Grass weed ecology and control of atrazine-resistant Palmer amaranth (*Amaranthus palmeri*) in grain sorghum (*Sorghum bicolor*).

by

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Abstract

An opportunity for postemergence (POST) grass weed control has recently been approved with ALS-resistant grain sorghum, however, grass weed emergence timing and crop tolerance to grass competition are not well understood. To address the importance of POST application timing, a critical period of weed control (CPWC) for grass competition in grain sorghum was developed. Field experiments were established near Manhattan and Hays, KS in 2016 and 2017, and near Hutchinson, KS in 2017 to determine the CPWC. Each site provided a different grass species community. A total of ten treatments were included, with four treatments maintained weed-free until 2, 3, 5, or 7 weeks after crop emergence, four treatments receiving no weed control until 2, 3, 5, or 7 weeks after crop emergence, and two treatments were maintained weed-free or weedy all season. Treatments did not influence grain yield at Hutchinson because of a lack of season-long weed emergence. At Hays the CPWC began at crop emergence and ended 28 days later. At Manhattan the CPWC began 27 days after emergence and continued through grain harvest. The CPWC in grain sorghum depends on rainfall and competitive ability of the weed species. The start of the CPWC began when weeds emerged, thus a POST application should be targeted 14 to 21 days after emergence of grain sorghum. Emergence and development of large crabgrass, barnyardgrass, shattercane, and giant, green, and yellow foxtails were studied near Manhattan, KS after seeding on April 11, 2017. Barnyardgrass had the longest duration of emergence, beginning at 180 GDD after seeding and continuing through July. Large crabgrass had the shortest duration of emergence from 325 to 630 GDD after seeding. In general, all grasses began to emerge in late April and most species completed 90% emergence by early June. Grain sorghum is typically planted at this time, so grass weed control prior to planting is critical.

Palmer amaranth is a troublesome weed in double-crop grain sorghum production fields in Kansas. The presence of herbicide-resistant populations limits options for weed management. Field experiments were conducted to evaluate 14 different herbicide programs for the management of atrazine-resistant Palmer amaranth in double-crop grain sorghum at Manhattan and Hutchinson, KS in 2016 and 2017. Programs included eight PRE only and six PRE followed by POST treatments. Programs that had very long chain fatty acid-inhibiting herbicides provided greater control of atrazine-resistant Palmer amaranth by three weeks after planting sorghum. Programs of PRE followed by POST provided greater control of both atrazine-resistant and -susceptible Palmer amaranth by eight WAP compared to PRE alone. These results illustrate the value of residual herbicides, as well as an effective postemergence application, in double-crop grain sorghum.

Early season grass and Palmer amaranth control with the use of residual herbicides such as very long chain fatty acid-inhibitors provide a competitive advantage to grain sorghum. Utilizing weed emergence patterns to time effective POST applications, in unison with residual herbicides, will provide season-long weed control in Kansas grain sorghum fields.

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Chapter 1 - Literature Review

Grain sorghum production

The Great Plains is a diverse region for cropping systems where the major factor contributing to this diversity is annual precipitation. The state of Kansas ranges from less than 40 cm up to 117 cm of annual precipitation (USDA-NRCS 2007). Low annual precipitation limits the crops that can successfully be grown. Crops that are more efficient users of water or those that requires less water per kg of grain are often the crop chosen by producers in the Great Plains.

Grain sorghum (*Sorghum bicolor*) will produce the first kernel of grain with only 18 cm of precipitation, compared to corn which produces the first kernel with 28 cm of precipitation (Rogers et al. 2006). Efficient water use makes grain sorghum an excellent summer crop in areas with low annual precipitation. Kansas is the leading state in the US in grain sorghum production, harvesting almost 1.2 million hectares of grain sorghum in 2016 (NASS 2017).

Weed Competition and Management

The undergraduate weed science course at Kansas State University teaches that a weed is merely “a plant out of place.” Since the beginning of cultivated agriculture, man has been struggling to raise food from desired plants while keeping undesired plants out of their field. Grain sorghum can have yield losses up to 57% from Palmer amaranth density of 1.6 m^{-2} (Moore et al. 2004). Timing of emergence, duration of competition, and competitive ability of a weed species are the most influential factors affecting negative competition (Burnside and Wicks 1967, Harris and Ritter 1987, Smith et al. 1990, Martin et al. 2001, Norsworthy and Oliveira 2004). Vanderlip (1993) reported that grain sorghum seedlings grow slowly in comparison to weed species for the first 20-25 days. The slow growth is made worse because grain sorghum and many summer annual weeds emerge within the same time frame, creating season long competition. This causes grain sorghum to have yield loss percentages greater than most other grain crops (Stahlman and Wicks 2000).

Palmer amaranth (*Amaranthus palmeri*) was rated as the most troublesome weed in all United States crop production by the Weed Science Society of America in a 2015 Survey (Van Wychen 2016), and is a problem weed in Kansas grain sorghum production (Peterson 1999). The same survey ranked giant foxtail (*Setaria faberi* Herrm.), green foxtail (*Setaria viridis*), yellow foxtail (Setaria *pumila* (Poir.) Roem. & Schult.), and large crabgrass (*Digitaria sanguinalis* (L.) Scop.) among the most common weeds in crop fields in the United States (Van Wychen 2016). All the above weeds have the potential to emerge with grain sorghum, and also exhibit extended emergence (Myers et al. 2004; Werle et al. 2014; Norsworthy et al. 2014).

To understand the crop-weed interaction with regards to time of weed and crop emergence and crop development, a critical period of weed control (CPWC) has been determined for other crops such as corn (Hall et al. 1992; Evans et al. 2003; Myers et al. 2005; Gantoli et al. 2013), soybean (Van Acker et al. 1993), spring canola (Martin et al. 2001), peanut (Everman et al. 2008), and lettuce (Odero and Wright 2013). The CPWC uses a set amount of allowable yield loss (AYL) to determine when weeds need to be controlled. The AYL is determined by the environment and economics particular to a crop (Knezevic et al. 2002). The beginning of the CPWC is the threshold of time that weeds are allowed to compete from crop emergence before they must be removed to prevent yield losses beyond the AYL. This is referred to as the critical threshold of weed removal (CTWR) (Knezevic et al. 2002). The ending of the CPWC is the duration of time that a crop must be kept weed free to prevent yield losses beyond the AYL. This is referred to as the critical weed-free period (CWFP) (Knezevic et al. 2002). The time between the CTWR and the CWFP determines the duration a crop must be maintained weed free. All weeds must be controlled at the start and maintained weed-free for the duration of the CPWC.

