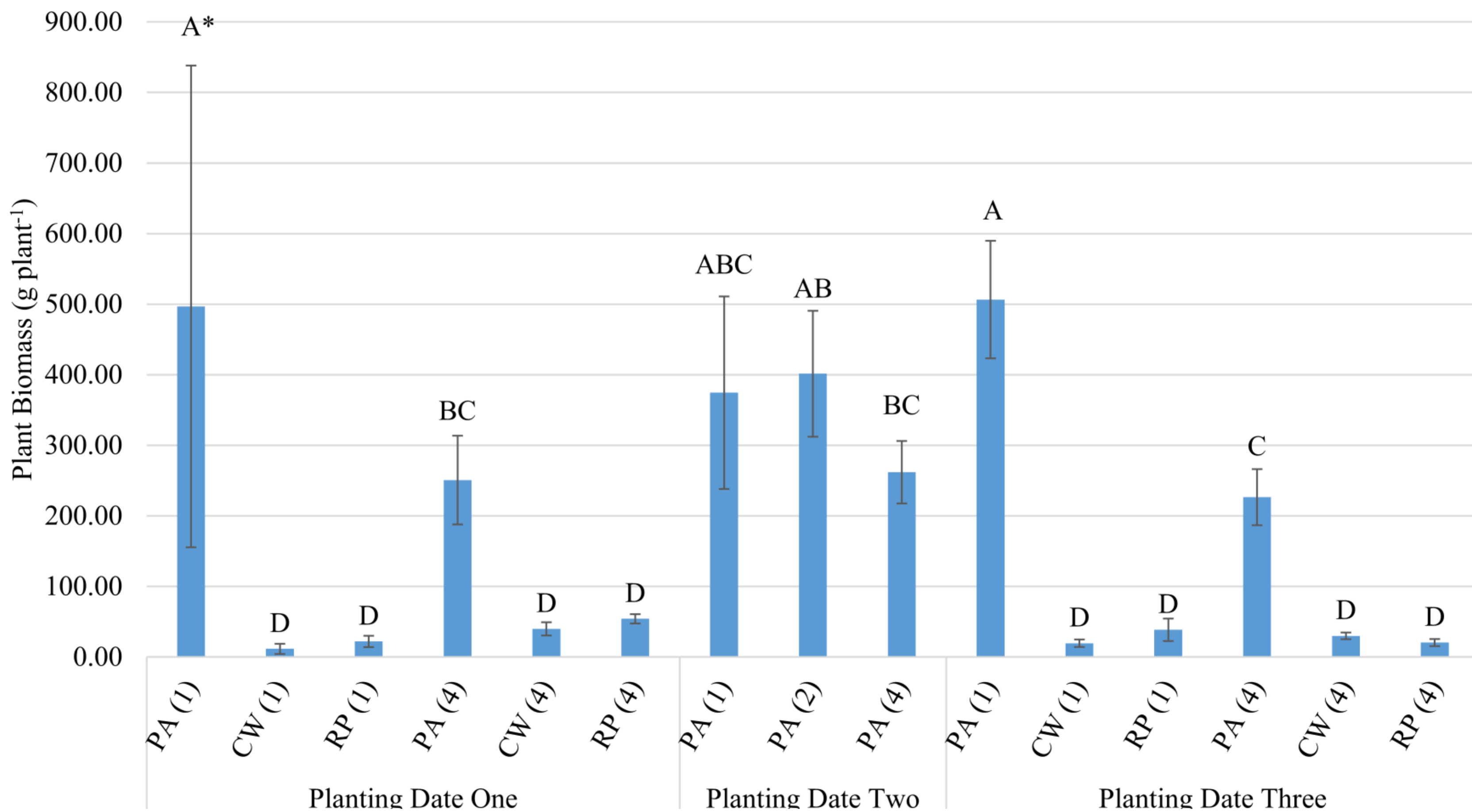
Biomass per plant (Figure 3.16) indicates that Palmer amaranth from the third planting at a density of 1 plant m^{-2} [PA3 (1)] had the largest average weight. However, PA1 (1), PA2 (1), and PA2 (2) were similar. Common waterhemp and redroot pigweed at each planting and density were not significantly different from each other, yet were much lower than any of the Palmer amaranth biomasses. Average biomass of Palmer amaranth at four plants m^{-2} was similar to plants grown in 2015 (about 250 g $plant^{-1}$). Palmer amaranth biomass in 2015 (10-12 plants m^{-2}) was about 200 g $plant^{-1}$ less than 2016 (four plants m^{-2}) at planting date two. Similar results were seen at planting date three between 2015 and 2016. Common waterhemp and redroot pigweed biomass was about 25 and 50 g $plant^{-1}$ greater in 2015 than 2016, respectively. These data support the findings by Puo and Al-Khatib (2003) who reported that Palmer amaranth grown in temperatures between 20 and 35 °C.

Table 3.9. Average plant volume comparison of Palmer amaranth among each planting and density in 2016.

	Date of Plant/Transplant	Density (plants m^{-2})	24-Jun	1-Jul	16-Jul	25-Jul	2-Aug	21-Aug
			Corn Growth Stage†					
			V5	V6	V12	R1	R2	R3
	Growing Degree Days Base 10 °C		299	369	538	670	769	971
			Volume (m^3 $plant^{-1}$)					
Planting Date One	10-May/25-May	1	0.0037 a*	0.0418 a	0.3428 a	1.15 a	2.03 a	9.57 a
		4	0.0006 b	0.0076 b	0.1103 c	0.34 c	0.91 b	3.29 bcd
	Growing Degree Days Base 10 °C		182	252	421	553	653	854
Planting Date Two	25-May/10-Jun	1	0.0002 bc	0.0022 bc	0.0628 cde	0.27 cd	0.75 bc	4.89 abc
		2	0.0003 bc	0.0086 b	0.1894 b	0.80 b	1.45 a	5.62 ab
		4	0.0003 bc	0.0033 bc	0.0670 cd	0.35 c	0.84 b	2.56 cd
	Growing Degree Days Base 10 °C		0	87	256	388	488	689
Planting Date Three	10-Jun/24-Jun	1	6.28E-06 c	3.40E-05 c	0.0061 de	0.14 cd	0.75 bc	4.68 bc
		4	6.28E-06 c	4.21E-05 c	0.0040 e	0.13 d	0.40 c	1.66 d

*Means followed by different letters are significantly different at $P<0.05$ in each column

†Corn growth stage is approximated and may vary over years, production environments, and locations



*Bars with different letters are significantly different at P<0.05

Figure 3.16. Biomass comparison of Palmer amaranth (PA), common waterhemp (CW), and redroot pigweed (RP) by planting date (May 25, June 10, June 24) and density [(1), (2), or (4) plants m^{-2}] in 2016.

Location study 2016

Seeds from different source locations were all planted in the field on June 10, 2016. Inflorescence was initiated by July 16th (Table 3.10) for all locations except for plants from seed from Manhattan, KS (July 25th). Inflorescence of plants from seed from Columbia, MO was initiated by July 16th, which included at least 50% of the Palmer amaranth plants associated with this location. Plants from seed from Manhattan, KS also experienced a narrow window of inflorescence initiation several days later (July 25th). Plants from seed from Fayetteville, AR, Las Cruces, NM, and Urbana, IL also had half of Palmer amaranth plants flower by July 25th, however inflorescence initiation took place slightly before July 16th. The number of Palmer amaranth plants that flowered reached 50% by August 2nd for plants from seed from Corsica, SD. Male inflorescence was initiated sooner and faster than female inflorescence. Some female plants initiated flowering quickly as well, however male plants were usually favored for earlier inflorescence.