The CPWC as a management strategy is part of cultural practices. Cultural practices are any management strategies that minimize crop-weed competition (Stahlman and Wicks 2000). Examples of cultural practices include: cultivar selection, row spacing, seeding rates, planting date, crop rotation, and placement and timing of fertilizers (Stahlman and Wicks 2000). Most cultural practices, by aiding in crop competitiveness, provide a yield boost when compared with using poor cultural practices (Norsworthy et al. 2012). Crop rotation should change timing of crop planting, changing weed management timing and altering weed selection pressure (Buhler et al. 1999). Row spacing in Kansas grain sorghum has shown to alter weed growth (Staggenborg et al. 1999). Narrow row spacing increases grain sorghum yields by facilitating more efficient use of soil nutrients and moisture (Stahlman and Wicks 2000); however, with limited soil moisture environments, grain sorghum competed better with weeds when planted in rows spaced 76 cm apart compared to 30 cm apart (Wiese et al. 1964). Seeding rate does not affect grain sorghum yield, if appropriate rates for the area are seeded (Hewitt 2015; Shaffer 2016). Placement of nitrogen and phosphorus near the seed has been shown to increase yield and hasten maturity of grain sorghum (O'Brien et al. 1998).

The need for continuous management of weeds is due to continuous emergence of weeds from a soil seed bank, where the persistence of a dormant seed on or in the soil ensures continued germination and emergence (Dekker 1999). Soil management can have an influence on the weed seed bank by influencing soil temperature, water, air, and light which are the main factors affecting seedling emergence (Forcella 2000). Soil fertility, salinity, compaction, tillage, and surface residue also have an influence on weed management (Forcella et al. 2000).

Mechanical weed control can be any method of controlling weeds by mechanical means but consists primarily of tillage. Tillage is used for controlling weeds and preparing a seedbed (Stahlman and Wicks 2000). Tillage carried out before a crop planting could utilize many different implements and has potentially the greatest impact on weed management through manipulation of temperature, moisture, air, light, compaction, and surface residue (Dekker 1999). Deep tillage can reduce weed seed germination by burying small seeds, so they cannot emerge from the soil, and has been shown to reduce Palmer amaranth emergence by 73% compared to no tillage, and greater than 98% when combined with a preemergence herbicide application (Farmer et al. 2017). A row crop cultivator, designed to till the soil between crop rows, and rotary hoe are tillage options after crop emergence. To utilize a row crop cultivator, the crop must be planted in rows spaced far enough apart to facilitate the implement moving between the rows without coming into contact with, and injuring, crop plants.

Conservation tillage is a management strategy that has been readily adopted by sorghum producers, especially those is semi-arid regions. Conservation tillage reduces tillage frequency and disturbance to maintain surface residue and has proven to conserve soil moisture (Stahlman and Wicks 2000). The conservation of soil moisture makes crop production more viable in dry climates, like those in Western Kansas, but it requires the use of herbicides to control weeds (Stahlman and Wicks 2000).

Chemical weed control is the most common method of weed control in grain sorghum. In 1992, 96% of the United States' grain sorghum hectares received one or more application(s) of herbicide(s) (Morrison et al. 1994). The first chemical compounds used to selectively control plants were synthesized for use during World War II by both the USA and United Kingdom (Kirby 1980). After the war, the naturally selective herbicides 2,4-D and MCPA were used to control those ‘plants out of place’ in agricultural fields (Kirby 1980). Through this new practice the discipline of weed science was born, and the development of more chemical compounds to be used in agriculture began. The widespread use of chemical weed control has led to herbicide resistance in many weeds; which has led weed scientists to learn the importance of a diverse approach to weed management (Vencill et al. 2012). An integrated weed management approach combines different methods of weed management from five broad categories: preventive, cultural, mechanical, biological, and chemical (Vencill et al. 2012). The idea of integrated weed management was transformed from five broad categories to 12 ‘Best Management Practices’ that weed scientists developed for a more directed approach to managing weeds without developing further herbicide resistance (Norsworthy et al. 2012).

The first objective of this research was to understand the sorghum-grass weed interaction with regards to development and time by determining a CPWC. To support the grass CPWC in grain sorghum, the second objective was to understand emergence and development of six summer annual grass weeds. With the increase in herbicide-resistant weeds, specifically Palmer amaranth, knowledge of herbicidal control in double-crop grain sorghum has become increasingly important. The third objective was to support grain sorghum producers with knowledge of weed management of atrazine-resistant Palmer amaranth in double-crop grain sorghum.

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Chapter 2 - Critical Period of Grass Weed Control in Grain Sorghum (*Sorghum bicolor*)

Abstract

The development of ALS-resistant grain sorghum provides an opportunity for postemergence (POST) grass weed control in grain sorghum, however, application timing for best management practices is not understood. A critical period of weed control (CPWC) concept describes the best POST application timing by determining the time a crop must be maintained weed-free to prevent yield loss beyond a chosen acceptable level. Field experiments were conducted to determine the CPWC for grass weed competition in grain sorghum. A total of 11 treatments were established with four treatments kept weed-free until 2, 3, 5, and 7 weeks after crop planting, while four treatments received no weed control until 2, 3, 5, and 7 weeks after crop planting two treatments were maintained weed-free or weedy all season, and the last treatment received a preemergence application of *S*-metolachlor + atrazine. A four-parameter log-logistic model was fit to weedy and weed-free relative grain yield data. At Manhattan the CPWC began 693 GDD after planting and continued through grain harvest in 2017. At Hays, if grain sorghum was maintained weed-free until 872 GDD after planting then 95% attainable yield was maintained. At Hutchinson if grass weeds were controlled from planting until 614 GDD or before 2546 GDD then 95%, or greater, grain yield would be maintained. The CPWC in grain sorghum depends on rainfall and competitive ability of the weed species. Planting grain sorghum into a clean field, applying a residual herbicide followed as needed by a postemergence application, will likely provide grass control during the CPWC.

Introduction

A major challenge for grain sorghum production is managing grass weeds that occur in the crop as there are limited herbicides labeled for postemergence (POST) use in-crop. The commercial release of Inzen™ Sorghum by DuPont Crop Protection in 2015, provided grain sorghum producers an opportunity to control grass weeds with a POST application of an ALS-inhibiting herbicide, nicosulfuron (Zest™). Nicosulfuron controls susceptible grass species including barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.), green foxtail (*Setaria viridis* (L.) P. Beauv.), giant foxtail (*Setaria faberi* Herrm.), yellow foxtail (*Setaria pumila* (Poir.) Roem. & Schult.), and large crabgrass (*Digitaria sanguinalis* (L.) Scop.). According to the Zest™ label, barnyardgrass and green, giant, and yellow foxtail must be sprayed before they reach 10 cm in height, and large crabgrass must be sprayed before it reaches 5 cm in height (Anonymous 2016). The label does not describe when in the lifecycle of the grain sorghum crop grasses reach maximum labeled height, nor which grass species that might include, nor whether those species have begun to compete with grain sorghum before the maximum labeled height. Therefore, the biological and ecological basis for timing of a POST application is not understood and needs to be investigated.

Previous research has answered these questions for other crops. The CPWC has been described for corn (Hall et al. 1992, Evans et al. 2003, Myers et al. 2005, Gantoli et al. 2013), soybean (Van Acker et al. 1993), spring canola (Martin et al. 2001), peanut (Everman et al. 2008), and lettuce (Odero and Wright 2013). It will be critically important to understand grass weed emergence, growth, and development to optimize the use of ALS-R grain sorghum hybrids and POST nicosulfuron applications for grass weed control. The potential impact will be preserving this new technology by guiding optimal applications of nicosulfuron and optimizing grass weed control for grain sorghum producers.

To understand the sorghum-grass weed interaction with regards to development and time, a critical period of weed control (CPWC) should be determined. The CPWC uses a set amount of allowable yield loss (AYL) to determine when weed control needs to begin and for how long weed control must be maintained. The AYL is set at a given level but can be changed according to the environment and economics for a particular crop. Five percent AYL has been chosen in many previous CPWC studies (Van Acker et al. 1993, Martin et al. 2001, Knezevic et al. 2002, Everman et al. 2008). The critical threshold of weed removal is used to determine the beginning of the CPWC and is defined as the time when weeds must be removed to prevent yield losses beyond the AYL. The critical weed-free period is used to determine the end of the CPWC and is defined as the duration of time, from crop emergence, that a crop must be maintained weed free to prevent yield losses beyond the AYL. All weeds must be controlled by the critical threshold of weed removal and maintained weed-free until the end of the critical weed-free period; this duration of time defines the CPWC (Knezevic et al. 2002). The objective of this research was to determine the CPWC for grain sorghum in the presence of grass weeds across sites in Kansas.

Materials and Methods

Field experiments were conducted near Manhattan and Hays, KS in 2016 and 2017 and near Hutchinson, KS in 2017, for a total of five site-years (Table 2.1). Manhattan and Hutchinson sites were rain fed while Hays had a lateral irrigation system to supplement rainfall. Data of precipitation and air temperature were recorded daily from weather stations within 1.6 km of plots at all sites (Table 2.2) by the Kansas Mesonet (Weather Data Library, Kansas State

University). Using air temperatures beginning at grain sorghum planting, growing degree days (GDD) for a grain sorghum crop were calculated each day:

$$GDD = \left(\frac{Daily\ Max\ Air\ Temp\ + Daily\ Min\ Air\ Temp}{2}\right) - Base\ Temp \qquad \text{Equation 2-1}$$

where DailyMaxAirTemp is the daily maximum air temperature (C) with no accumulation above a threshold of 37.8 C, DailyMinAirTemp is the daily minimum air temperature (C) with no accumulation below a threshold of 10 C, and BaseTemp is the grain sorghum base temperature of 10 C (Gerik et al. 2003). Daily GDD data were summed to calculate cumulative GDD.

A total of eleven treatments were established in a randomized complete block design with four replications at each site. Four treatments were kept weed-free until 2, 3, 5, and 7 weeks after crop planting, after which grass weeds could emerge, grow, and compete with the grain sorghum. Four treatments had no weed control until 2, 3, 5, and 7 weeks after crop planting, when weeds were removed and plots kept weed-free for the remainder of the season. Two treatments were maintained weed-free or weedy all season. The final treatment was a single preemergence (PRE) application of *S*-metolachlor (1825 g ai ha^{-1}) + atrazine (1413 g ai ha^{-1}) (Bicep II Magnum, Syngenta Crop Protection, Greensboro, NC). Plot dimensions were 7.6 m long by 3 m wide with grain sorghum planted in rows spaced 76-cm apart and each plot having four rows. All measurements were taken between the center two rows. Directly after planting, 25 kg N ha^{-1} was spread as urea (46-0-0), and the single PRE treatment was applied at all sites. Large crabgrass, barnyardgrass, green, yellow, and giant foxtail were over-seeded across the entire plot area at Hays in both years because of a lack of natural grass weed population. Broadleaf weeds that emerged after grain sorghum planting at Hays and Hutchinson in 2017 were controlled with a POST application of pyrasulfotole + bromoxynil (289 g ha^{-1}) (Huskie, Bayer CropScience LP, Research Triangle Park, NC), dicamba (560 g ae ha^{-1}) (Clarity, BASF Corporation, Research

Triangle Park, NC), atrazine (280 g ha^{-1}) (Aatrex, Syngenta Crop Protection, LLC, Greensboro, NC), and ammonia sulfate (1% v/v) (N-Pact, Winfield Solutions, St. Paul, MN). Weed removal timing treatments began two weeks after grain sorghum planting and were accomplished by applying glufosinate (449 g ha^{-1}) (Bayer CropScience LP, Research Triangle Park, NC) and ammonia sulfate (1% v/v) (N-Pact, Winfield Solutions, St. Paul, MN) between rows with a CO$_2$ backpack sprayer and a hooded single nozzle.

Biomass and Grain Yield

Each week, grass weed density was counted in two permanent 0.05-m^2 rings within each plot before the weed-free treatments were applied. Prior to each removal treatment, weed biomass was collected from a 0.25 m^2 quadrat by clipping plants at the soil surface. Weed species were not separated but bagged together and dried at 65 C for one week when dry weights were recorded. At grain sorghum mid-bloom, grain sorghum biomass was harvested across all treatments and weed biomass was harvested from the weed-free, weedy all-season, and PRE treatments. Grain sorghum plants from 1 meter of row were clipped at the soil surface, and total wet weight recorded. Two grain sorghum plants were randomly chosen from the sample and two-plant wet weights recorded. For the sub-sample, leaves, stems, and reproductive structures of the two-plant sample were separated, bagged, and dried at 65 C for one week, and then dry weights were recorded. The weights of the partitioned plant parts were summed for the total two-plant dry weight and the relationship of the two-plant wet weight to the 1 meter of row wet weight was used to determine total dry weight of 1 meter of row sample.

In 2016, no grain was harvested from either field site due to the hybrid being male sterile (personal observation). In 2017, grain was harvested using a plot combine from the center two rows of each plot at Hays and at Manhattan. Sorghum heads were hand harvested from the center two rows for 2.34 m of the plot length at Hutchinson in 2017, and grain weights and moisture were determined by threshing collected heads with a plot combine. All grain yield data were adjusted to 14.5% moisture.

Statistics

Relative grain yield and grain sorghum biomass data were subjected to ANOVA using PROC MIXED in SAS 9.4 (Statistical Analysis Systems Institute, Cary NC) to test for significance ($P < 0.05$) of site, year, replication, treatment, and their interactions. Weed density, weed biomass, grain sorghum biomass, and grain yield data were subjected to ANOVA using PROC MIXED in SAS 9.4 and means were presented as least square means.

Percent relative grain yield was calculated by dividing the grain yield of each treatment by the grain yield of the weed-free all-season treatment for each replication. The weed-free all-season plot was considered 100% or maximum attainable grain yield. Using R statistical software (R Development Core Team, Vienna Austria) the four-parameter log-logistic model was fit to sets of weed-free or weedy relative grain yield data as described by Knezevic and Datta (2015) using:

$$Y = \frac{\mathrm{C} + (\mathrm{D} - \mathrm{C})}{1 + e^{\mathrm{B}(\log\mathrm{X} - \log\mathrm{E})}} \qquad \text{Equation 2-2}$$

where Y is relative yield (%), C is the lower limit, D is the upper limit, X is the time (expressed as GDD), E is the GDD giving a 50% response between the upper and lower limits (inflection point), and B is the slope of the line at the inflection point. The estimated dose (ED) command in R statistical software was adapted to estimate the GDD at 5% AYL (Knezevic and Datta 2015).