Variances in plant volume measurements may be associated with the harvest period from July 25th to August 21st. Palmer amaranth from Columbia, MO had the highest final volume of 6.84 m^3 followed by Corsica, SD at 4.21 m^3 (Table 3.11). Differentiation of location accessions were observed soon after planting but were markedly different starting in late July. Manhattan, KS and Jenkins, GA displayed the most similar growth rate and final volume, 3.56 m^3 and 3.36 m^3, respectively.

Table 3.10. Dates of initial inflorescence noted in 2016 for male and female plants and number of plants of each that were flowering.

	Male Plants				Female Plants			
		Initial Inflorescence				Initial Inflorescence		
Source	Total Plants	% Flowered (#)	Date	Acc GDD*	Total Plants	% Flowered (#)	Date	Acc GDD
Columbia, MO	2	100 (2)	16-Jul	421	6	83 (5)	16-Jul	421
Corsica, SD	2	50 (1)	16-Jul	421	6	17 (1)	25-Jul	553
Fayetteville, AR	4	25 (1)	16-Jul	421	4	75 (3)	25-Jul	553
Jenkins, GA	3	33 (1)	16-Jul	421	5	20 (1)	25-Jul	553
Las Cruces, NM	4	75 (3)	16-Jul	421	4	25 (1)	25-Jul	553
Urbana, IL	4	75 (3)	16-Jul	421	4	100 (4)	25-Jul	553
Manhattan, KS	4	50 (2)	25-Jul	553	4	50 (2)	25-Jul	553

*Acc GDD is Accumulated Growing Degrees base 10 °C

Table 3.11. Average plant volume comparison of Palmer amaranth planted June 10th from different seed source locations in 2016.

Initial Seed Source Location	Growing Degree Days Base 10°C 182 24-Jun	252 1-Jul	421 16-Jul	553 25-Jul	653 2-Aug	854 21-Aug
	Volume (m^3)					
Columbia, MO	<0.0006 a*	0.0054 abc	0.15 abc	0.72 ab	1.66 a	6.84 a
Corsica, SD	<0.0006 a	0.0086 a	0.19 a	0.80 a	1.45 a	4.21 b
Fayetteville, AR	<0.0006 a	0.0049 bc	0.13 abc	0.67 ab	1.20 a	1.98 cd
Jenkins, GA	<0.0006 a	0.0035 bc	0.08 cd	0.54 b	1.16 a	3.37 bc
Las Cruces, NM	<0.0006 a	0.0020 c	0.04 d	0.30 c	0.47 b	1.17 d
Manhattan, KS	<0.0006 a	0.0040 bc	0.11 bc	0.57 ab	1.19 a	3.56 bc
Urbana, IL	<0.0006 a	0.0066 ab	0.16 ab	0.67 ab	1.68 a	--†

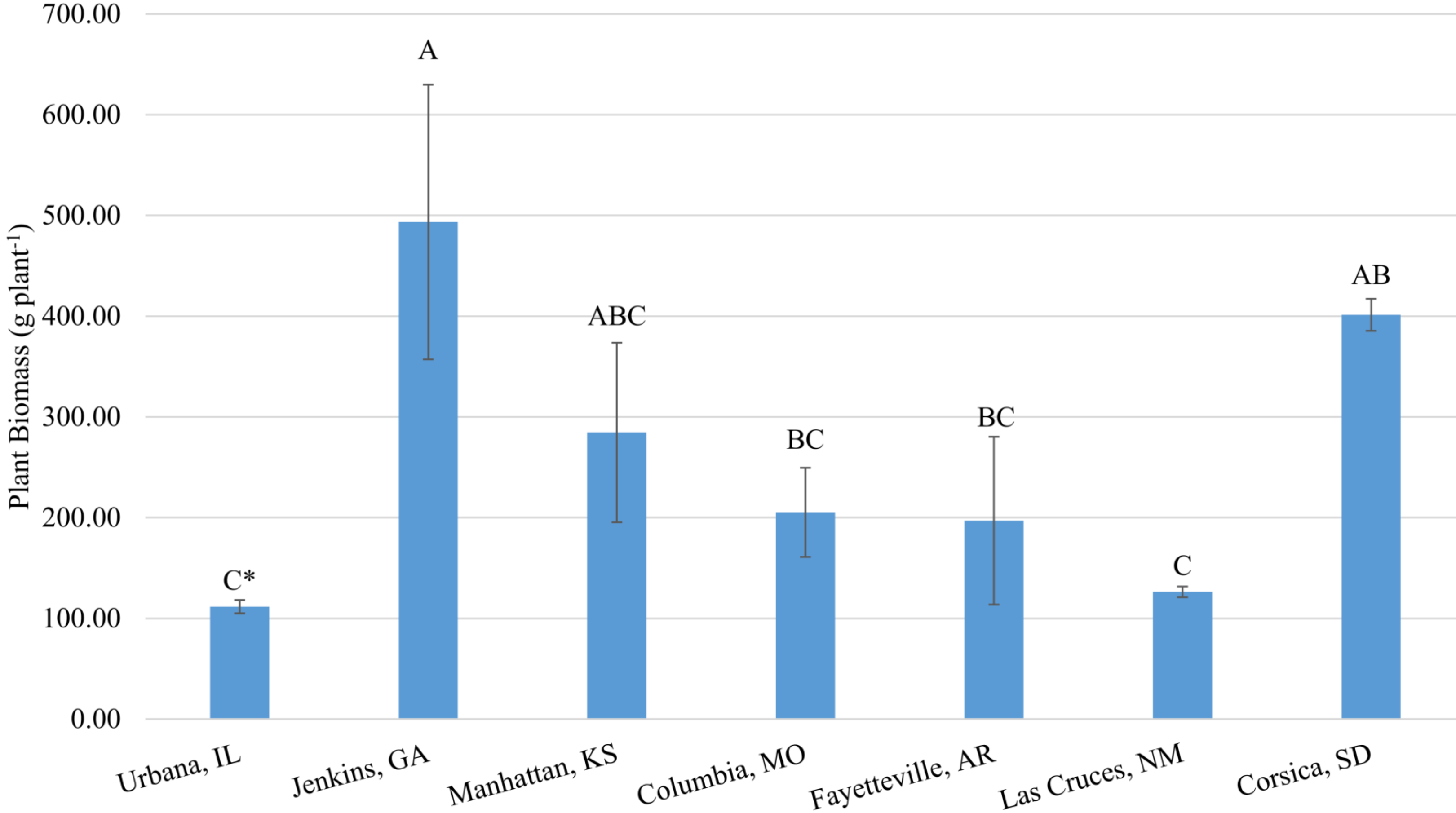
* Means followed by different letters are significantly different at $P<0.05$ in each column

† All plants previously harvested

From the data in Figure 3.17, the biotype from Missouri was similar to the Corsica biotype in biomass (205 and 401 g $plant^{-1}$, respectively). However, the Georgia biotype had a biomass of 493.50 grams, which was similar to Corsica, but larger than Missouri. Other biotypes from seed source locations that experience shorter daylength may have been able to take advantage the longer daylight in Brookings, SD, resulting in a larger plant volume and greater biomass. This does not hold true for biotypes such as those from Las Cruces, NM, which had one of the lowest average plant volume and smallest biomass.

From these data, it could be assumed that biotypes from Missouri may pose the largest threat to South Dakota soybean production in terms of overall plant growth and volume. Average growing degree days from June through August (Columbia, MO 1981-2010) averaged 1,390 accumulated growing degree days (Table 3.12). Brookings, SD averaged 926 accumulated growing degree days during this same period. In 2016, Brookings reported 1,036 growing degree days. Biotypes from Georgia had the largest average biomass, which may also be extremely competitive in South Dakota in crops such as soybeans. Palmer amaranth seed from all other source locations are subjected to more heat units than when grown in South Dakota, which does not adequately explain the ranking of Palmer amaranth volume of plants from seed sources with warmer climates.