To determine the beginning and end of the CPWC, the effective dose (ED) command in R was used to estimate the GDD at 5% AYL. Five percent AYL was chosen as the start of the

CPWC because 5% was determined as likely to provide statistically measurable yield loss and economic AYL. The level of AYL could change depending on factors such as crop price and cost of weed control (Knezevic and Datta 2015).

The impact of grass weeds on grain sorghum growth was described using relative sorghum biomass (%) for both 2016 and 2017. Relative grain sorghum biomass was calculated by dividing the biomass (g m^{-2}) of each treatment by the biomass of weed-free all-season treatment for each replication. The weed-free all-season plot was considered 100% or maximum attainable biomass. Using R statistical software, the four-parameter log-logistic model was fit to the biomass data from sets of weed-free and weedy treatments (Equation 2-2) as described above (Knezevic and Datta 2015).

Results and Discussion

Grass Weed Densities and Biomass

Grass weed densities were relatively high but variable across sites and years (Table 2.3). A mixed grass species population was observed at Hays in 2016 and 2017 with the majority being green foxtail (personal observation). The weedy all-season treatment had a mean weed density of 405 plants m^{-2} in 2016 and 395 plants m^{-2} in 2017. A study in Ontario, Canada found green foxtail reduced corn dry matter and grain yield with densities of 160 plants m^{-2} (Cathart and Swanton, 2004).

A natural population of giant foxtail was present at the Manhattan site and the weedy all-season treatment had weed densities of 500 plants m^{-2} in 2016 and 140 plants m^{-2} in 2017 (Table 2.3). A mixed population of giant green foxtail (*Setaria viridis* var. *major*) with densities ranging from 32 to 118 plants m^{-2} generated a CPWC in soybean (Harris and Ritter 1987), suggesting that densities at Manhattan were likely great enough to provide competition with grain sorghum.

A natural population of large crabgrass at the Hutchinson site had a density of 85 plants m^{-2} in 2017 in the weedy all-season treatment (Table 2.3). A study conducted in Oklahoma found grain sorghum grain yield losses of 3.6% per week through competition with large crabgrass, barnyardgrass, and Texas panicum (*Panicum texanum* Buckley) at a combined density of 196 plants m^{-2} (Smith et al. 1990). Competition from large crabgrass at Hutchinson decreased yields, however, the density of large crabgrass may not have been great enough to cause yield losses comparable to previous studies.

The grass weed biomass at grain sorghum mid-bloom from weedy all-season treatment was comparable across years at each site (Table 2.3). For all site-years, weed biomass decreased as the weed-free duration increased and, if grain sorghum was kept weed-free for seven weeks, no weed biomass was produced at Hays in 2017 nor at Manhattan in 2016 and 2017. In 2017 no weed biomass was produced if weeds were removed by 3 WAP at Manhattan and Hutchinson. Weed biomass increased as the duration of weed interference increased across all sites and years. The increasing of weed biomass was similar to that observed with a mixed weed population in cotton (Korres and Norsworthy 2015) and a mixed weed population in corn (Norsworthy and Olivera 2004). The biomass weights observed for the weedy all-season treatments were similar to those observed in mixed weed populations competing with soybean (Van Acker et al. 1993).

Grain Yield

All grain yield results and discussion are from 2017 only (Table 2.4) because no grain was produced in 2016. The weedy (Figure 2.1) and weed-free (Figure 2.2) regression curves for relative grain sorghum yield passed the lack-of-fit test for all sites in 2017 and, therefore, adequately described yield loss (Table 2.5Table 2.1). The ED_5 and ED_{95} parameter estimates for each curve estimate the GDD at 5% AYL to mark the beginning and end of the CPWC (Table

2.6). No CPWC was identified at Hays because weeds that emerged and grew with the grain sorghum did not decrease grain yield. The critical weed-free period did occur at Hays (872 GDD) marking the end of the duration that grain sorghum would need to be maintained weed-free to maintain 95%, or greater, grain yield. The critical threshold of weed removal occurred at 693 GDD at Manhattan marking the beginning of the CPWC and the critical weed-free period lasted through grain harvest. Grain sorghum in Manhattan would tolerate giant foxtail competition until 693 GDD when weeds would need to be removed, and then the crop maintained weed-free through the end of the season. No CPWC was identified at Hutchinson because the critical threshold of weed removal occurred after the critical weed-free period which implies that if large crabgrass was controlled after planting for 614 GDD or before 2546 GDD then 95%, or greater, grain yield would be maintained.

Soil moisture is one of the main factors needed for seed germination (Forcella et al. 2000). No site received rainfall for two weeks after grain sorghum planting in 2017 (Table 2.2). Surface soil moisture is especially important for small-seeded species such as the grass weeds observed in this study because they cannot emerge from very deep in the soil (Forcella et al. 2000). The CPWC at Manhattan began approximately ten days after receiving the first rainfall after planting, when giant foxtail germination and emergence was stimulated. No CPWC could be identified at Hutchinson and weeds that were allowed to emerge and compete with grain sorghum from planting at Hays did not decrease grain yield, likely due to lack of early season grass weed competition.

These results are supported by previous findings of grain sorghum maintained weed-free for 20 days after planting (Everaarts 1993), or 4 weeks after planting (Burnside and Wicks 1967), having little to no grain yield loss, and grain sorghum has been found sensitive to early-season competition due to slow early growth relative to other species (Vanderlip 1993). Timing of emergence, duration of competition, and competitive ability of a weed species are the most crucial factors affecting crop-weed competition (Burnside and Wicks 1967, Harris and Ritter 1987, Smith et al. 1990, Martin et al. 2001, Norsworthy and Oliveira 2004).

Grain Sorghum Biomass

Weedy and weed-free regression curves for relative grain sorghum biomass passed the lack-of-fit test for all site-years (Table 2.5). The ED_5 estimates were calculated for the threshold of weed removal curve, and ED_{95} estimates were calculated for the weed-free period which provides the GDD at 5% AYL and marked the beginning and end of the CPWC based on grain sorghum biomass at grain sorghum mid-bloom. The threshold of weed removal at Hays began a little more than two weeks after planting in 2016 and before four weeks after planting in 2017 (Table 2.7). However, weed competition did not affect grain sorghum biomass in 2016 and the weed-free period could not be determined at Hays in 2017. The lack of the weed-free period at Hays implies that if grass weed emergence does not occur within the first two weeks then grain sorghum can out-compete those grasses and grain sorghum biomass will not decrease more than 5% AYL. The threshold of weed removal at Manhattan began at planting in 2016 and 55 days after planting in 2017. The weed-free period at Manhattan occurred almost 40 days after planting in 2016 and almost 30 days after planting in 2017. This suggests that in 2016 grain sorghum would need to be maintained weed-free from planting until almost 40 days after planting to maintain 95% or greater grain sorghum biomass. In 2017 at Manhattan, either allowing giant foxtail competition until 55 days after planting then removing giant foxtail competition through the end of the season or maintaining the grain sorghum weed-free from planting through 28 days after planting would maintain 95% or greater grain sorghum biomass. The weed-free period could not be determined at Hutchinson in 2017, however, the threshold of weed removal was 65 days after planting. This suggests that grain sorghum can tolerate competition from large crabgrass for 64 days after planting and maintain 95% grain sorghum biomass.