A daylight comparison of 30-year averages (1981-2010) between Brookings, SD on June 10th, July 1st, and August 21st and seed source locations is shown in Table 3.13. The larger percentage of flower initiation may also be attributed to daylight length as well. Corsica, SD seed source location has the longest hours of daylight followed by a faster decrease in daylength. Plants from seed from this location also took longer from initial inflorescence to inflorescence on 50% of the plants. It is possible that plants from seed from other source locations were more affected by the daylength change, which was reflected in inflorescence timing. However, Jenkins, GA (Midville, GA station) had one of the shortest daylength and smallest change and required the same amount of time from initial inflorescence to inflorescence on at least 50% of the plants as Corsica, SD. Overall growth may be attributed to seed source location, however biotype fitness and flexibility may have a larger impact. Seeds from these locations may not have been present in each area for long enough to fully adapt to environmental conditions. Previous seed may have come from other geographical locations with different environmental conditions. Plants in Corsica, SD are thought to have come from a southern state, most likely Texas, which may also explain some of the similarities in growth to biotypes from other sources. These data are from one year and should be replicated to provide more insight into differences that may occur by accession with a single location and grown in a common garden.



*Bars with different letters are significantly different at $P<0.05$

Figure 3.17. Comparison of Palmer amaranth biomass started from seed collected from each location in 2016.

Table 3.12. Growing degree days (base 10 °C) and average monthly temperature (°C) in 2016 at Brookings, SD and 30-year average (1981-2010) at Brookings and closest reporting weather stations to initial seed source locations.

		------GDD Base 10 °C------				--Average Temp. (°C)--		
		Jun	Jul	Aug	Total	Jun	Jul	Aug
2016 →	Brookings, SD	324	383	329	1036	21.3	21.6	20.9
-----30 Year Average (1981-2010)-----	Brookings, SD	262	351	314	926	18.7	21.3	20.1
	Parkston, SD	310	416	383	1109	21.1	24.4	22.2
	Champaign, IL	370	429	403	1202	22.3	23.8	23.0
	Columbia, MO	409	503	478	1390	23.6	26.2	25.4
	Fayetteville, AR	402	499	491	1392	23.4	26.1	25.8
	Las Cruces, NM	427	500	467	1394	24.2	26.2	25.1
	Manhattan, KS	409	515	482	1406	23.7	26.6	25.6
	Midville, GA	472	533	514	1519	25.7	27.2	26.6

Table 3.13. Hours and minutes of daylight near initial seed source locations at select dates and daylight change.

Location	10-Jun	1-Jul	21-Aug	Daylight Change 1-Jul to 21-Aug
Brookings, SD	15:28*	15:28	13:45	-1:43
Parkston, SD	15:21	15:21	13:42	-1:39
Champaign, IL	14:58	14:58	13:31	-1:27
Columbia, MO	14:51	14:51	13:27	-1:24
Fayetteville, AR	14:34	14:34	13:19	-1:15
Las Cruces, NM	14:14	14:14	13:09	-1:05
Manhattan, KS	14:52	14:53	13:28	-1:25
Midville, GA	14:16	14:17	13:11	-1:06

*Expressed as hours:minutes of daylight

<u>Greenhouse herbicide study</u>

Table 3.14 describes the percentage of Palmer amaranth control for each treatment in both trials. Atrazine, glyphosate, and thifensulfuron had little effect , 0-25%, 60%, and 0% control, respectively, in both studies on Palmer amaranth control while S-metolachlor (85-95% in potting mix and 95-100% in sand), dicamba (90-100%), and glufosinate (90%) exhibited the greatest control of Palmer amaranth. Control of Palmer was greater when pre-emergence herbicides (atrazine and S-metolachlor) were applied to sand. Potting mix contains more organic matter than sand, which has the potential to bind with certain herbicides and reduce herbicide activity. Atrazine over sand had 10% more control and S-metolachlor gained 5% and 10% more control in sand in trial one and two, respectively. Figure 3.18 illustrates atrazine pre- and pre- plus post-emergence control ratings of Palmer amaranth compared to control plants. Control of Palmer amaranth from a post-emergence application of dicamba is shown in Figure 3.19. Trial two contained plants at heights of 5- to 10-cm and 10- to 20-cm due to variability in plant height despite a similar growth stage (three to four true leaves), however no differences in control were seen among height ranges. Post-emergence herbicide applications are typically made at or before the three to four true leaf stage or before a weed exceeds 10 cm for optimum control. Herbicide application based on growth stage may be more effective than weed height, however more studies should be performed.

Mesotrione applied post-emergence had variable control between trial one (90%) and trial two (40%). Mesotrione inhibits carotenoids, which increases free radicals in the plant. An excess of free radicals causes destruction of plant tissue such as chlorophyll (Skelton, 2012). This produces the white, “bleached” appearance symptomology. Control of Palmer amaranth varied, although to a lesser extent, among other greenhouse studies as well with a similar rate of mesotrione (105 g ai ha^{-1}). Chahal et al. (2017) reported Palmer amaranth control of 44 and 54% 7 and 21 days after treatment, respectively. A study by Jhala et al. (2014) reported 85 to 90% (experiment one) and 99% (experiment two) control of HPPD-susceptible Palmer amaranth and 58 and 66% control of HPPD-resistant Palmer amaranth in experiment one and two, respectively. Palmer amaranth control of ≥79% in glyphosate-resistant and glyphosate-susceptible plants was reported by Norsworthy et al. (2008).