Conclusions

The knowledge gained from this research will help sorghum producers with grass weed management through a greater understanding of competition timing and competitive ability of weed species. The CPWC in grain sorghum depends on timing of rainfall to stimulate emergence and competitive ability of grass weed species. The results of this study show that the CPWC is likely to start when weeds begin to emerge, because grain sorghum is most sensitive to early season competition. Therefore, grain sorghum needs to be planted into a weed-free field, and if grass weeds do emerge in-season, a POST application should target small grass weeds 14 to 21 days after the start of grass weed emergence.

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Tables and Figures

Table 2.1 Dates and grain sorghum production activities for all Kansas sites in 2016 and 2017.

Activity	Hays		Manhattan		Hutchinson
	2016	2017	2016	2017	2017
Planting	June 3	June 5	June 10	May 31	May 29
Hybrid	XG31017ALS	HG 48-B	XG31017ALS	HG 48-B	HG 48-B
Hybrid Ownership	Advanta	Heartland Genetics	Advanta	Heartland Genetics	Heartland Genetics
Seeding rate [b]	110K seeds ha^{-1}		120K seeds ha^{-1}		120K seeds ha^{-1}
POST Application	-[a]	June 17	-	-	June 17
Biomass Harvest	August 15	August 10	August 29	August 3	August 2
Grain Harvest	-	October 25	-	October 17	September 29

[a] dashes (-) denote that activity was not carried out
[b] All sites planted with a row-crop planter in rows spaced 76 cm apart

Table 2.2 Rainfall and irrigation received each week after grain sorghum planting at Hays and Manhattan KS in 2016 and 2017, and Hutchinson KS in 2017. Rainfall recorded through the Kansas Mesonet weather stations at each site.

		Rainfall												
		Weeks after planting												
Site	Year	1	2	3	4	5	6	7	8	9	10	11	12	Total
		mm												
Hays	2016	0	41[a]	19	61	32	20	18[a]	27	0	67	0	0	284
	2017	1	0	32	19	21[a]	2	2	0	21	39	-[b]	-	135
Manhattan	2016	2	0	17	38	61	0	10	23	28	23	32	49	284
	2017	4	0	17	2	28	4	0	0	18	104	-	-	178
Hutchinson	2017	3	1	25	0	19	0	8	3	4	34	-	-	97

[a] Irrigation
[b] Biomass harvested prior to this week

Table 2.3 Grass weed densities and biomass (with standard error) for all treatments at Hays and Manhattan KS in 2016 and 2017, and Hutchinson, KS in 2017. Grass weed density and biomass recorded at grain sorghum mid-bloom for PRE, weedy all season, and all weed-free treatments. Grass weed density and biomass were recorded at treatment week prior to weedy removal treatment[a].

Treatment	Hays				Manhattan				Hutchinson	
	2016		2017		2016		2017		2017	
	Density	Biomass	Density	Biomass	Density	Biomass	Density	Biomass	Density	Biomass
	# m^{-2}	g m^{-2}	# m^{-2}	g m^{-2}	# m^{-2}	g m^{-2}	# m^{-2}	g m^{-2}	# m^{-2}	g m^{-2}
PRE (*S*-metolachlor + atrazine)	55 (38)	40 (13)	15 (10)	70 (40)	515 (49)	129 (33)	90 (40)	93 (59)	10 (6)	28 (16)
Weedy All Season	175 (25)	211 (38)	395 (39)	217 (30)	670 (66)	253 (56)	140 (8)	160 (17)	85 (65)	110 (26)
Weed-Free until 2 Weeks	100 (26)	54 (1)	250 (29)	187 (22)	540 (71)	277 (39)	140 (42)	115 (5)	3 (2.6)	68 (3)
Weed-Free until 3 Weeks	90 (19)	61 (4)	235 (32)	189 (65)	510 (29)	174 (34)	65 (10)	76 (25)	3 (5)	54 (18)
Weed-Free until 5 Weeks	85 (34)	61 (9)	20 (8)	71 (53)	90 (31)	0 (0)	80 (18)	83 (28)	2 (0)	57 (2)
Weed-Free until 7 Weeks	70 (13)	12 (12)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1 (4)	13 (13)
Weed-Free All Season	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Weedy until 2 Weeks [a]	135 (24)	-[b]	0 (0)	0 (0)	85 (25)	-	45 (5)	0 (0)	150 (304)	0 (0)
Weedy until 3 Weeks	140 (23)	-	325 (139)	35 (80)	65 (25)	-	75 (33)	0 (0)	130 (500)	0(0)
Weedy until 5 Weeks	145 (39)	-	630 (125)	112 (4)	470 (26)	-	320 (70)	120 (9)	130 (500)	46 (17)
Weedy until 7 Weeks	115 (20)	-	119 (32)	187 (8)	655 (66)	-	95 (15)	132 (10)	30 (96)	89 (9)

[b] dashes (-) denote that no measurement was taken

Table 2.4 Grain sorghum grain yield (with standard error) for all treatments at Hays, Manhattan, and Hutchinson, KS in 2017. Grain yield was combined harvested after allowing to field dry, and grain moisture adjusted to 14.5% moisture.

Treatment		Hays	Manhattan	Hutchinson
			kg ha^{-1}	
PRE (*S*-metolachlor + Atrazine)	1	8140 (539) a	4250 (423) bc	4460 (544) ab
Weedy All Season	3	6720 (557) b	4490 (375) c	3350 (715) c
Weed-Free until 2 Weeks	8	6940 (490) b	5550 (458) a	4410 (346) c
Weed-Free until 3 Weeks	9	6510 (511) b	3970 (942) a	4650 (547) ab
Weed-Free until 5 Weeks	10	7250 (753) b	5630 (556) ab	4930 (443) abc
Weed-Free until 7 Weeks	11	6780 (249) b	4500 (629) a	4370 (440) abc
Weed-Free All Season	2	6060 (580) b	5540 (333) a	4250 (581) abc
Weedy until 2 Weeks	4	6760 (136) b	4260 (832) a	4700 (458) ab
Weedy until 3 Weeks	5	6500 (267) ab	6640 (208) ab	5350 (554) bc
Weedy until 5 Weeks	6	7380 (205) ab	5360 (801) ab	4110 (184) a
Weedy until 7 Weeks	7	6970 (702) ab	5090 (281) ab	3910 (173) abc

Table 2.5 P-values ($P < 0.05$) from the lack-of-fit test for weedy and weed-free regression models for relative grain yield combined across sites for 2017 and relative grain sorghum biomass at each site combined across 2016 and 2017. Grain sorghum biomass were harvested at grain sorghum mid-bloom

Regression Curve	Site	Weedy	Weed-Free
		P-value	
Relative Grain Yield	All Sites	0.62	0.77
Relative Biomass	Hays	0.67	0.79
	Manhattan	0.08	0.99
	Hutchinson	0.14	0.11

Table 2.6 Parameter estimates (SE) of relative grain sorghum grain yield regression from Equation 2-2 from all sites in 2017.