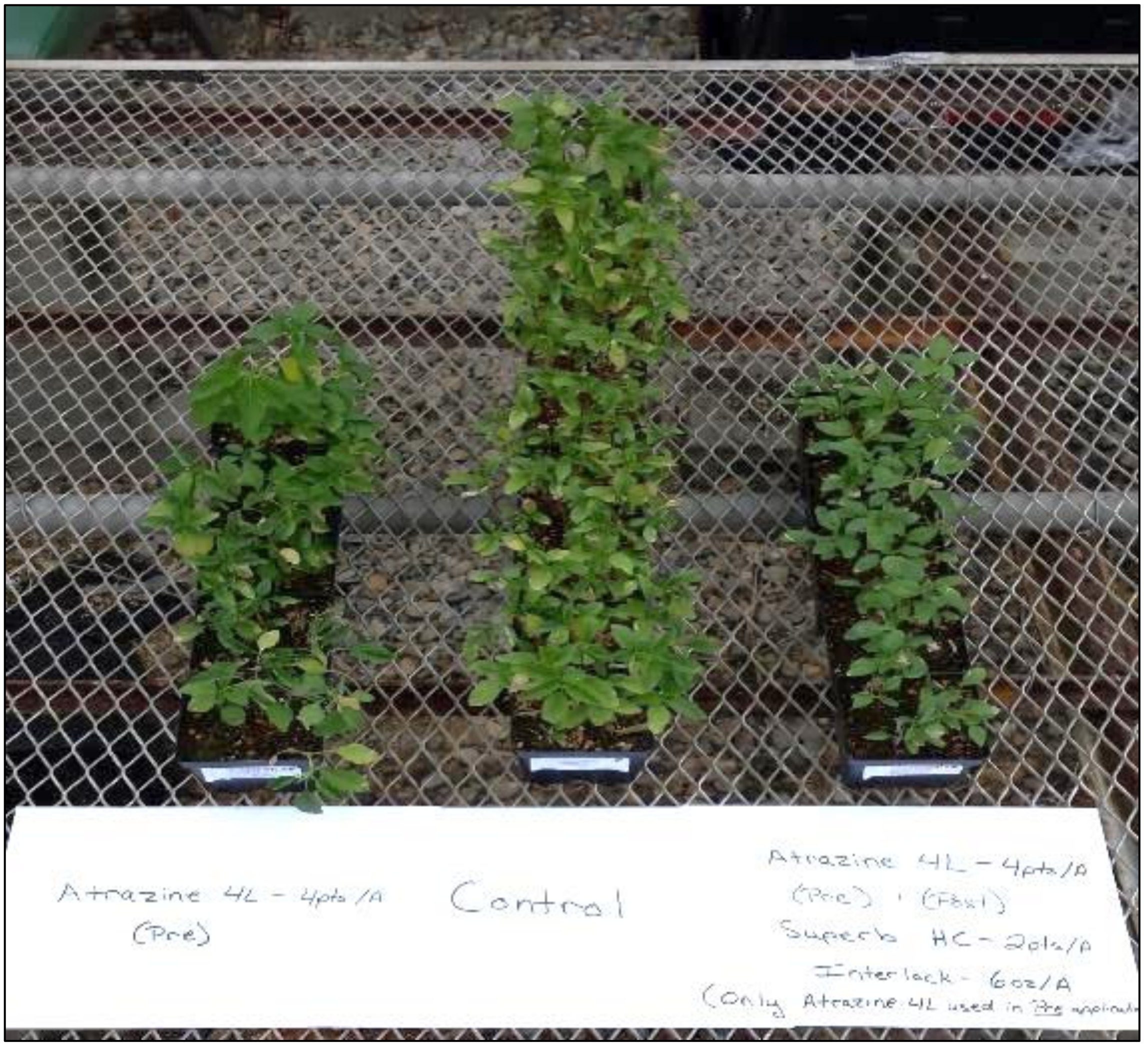


Figure 3.18. Palmer amaranth 21 days after atrazine herbicide application [left (0% control) and right (25% control)] compared to control plants (center).

Figure 3.19. Palmer amaranth 21 days after dicamba application [left (100% control)] compared to control plants (right).

Palmer amaranth control was equal to or less on all treatments in the second trial from each herbicide. During trial two, inflorescence was initiated despite a 12-hour day/night light cycle. This initiation of reproductive structures may have hindered herbicide efficacy. Herbicides are most effective on small plants and decreases in efficacy as plants grow larger and start to flower.

The seed source (Corsica, SD) of the Palmer amaranth used in this study reflects a strong resistance to atrazine and thifensulfuron, a mild level of resistance to glyphosate as well as mesotrione. The infestation in Corsica, SD was thought to derive from a southern state when swine was brought in and the trailer was washed out afterwards. The washout was then spread where the infestations now occur. Glyphosate resistance has been reported in many states around the US such as Kansas, Texas, Nebraska, Missouri, Florida, Arkansas, and Arizona. Cases of resistance to thifensulfuron have been reported in Kansas, South Carolina, and Wisconsin. Mesotrione resistance was reported in Nebraska and Kansas (Heap, 2017). Resistance to atrazine has also developed in Texas, Kansas, Georgia, and Nebraska. These cases of resistance support the theory of Palmer amaranth spread from a southern state to Corsica, SD.

Table 3.14. Palmer amaranth control percentages for each herbicide treatment in both trials.

			----Percent Control----	
Herbicide	Application	Soil Type	Study 1	Study 2
Check		Sand	0	0
		Potting Mix	0	0
Atrazine	Pre	Sand	10	10
	Pre & Post	Potting Mix	25	0
	Pre	Potting Mix	0	0
	Post	Potting Mix	25	0
Dicamba	Post	Potting Mix	100	90
Glufosinate	Post	Potting Mix	90	90
Glyphosate	Post	Potting Mix	60	60
Mesotrione	Post	Potting Mix	90	40
S-metolachlor	Pre	Sand	100	95
	Pre	Potting Mix	95	85
Thifensulfuron	Post	Potting Mix	0	0

Soybean yield study

In 2016, changes in Palmer amaranth density explained 65% of the change in soybean yield. The effect of Palmer amaranth density on soybean yield loss was fit to rectangular hyperbolic yield-loss function (Cousens, 1985). Incremental yield loss was determined to be 9% (I), whereas maximum predicted yield loss (A) was 35% (Figure 3.20). Davis et al. (2015) reported yield losses of 2 to 30% at 8 plants m^{-2}, which was similar to what was found in 2016. Figure 3.21 illustrates the yield loss of soybeans at the total Palmer amaranth biomass m^{-2} for each plot. The polynomial trendline indicates that soybean yield loss increased as the total biomass of Palmer amaranth increased in a linear fashion. The rate of yield loss decreased after Palmer amaranth biomass reached about 350 g m^{-2}.

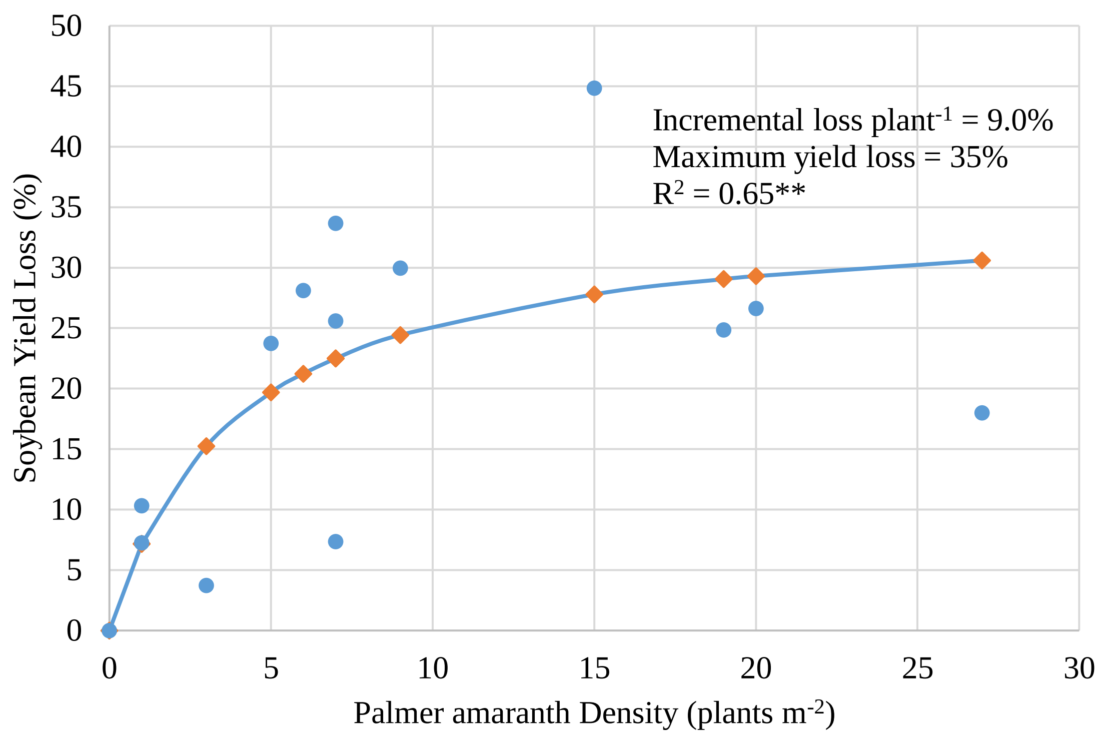


Figure 3.20. Soybean yield loss prediction (Cousens, 1985) from Palmer amaranth density in 2016.