Site	Parameter estimates				Threshold of Weed Removal (Weedy)	
	B	C	D	E		
		%	%	GDD	GDD	DAP
Hays	-0.2 (1.4)	100.0 (1.0)	110 (0)	1004 (0)	-	-
Manhattan	1.3 (1.1)	-91.3 (6.2)	99.4 (8.9)	6817 (2659)	693 (1854)	27
Hutchinson	8.5 (7.7)	-10.2 (4.6)	101 (4.5)	3596 (2459)	2546 (15141)	96
	Parameter estimates				Weed-Free Period (Weed-Free)	
Hays	-22.2 (85.2)	90.3 (12.6)	104 (12.6)	764 (808)	872 (1040)	34
Manhattan	-1.4 (4.2)	63.9 (17.7)	103 (42.9)	409 (859)	3258 (23921)	*[b]
Hutchinson	-52.1 (2846)	72.0 (14.5)	96.4 (11.2)	580 (7523)	614 (9096)	23

[a] (-) denotes no yield loss

[b] (*) after grain harvest

Abbreviations: CPWC, critical period of weed control; B, slope at the inflection point; C, lower limit; D, upper limit; E, 50% response between the upper and lower limits (inflection point); GDD is the accumulated growing degree days at either the start or end of the CPWC; and DAP is days after planting

Table 2.7 Parameter estimates (SE) for relative grain sorghum biomass regression from Equation 2-2 from Hays and Manhattan in 2016 and 2017 and Hutchinson in 2017.

Site	Year	Parameter Estimates				Threshold of Weed Removal (Weedy)	
		B	C	D	E		
			%	%	GDD	GDD	DAP
Hays	2016	16.2 (420)	76.3 (8.9)	100 (17.8)	432 (723)	361 (1106)	16
Hays	2017	-22.4 (103)	95.9 (10.3)	107 (10.3)	770 (985)	675 (909)	26
Manhattan	2016	-31.3 (0.94)	88.2 (6.62)	96.3 (9.36)	1570 (913)	0.82 (21)	0
Manhattan	2017	0.35 (0.94)	150 (145)	100 (13.6)	3679 (47568)	1429 (949)	55
Hutchinson	2017	30.3 (82.3)	-340 (1448)	99.7 (2.9)	2073 (2462)	1882 (2157)	65
		Parameter Estimates				Weed-Free Period (Weed-Free)	
Hays	2016	0.0 (-)	95.4 (21.6)	162 (0.056)	66.1 (62549)	-[a]	-
Hays	2017	0.33 (3.01)	105 (44.3)	78.9 (405.6)	44463 (3582)	*[b]	*
Manhattan	2016	9.4 (58.9)	94.2 (11.9)	106 (14.9)	871 (723)	1193 (2492)	39
Manhattan	2017	23.1 (104.6)	102.4 (11.6)	136 (11.6)	584 (698)	663 (888)	28
Hutchinson	2017	0.0 (0.002)	134 (20.4)	76.5 (9.3)	615 (10.0)	*	*

[a] (-) Denotes no decrease in grain sorghum biomass

[b] (*) Could not be determined

Abbreviations: CPWC, critical period of weed control; B, slope at the inflection point; C, lower limit; D, upper limit; E, 50% response between the upper and lower limits (inflection point); GDD is the accumulated growing degree days at either the start or end of the CPWC; and DAP is days after planting

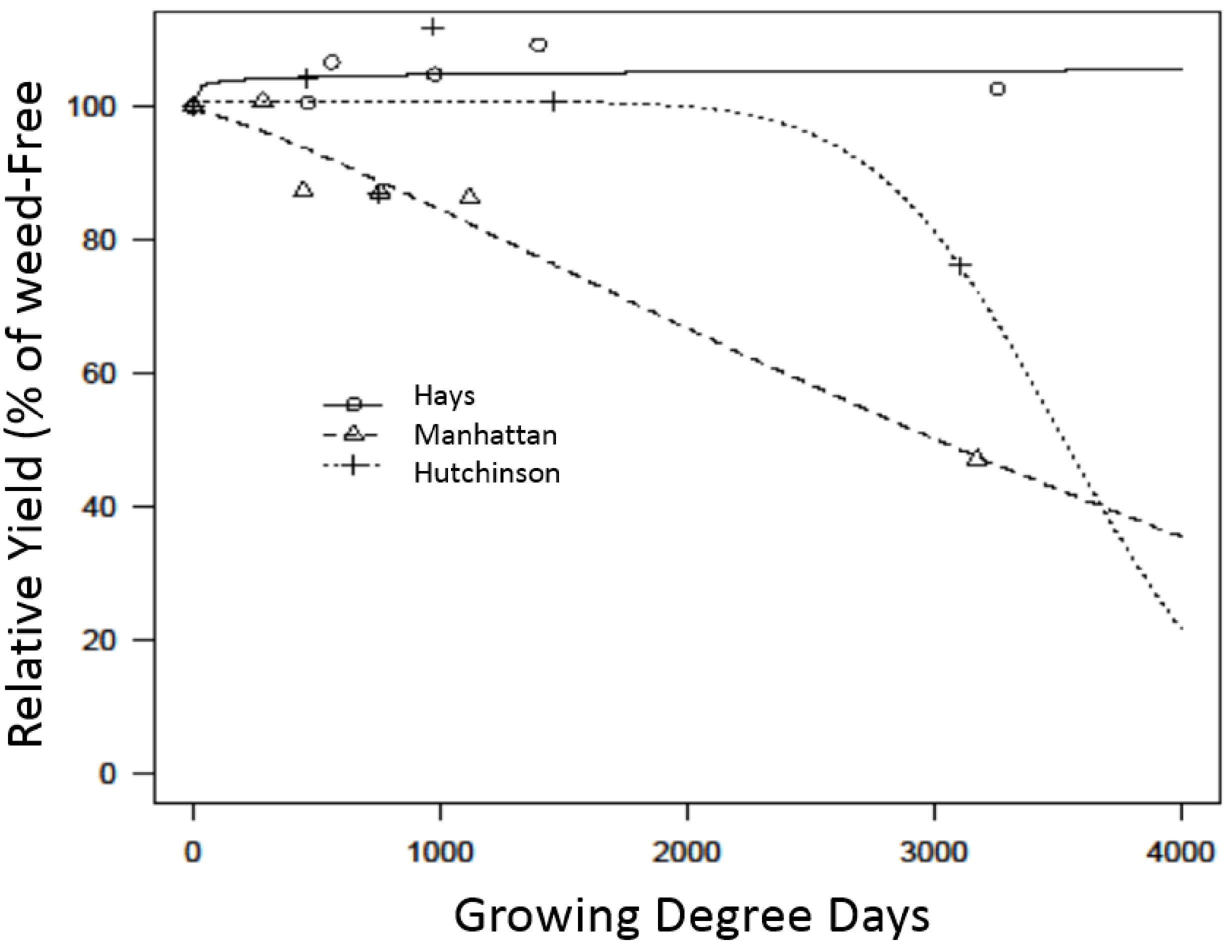

Figure 2.1 Relative grain sorghum yield (%) as a function of increasing duration of weed interference at Hays (o), Manhattan (Δ), and Hutchinson, KS (+) in 2017. Lines were predicted by fitting Equation 2-2 to weedy treatments.

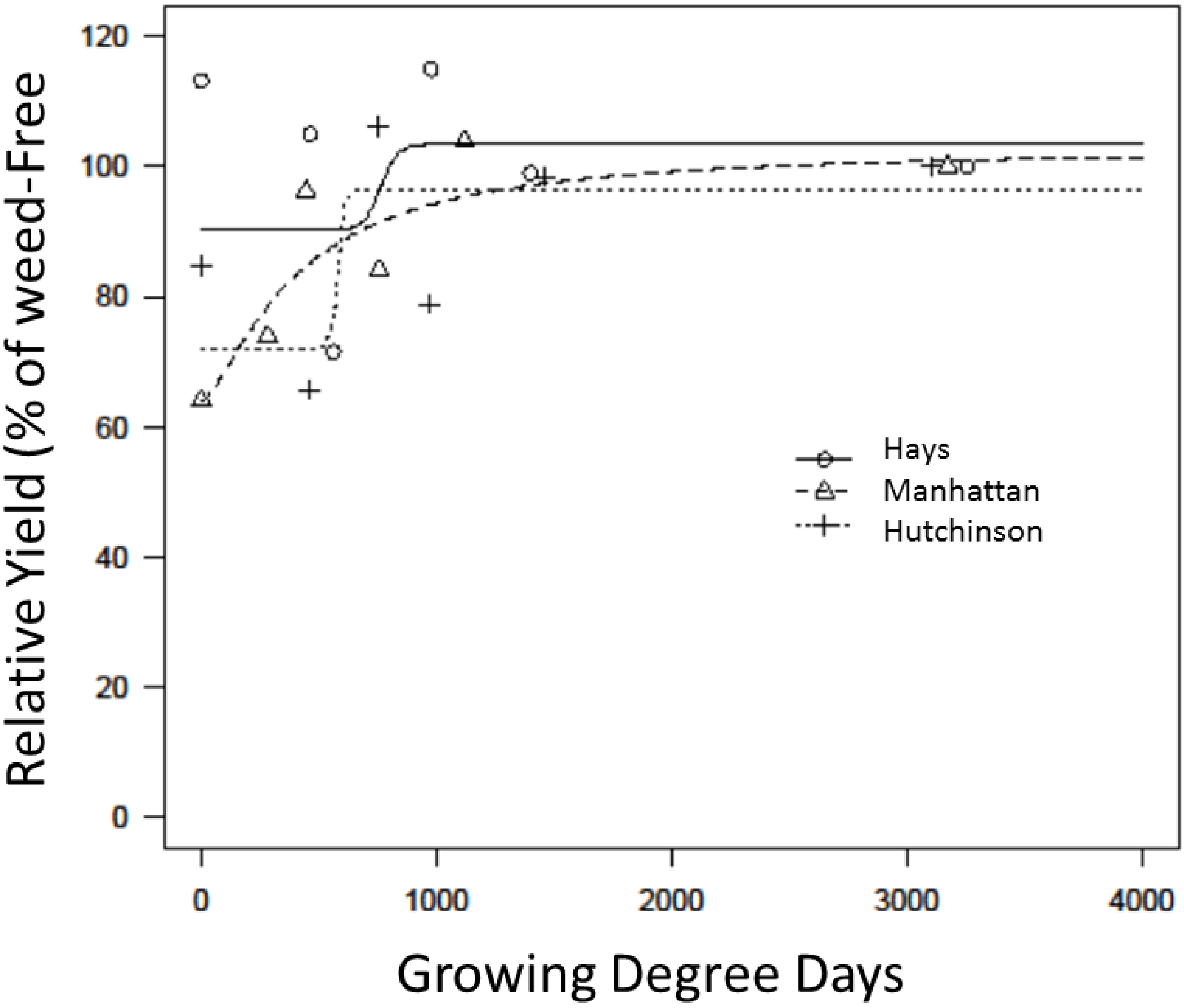

Figure 2.2 Relative grain sorghum yield (%) as a function of increasing weed-free period at Hays (o), Manhattan (Δ), and Hutchinson, KS (+) in 2017. Lines were predicted from fitting Equation 2-2 to weed-free treatments.

Chapter 3 - Emergence of Six Grass Species in Kansas

Abstract

Time of weed emergence relative to crop emergence determines the extent to which weeds effectively compete with a crop. Knowing the timing and duration of weed emergence must be understood to implement an effective weed management strategy. Few herbicidal options are available for POST grass control in grain sorghum, however, an ALS-resistant grain sorghum has recently been developed to allow for use of nicosulfuron as POST grass weed control. Maximum labeled height for control of grass species is listed on nicosulfuron label. Emergence and height development of large crabgrass, barnyardgrass, shattercane, and giant, green, and yellow foxtails were studied near Manhattan, KS after seeding on April 11, 2017. Barnyardgrass had the longest duration of emergence, beginning at 180 GDD after seeding and continued through ending of observations. Large crabgrass had the shortest duration of emergence from 316 to 628 GDD after seeding. The foxtail species began emergence after barnyardgrass but before large crabgrass and finished emergence similar to large crabgrass. Five species achieved 90% emergence by 676 GDD, while barnyardgrass achieved 90% emergence by 3439 GDD. Large crabgrass achieved 5-cm height by 653 GDD. Shattercane achieved 10-cm height by 657 GDD, giant/yellow foxtail mix by 875 GDD, yellow foxtail by 1052 GDD, green foxtail by 1063 GDD, and barnyardgrass by 1743 GDD. Five of the six species achieved 90% emergence during the 6th week after seeding, and no species had achieved the maximum labeled height for herbicidal control. If planting of grain sorghum can be delayed until after 90% emergence has been achieved, then a non-selective method of weed control can remove grasses prior to grain sorghum planting or emergence and limit weed competition with the crop.

Introduction

Weeds must be controlled so that they do not compete with crops for the vital resources that are necessary to grow, develop, and reproduce. Time of weed emergence relative to the crop determines the extent to which weeds effectively compete with a crop (Forcella et al. 2000). Weed species are known to begin and end their emergence pattern at various times throughout a season and for differing durations (Werle et al. 2014). Therefore, if a weed species emerges early and can be controlled with tillage or herbicides before the grain sorghum crop is planted and emerges, it will not compete with the grain sorghum crop (Forcella et al. 1993). However, if grass weeds emerge in the grain sorghum crop a weed manager is left with weed control tools of row-crop cultivation, hand-weeding, application of a POST herbicide, or allowing competition between grain sorghum and grass weeds.