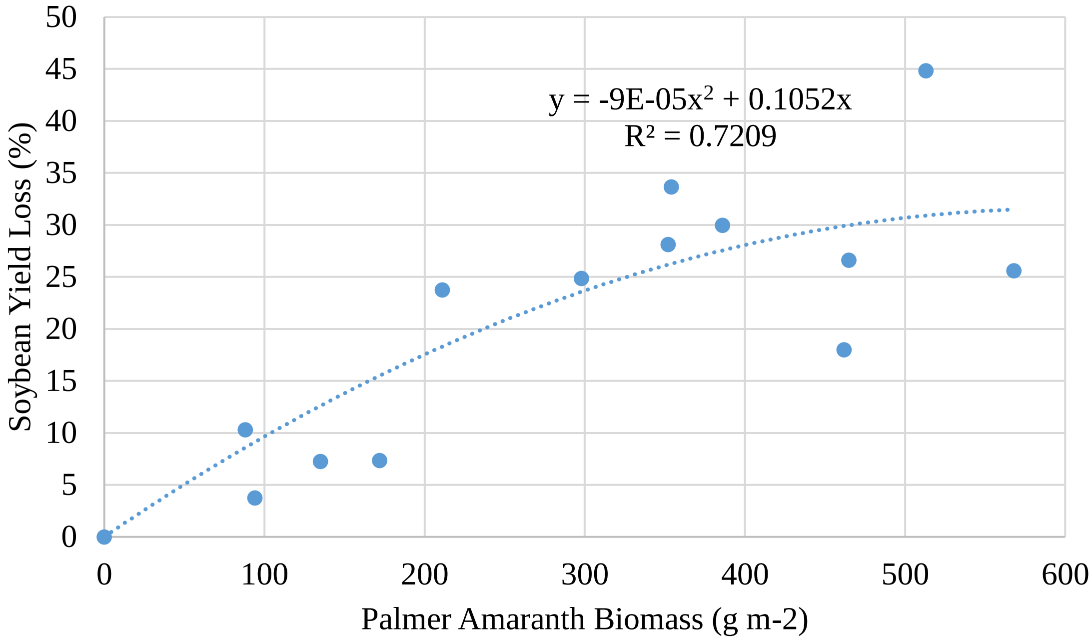


Figure 3.21. Soybean yield loss by Palmer amaranth total biomass m^{-2} in 2016.

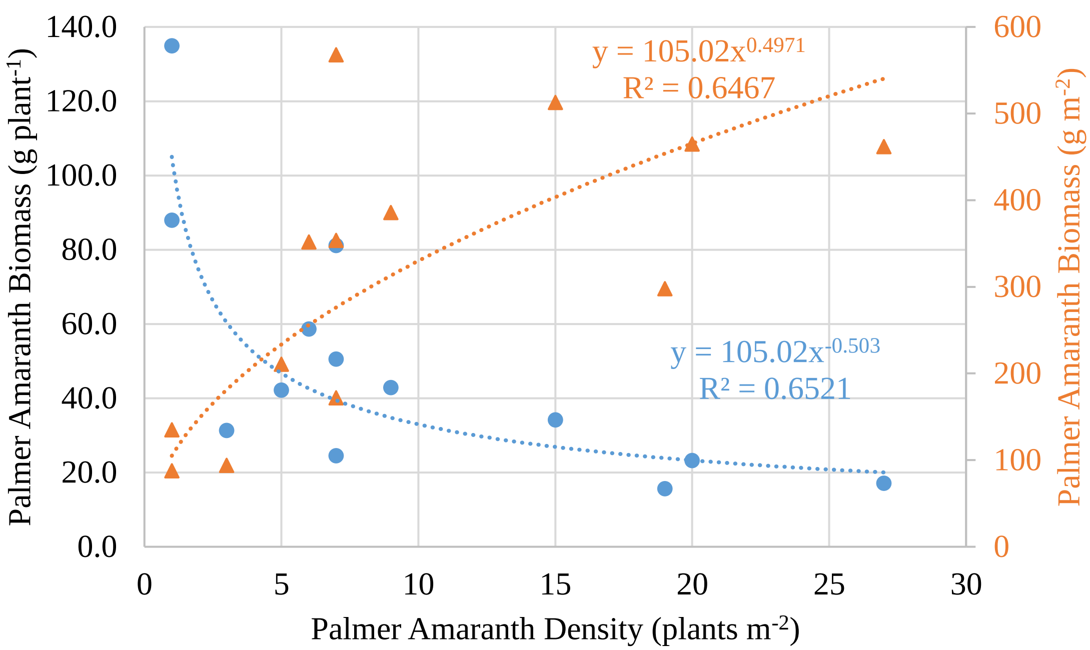


Figure 3.22. Palmer amaranth individual and total biomass by density in 2016.

As the density increased, individual weight of Palmer amaranth decreased while total biomass per plot (m^2) increased (Figure 3.22). Power trendlines describe predicted values for each data set. Individual weight sharply decreased when Palmer amaranth density was greater than one plant m^{-2} and predicted values followed a more linear trend above 10 plants m^{-2}. Total Palmer amaranth biomass showed a similar trend in predicted values, although the overall trend was increasing with Palmer amaranth density.

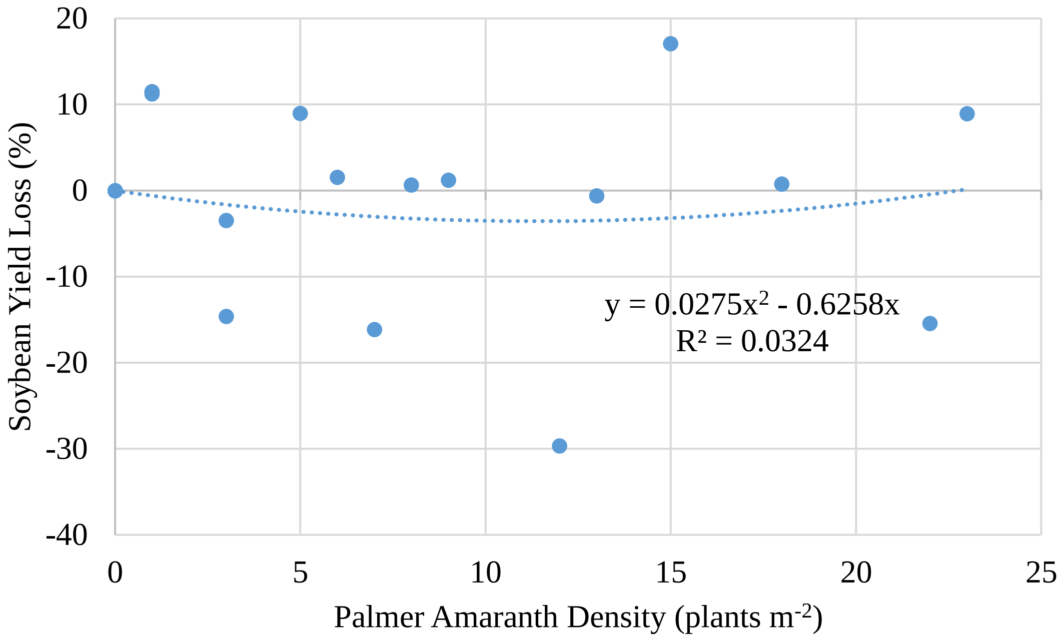


Figure 3.23. Soybean yield loss by Palmer amaranth density in 2017.

Results in 2017 showed a great amount of variation in soybean yield due to Palmer amaranth density. There was no significant relationship between soybean yield and Palmer amaranth density (Figure 3.23). Change in palmer amaranth density did not adequately explain the change in soybean yield loss (R^2=0.05). This may elude to factors which affected soybean yield that were not able to be measured.

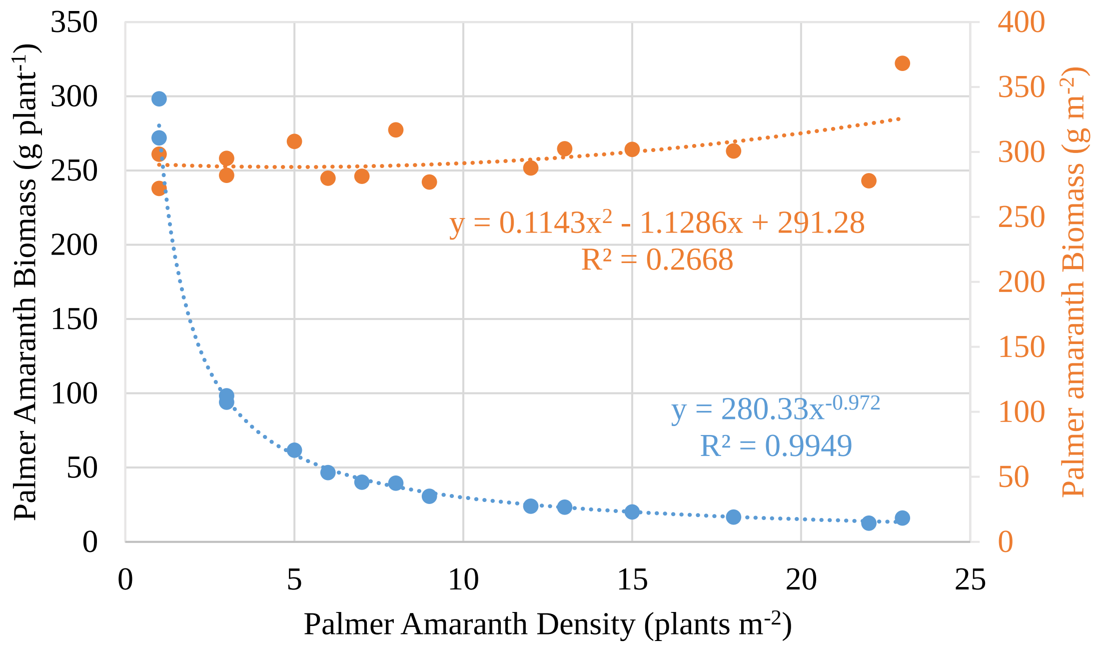


Figure 3.24. Palmer amaranth individual and total biomass by density in 2017.

Figure 3.24 shows a relationship between average Palmer amaranth biomass and density as well as total biomass and density. Average biomass sharply decreases as density increases above one plant m^{-2} (275 g $plant^{-1}$) to an average biomass of 100 g $plant^{-1}$ at three plants m^{-2}. Decrease in individual biomass becomes less pronounced higher than 10 plants m^{-2}. Total Palmer amaranth biomass per plot maintained a trendline that increased slightly as density increased in a more linear fashion. Predicted values were 250 g m^{-2} at one plant m^{-2} to 275 g m^{-2} at 23 plants m^{-2}. Soybean yield loss cannot be predicted by Palmer amaranth individual or total biomass (Figures 3.25 and 3.26) despite the trendlines illustrated by Figure 3.24.

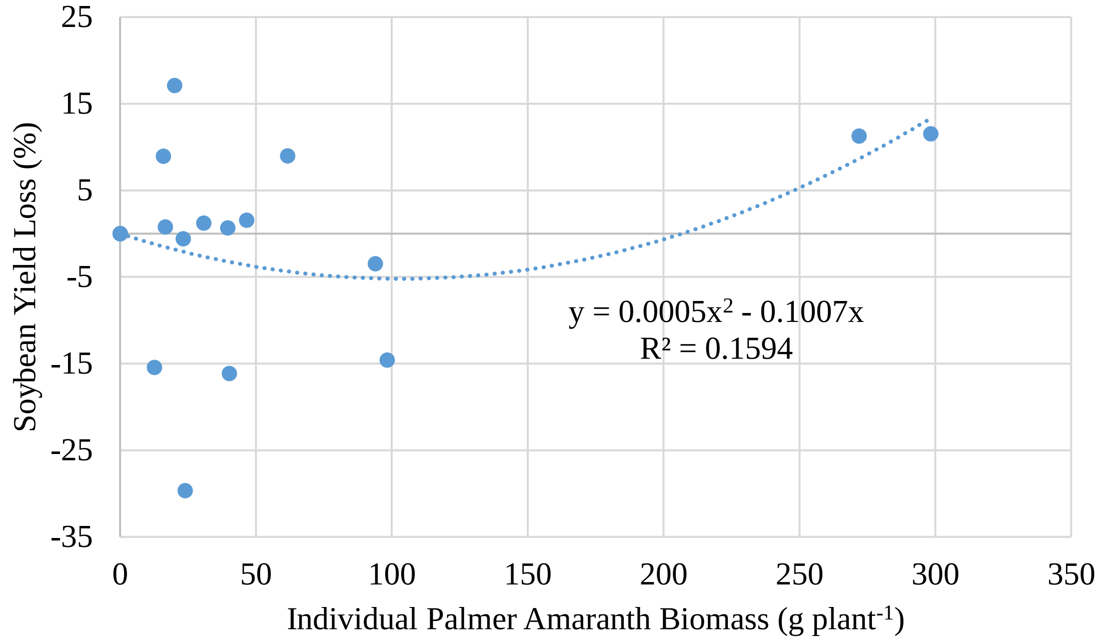


Figure 3.25. Soybean yield loss by individual Palmer amaranth biomass in 2017.

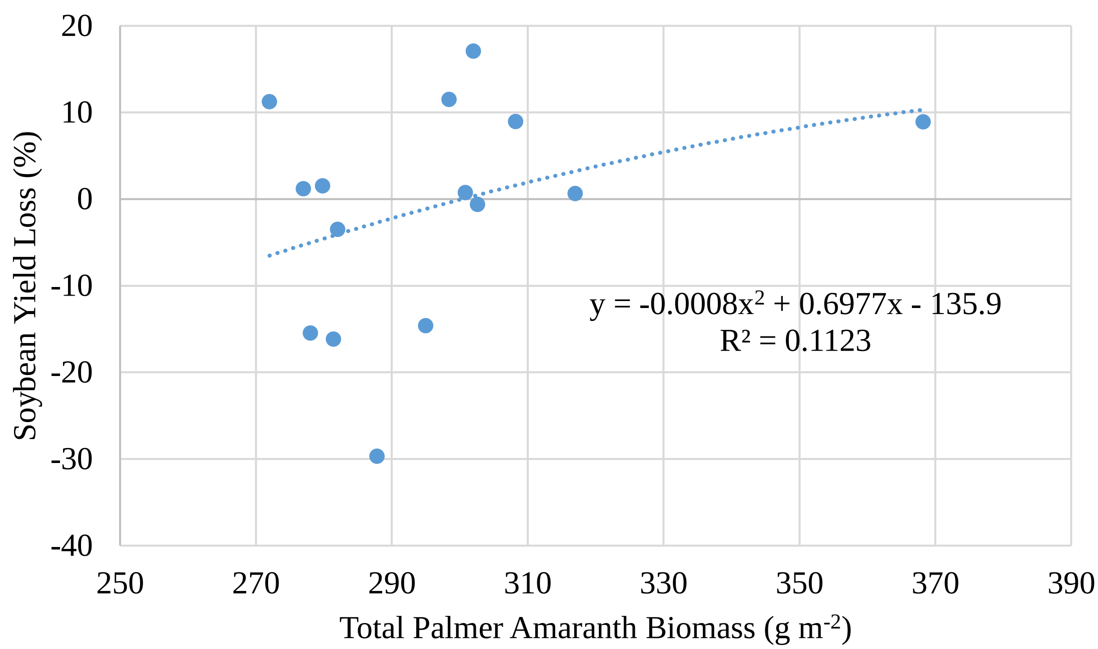


Figure 3.26. Soybean yield loss by total Palmer amaranth biomass.

Studies for both years were performed in the same area of the same field (Figure 3.27). Average soybean yield in weed-free plots was 3,792 kg ha^{-1} and 2,484 kg ha^{-1} for 2016 and 2017, respectively. Table 3.15 shows Palmer amaranth density, biomass, and soybean yield in 2016 and 2017. Extend soybeans were planted in 2017 and were subjected to an application of dicamba between V3 and V4 soybean growth stages. Palmer amaranth plants were estimated at 30 to 40 cm in height at the time of application. Plants that emerged early were controlled with herbicide effectiveness of 90% based on visual injury. Plants that survived showed severe epinasty and did not show signs of regrowth for several weeks. However, a late emerging cohort of Palmer amaranth in the field in 2017 occurred four to five weeks after dicamba application.

Large patches of small Palmer amaranth plants were noticed in late-July when soybean was between R2 and R4 soybean growth stages. Reduced Palmer amaranth during the soybean critical weed free stage [emergence to R1 (Halford et al.,2001; Van Acker et al., 1993; Knezevic et al., 2003)] may have attributed to the lack of significance. Despite the lack of negative effects of Palmer amaranth to soybean yield in 2017, yield loss could potentially become 100%. Some producers may not want to harvest through patches of Palmer amaranth such as in Figure 3.27. This could be due to combines that cannot handle the wetter plant material and/or the producer may not want to spread infestation further throughout the field. As a result, portions of the field may be a complete loss.

Table 3.15. Palmer amaranth density, biomass, and soybean yield in 2016 and 2017.

2016 Palmer Amaranth Density (plants m^{-2})	2016 Palmer Amaranth Biomass (g m^{-2})	2016 Soybean Yield (kg ha^{-1})	2017 Palmer Amaranth Density (plants m^{-2})	2017 Palmer Amaranth Biomass (g m^{-2})	2017 Soybean Yield (kg ha^{-1})
0	0	3792	0	0	2484.2
1	135	3517.3	1	272	2204.8
1	88	3401.1	1	298	2198
3	94	3650.2	3	295	2847.1
5	211	2892.1	3	282	2570.5
6	352	2726	5	308	2261
7	172	3513.6	6	280	2445.9
7	568	2821.9	7	281	2885.5
7	354	2515.7	8	317	2467.8
9	386	2656.1	9	277	2454.1
15	513	2091.8	12	288	3221
19	298	2850	13	303	2499.3
20	465	2782.7	15	302	2059.7
27	462	3109.3	18	301	2465
			22	278	2867.7
			23	368	2262.4

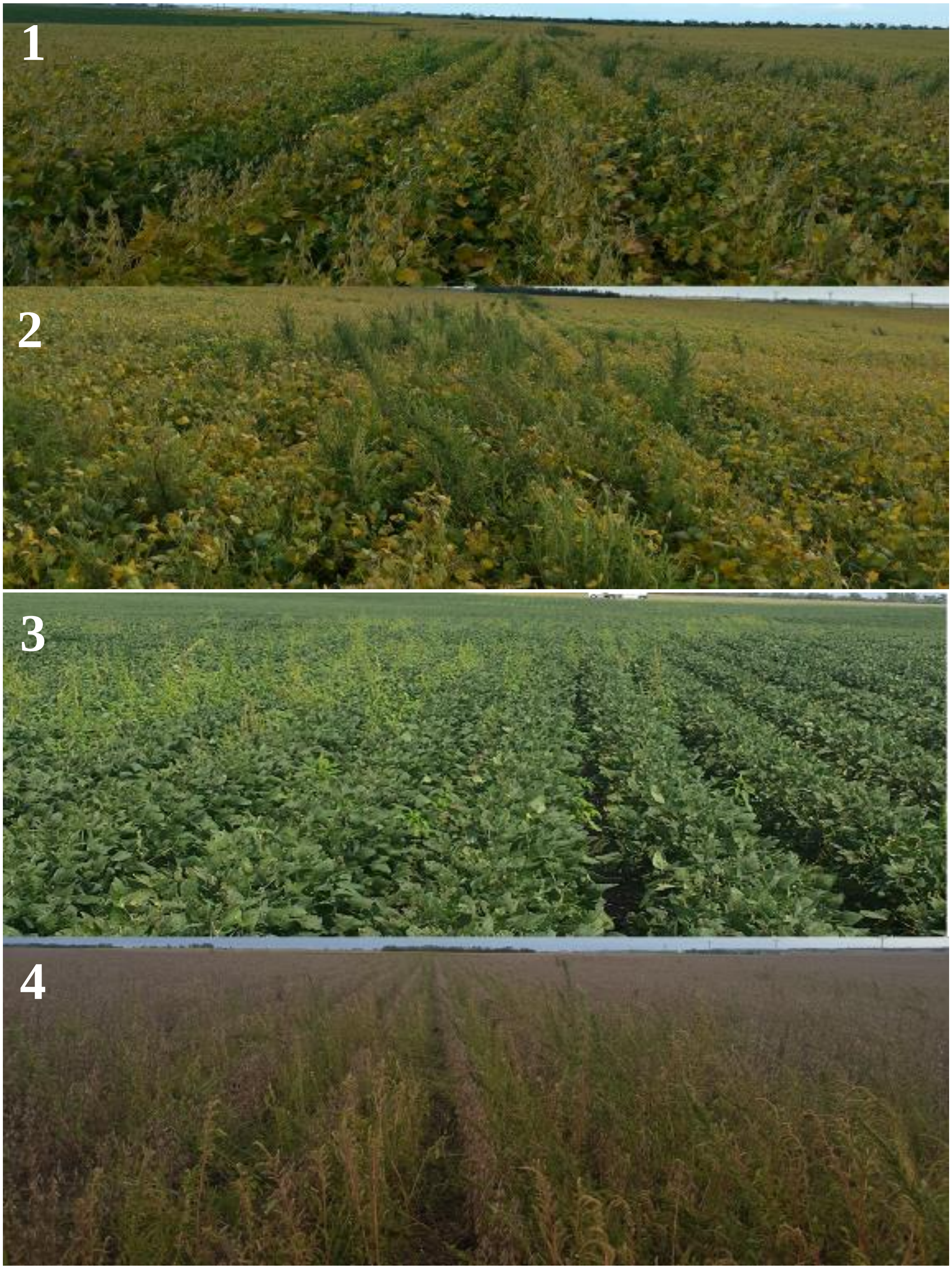


Figure 3.27. Corsica infestation in 2016 (1 and 2) and 2017 (3 and 4) facing north (1 and 3) and south (2 and 4).

Soybean yield loss in Corsica, SD in 2016 was less than that reported by Bensch et al. (2003) in Kansas. Reported incremental yield losses in soybean from Palmer amaranth ranged from 12 to 105%. High variability was assumed to be due to weed emergence timing and location, which is what was seen in Corsica in 2017. Bensch et al. (2003) also reported maximum yield losses from 38 to 87% in soybean from Palmer amaranth competition. Soybean yield loss due to common waterhemp and redroot pigweed competition was similar to slightly lower than that of Palmer amaranth in Kansas. Klingaman and Oliver (1994) reported more similar soybean yield losses that were seen due to Palmer amaranth of 17 to 68% for densities of 0.33 to 10 plants m^{-1} of row, respectively, in Arkansas.

Despite greater competitiveness among amaranth species, Palmer amaranth does not seem to be as competitive as some broadleaf plants. Yield loss in soybean due to Palmer amaranth at Corsica in 2016 (I=9%, A=35%) was considerably less than yield loss due to volunteer corn (*Zea mays*) in Brookings, South Dakota, which caused 39.7% yield loss low densities and a maximum loss of 71% (Alms et al., 2016). Common cocklebur (*Xanthium pensylvanicum*) at 4.4 plants m^{-2} reduced soybean yield by 50% in Mississippi (Barrentine, 1974), whereas Palmer amaranth caused about 20% yield loss at a similar density. Common sunflower (*Helianthus annuus*) at one plant m^{-2} can reduce soybean yield by 48 to 51% in Kansas (Geier et al., 1996), which was much higher than Palmer amaranth. One giant ragweed (*Ambrosia trifida*) m^{-2} caused 60 to 70% loss of soybean yield in Missouri according to Baysinger and Sims (1991). Velvetleaf at five plants m^{-2} reduced soybean yield by 41 to 46% in Texas (Munger et al., 1987), which was more competitive than Palmer amaranth at this density. Conley et al. (2003) in Wisconsin reported incremental soybean yield loss of 0 to 1.2% due to common lambsquarters (*Chenopodium album*), which is less than what was seen due to Palmer amaranth competition.

Palmer amaranth was more competitive than some common grass weeds in Midwestern agriculture. Giant foxtail (*Setaria faberi*) at 13.2 to 26.4 plants m^{-2} caused 26% soybean yield loss in Illinois (Harrison et al., 1985), whereas similar reduction was seen at 15 plants m^{-2} of Palmer amaranth. Barnyardgrass (*Echinochloa crus-galli*) reduced soybean yield by 10, 25, and 50% at 42, 110, and 250 plants m^{-2} in Arkansas (Vail and Oliver, 1993). According to Weaver (2001) in Ontario, Canada, incremental and maximum yield loss due to green foxtail (*Setaria viridis*) was 0.07 and 80%, respectively, at densities of 0, 8, 16, 32, 48, 64, 96, and 128 plants m^{-2}, as well as a high density non-thinned stand.

CHAPTER 4. CONCLUSIONS

Survey results in 2016 showed that infestations of Palmer amaranth may be more widespread in South Dakota than what was previously reported. Some of the issues regarding Palmer amaranth sightings is the ability to properly distinguish this species from other amaranth species such as common waterhemp and redroot pigweed. These are the two most prevalent amaranth species in South Dakota and can become confused with Palmer amaranth. Possible hybridization of these species also increases the difficulty of proper weed identification. Brochures highlighting distinguishable characteristics of Palmer amaranth were handed out along with the surveys, however, it would appear that greater efforts are needed to pass information to the public.

There are several avenues of information distribution such as newsletters, email, and sessions at larger events such as conferences or recertification meetings. During these meetings, more technological methods could be utilized to gauge the knowledge of the public. This may involve polling over smartphone applications at special events that cater to a large diversity of people.

Studies comparing Palmer amaranth, common waterhemp, and redroot pigweed growth showed that Palmer amaranth has the potential to outcompete these other two species. Indications of a higher competitiveness in crops such as soybean are also seen regarding growth rate, overall size, and biomass of Palmer amaranth. Early-emerging Palmer amaranth has the most potential to cause problems in crops, however, later-emerging Palmer amaranth can also cause a large impact. Palmer amaranth that emerges late can still produce seed, which can increase the infestation in following years. Decreasing daylength was seen to effect anthesis of Palmer amaranth, indicating a short-day plant. Management strategies to combat the competitiveness of Palmer amaranth should be considered. Tillage can be a viable option to limit a flush of Palmer amaranth that can cause problems before the crop emerges. Early planting and/or narrow row spacing can also reduce Palmer amaranth impact.

There are a few herbicide options to control Palmer amaranth or mitigate its impact on crop production. A pre-emergence application of S-metolachlor controlled Palmer amaranth very well, whereas atrazine did not provide good control at any timing. Post applications of dicamba or glufosinate provided good control of emerged Palmer amaranth. Mesotrione applications provided mixed results, which may elude to a level of tolerance. Glyphosate provided moderate control and should not be solely relied on to control Palmer amaranth. To help prevent further resistance of Palmer amaranth to certain herbicides, herbicide programs that use multiple modes of action and rotate between modes of action are recommended.

The location study determined that Palmer amaranth seed from different geographical locations, if transferred to South Dakota, can establish itself, produce seed, and cause future infestations. Further studies should be done to determine how Palmer amaranth plants from seed from other source locations adapts to different climates and becomes a successful weed. Palmer amaranth has established in South Dakota due to seed spread and will continue to be a weed species to contend with in crop production.

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APPENDIX

Supplemental Table 1. Confirmed Palmer amaranth infestation by county in South Dakota, number of survey respondents from each county, and number of respondents said yes to a Palmer amaranth infestation split into identification groups (correct seedling AND mature plant ID, correct seedling OR mature plant ID, and NO correct Palmer amaranth ID).

	--Yes to a Palmer Amaranth Infestation--				
County	Seedling AND Mature Plant ID	Seedling OR Mature Plant ID	NO Plant ID	Total Survey Respondents	Confirmed PA Infestation
Aurora	0	0	0	5	NO
Beadle	1	0	0	8	NO
Bennett	0	0	0	0	YES
Bon Homme	1	0	0	5	NO
Brookings	5	6	4	39	NO
Brown	1	0	0	9	NO
Brule	0	1	0	6	YES
Buffalo	0	1	0	3	YES
Butte	0	0	0	0	NO
Campbell	0	0	0	0	NO
Charles Mix	0	0	0	3	NO
Clark	0	1	0	7	NO
Clay	0	1	0	1	NO
Codington	1	3	0	6	NO
Corson	0	0	0	0	NO
Custer	0	0	0	0	NO
Davison	1	1	0	5	NO
Day	1	0	0	7	NO
Deuel	0	0	0	8	NO
Dewey	0	0	0	0	NO
Douglas	0	0	0	2	YES
Edmunds	0	0	0	8	NO
Fall River	0	0	1	1	NO
Faulk	0	1	0	4	NO
Grant	1	0	0	8	NO
Gregory	0	0	0	0	YES
Haakon	0	0	0	1	NO
Hamlin	1	1	0	7	NO
Hand	0	0	0	3	NO
Hanson	0	1	0	1	NO
Harding	0	0	0	0	NO

Hughes	0	0	0	1	YES
Hutchinson	1	1	0	4	NO
Hyde	0	0	0	0	NO
Jackson	0	0	0	0	NO
Jerauld	0	0	0	1	NO
Jones	0	0	0	0	NO
Kingsbury	0	1	0	9	NO
Lake	1	1	1	9	NO
Lawrence	0	0	0	0	NO
Lincoln	0	0	0	2	NO
Lyman	0	0	0	4	YES
Marshall	0	0	1	6	NO
McCook	1	0	0	4	NO
McPherson	0	0	0	5	NO
Meade	0	0	0	0	NO
Mellette	0	0	0	0	NO
Miner	0	0	0	2	NO
Minnehaha	1	1	1	12	NO
Moody	3	0	0	10	NO
Oglala Lakota	0	0	0	0	NO
Pennington	0	0	0	0	NO
Perkins	0	0	0	0	NO
Potter	0	0	0	1	YES
Roberts	0	0	0	8	NO
Sanborn	0	0	0	1	NO
Spink	1	1	0	14	NO
Stanley	0	0	0	0	NO
Sully	0	0	0	0	YES
Todd	0	0	0	0	NO
Tripp	0	0	0	0	NO
Turner	0	0	0	7	NO
Union	1	0	0	2	NO
Walworth	0	0	0	0	NO
Yankton	1	0	0	2	NO
Ziebach	0	0	0	0	NO