Understanding the emergence timing of weed species is important when determining the most effective method of protecting grain sorghum from competition. The process of emergence was categorized as beginning, ending, and duration of emergence; with the start of emergence at 10%, end of emergence at 90%, and duration of emergence from 10 to 90% (Myers et al. 2004, Werle et al. 2014). The justification for the duration of emergence from 10 to 90% is that weed species often have a few seeds germinate and emerge before and after the bulk of emergence, however, these are difficult to predict. The duration from 10 to 90% emergence is easier to predict and give a reference to base weed management decisions. Weeds were further classified as early-, middle-, and late-emerging species over the summer growing season. Barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.), green foxtail (*Setaria viridis* (L.) P. Beauv.), yellow foxtail (*Setaria pumila* (Poir.) Roem. & Schult.), and giant foxtail (*Setaria faberi* Herrm.) were classified as middle-emerging species, with emergence starting in late April and continuing through May in Iowa (Werle et al. 2014). Large crabgrass (*Digitaria sanguinalis* (L.) Scop.) was classified as a late-emerging species, starting in May and continuing into June in three northeastern US states (Myers et al. 2004). Shattercane (*Sorghum bicolor* (L.) Moench ssp. *verticilliflorum* (Steud.) de Wet ex Wiersema & J. Dahlb) was classified as a late-emerging species by Werle et al. (2014) and was shown to increase germination rate with fluctuating temperatures by Kegode et al. (1998). Emergence timing of all grass weed species coincides with the planting and emergence of grain sorghum in Kansas (Shroyer et al. 1996).

Knowledge about emergence timing allows a manager to understand how long management of a grass weed species should be maintained. An emergence study conducted in a drier and warmer Kansas climate could have different results than studies in Iowa and the northeastern U.S. and have a greater relevance to Kansas grain sorghum producers. The objectives of this research were to determine the start and duration of weed emergence of six grass species and height development relative to a grain sorghum crop in Kansas.

Materials and Methods

Six grass weed species were seeded on April 11, 2017 and included large crabgrass barnyardgrass, green foxtail, yellow foxtail, giant/yellow foxtail mix, and shattercane. Large crabgrass, barnyardgrass, yellow, and giant foxtail seeds were obtained from Azlin Seed Services (Leland MS) and stored frozen until time of seeding. Green foxtail was harvested in Hays, KS in Fall of 2012 and stored in a cold room until time of seeding. Shattercane was harvested near Manhattan, KS and stored frozen until time of planting. The experimental area was prepared in the fall of 2016 with a chisel plow and prior to seeding in the spring with a field cultivator at the Department of Agronomy Ashland Bottoms Experiment Field near Manhattan, KS (39.07^{o}N, -96.38^{o}W). Seeds were packed in small envelopes of either high density (targeting 100 viable seeds) or low density (targeting 25 viable seeds) to facilitate hand spreading. Plots were arranged as paired 0.25 m^2 quadrats in a randomized complete block design with a total of 12 treatments, consisting of six grass species and two densities, with five replications. Each pair of quadrats was separated by one meter. After spreading, soil was lightly raked to mix seed into the top 2 cm of soil. Grain sorghum was planted into rows spaced 76-cm apart on June 8, 2017 so that quadrats were between crop rows. This placement facilitated competition between the grain sorghum and weed species. All other weed species within the plot area were removed by hand as needed.

For each pair of quadrats, one quadrat was maintained as a growth and development quadrat where the average height and tiller count were recorded weekly. These measurements were taken on five plants in the low-density quadrat and 25 plants in the high-density quadrat. In the second quadrat, newly emerged plants were counted and removed to determine weekly emergence, however, if the seedlings were too small and underdeveloped to differentiate between grass species, they were left until the following week when they could be identified. Data on precipitation, air, and soil temperature at 5-cm depth were recorded daily by the Kansas Mesonet (Weather Data Library, Kansas State University) beginning with grass weed seeding. Using air temperature, growing degree days (GDD) were calculated daily with the Equation:

$$GDD = \left(\frac{Daily\ Max\ Air\ Temp\ + Daily\ Min\ Air\ Temp}{2}\right) - Base\ Temp \qquad \text{Equation 3-1}$$

where DailyMaxAirTemp is the daily maximum air temperature (C) with no accumulation above a threshold of 37.8 C, DailyMinAirTemp is the daily minimum air temperature (C) with no accumulation below a threshold of 10 C, and BaseTemp is the grain sorghum base temperature of 10 C (Gerik et al. 2003). Daily GDD data were summed to calculate cumulative GDD.

Aboveground grass weed biomass was harvested by clipping all plants at the soil surface, from the growth and development quadrat on July 31, 2017 when all grass weed species had reached mid-bloom. All grain sorghum plants located in 0.5-m of row along each side of the corresponding quadrat were also harvested to total of 1-m of row of grain sorghum biomass. Biomass samples were bagged separately by species and dried at 65 C for two weeks, when dry weights were recorded.

Statistics

Grass species emergence counts, weed biomass, grain sorghum biomass, weed height, and grain sorghum height were presented as least square means attained from ANOVA in SAS 9.4 (Statistical Analysis Systems Institute, Cary NC) using PROC MIXED with the Satterthwaite degrees of freedom method. The interaction of species and density was not significant; therefore, emergence data for each species were combined across densities for ten replications per species. Percent cumulative emergence was calculated in each replication by summing all emerged plants for each species each week and dividing by the total emerged.

Percent cumulative emergence data for each species were regressed using a 3-parameter logistic curve in R statistical software with the drc package (R Development Core Team, 2018):

$$\mathbf{Y = \frac{D}{1 + e^{B(\log X - \log E)}}} \qquad \text{Equation 3-2}$$

where Y is cumulative emergence (%), D is the upper limit (%), X is the time (expressed as GDD), E is the GDD giving a 50% response between the upper and lower limits (inflection point), and the parameter B is the slope of the line at the inflection point (Knezevic and Datta 2015). Parameter B indicates the emergence rate of each species over GDD, and the more negative the slope the greater the emergence rate. This method was used by Kumar et al. (2018) to describe the emergence of kochia (*Kochia scoparia* (L.) Schrad.), where the estimated dose

(ED) command in R statistical software was adapted to determine the GDD for emergence initiation (ED_{10}), end (ED_{90}), and duration (ED_{90}-ED_{10}) for each grass species. Parameter estimates for the ED values where compared using the Comp-Parm command in R to determine differences of emergence timing among species.

To determine when grass species reached 5 and 10 cm heights a linear equation was fit to height data from the first seven observation timings using SigmaPlot 12.3 (Systat Software, Inc., San Jose, CA):

$$\mathbf{Y = mx + y_0} \qquad \text{Equation 3-3}$$

where Y is the height (cm), m is the slope of the line, x is the GDD, and y_0 is the intercept.

Results and Discussion

The model for cumulative emergence for all species did not pass the lack-of-fit test with a p-value of 0.0001. The lack-of-fit test determines if the model fits the data; with a significant p-value (<0.05) the model has a lack-of-fit, therefore, the model does not describe the data well. This was likely because emergence data from six different species were fit using a single model, and the species are expected to have different emergence patterns. To illustrate this point yellow foxtail reached 100% cumulative emergence by the 5th observation timing, whereas barnyardgrass continued steady emergence through the last observation timing at the end of July (Figure 3.1). These two species had very different emergence data, however, the figure appears to model the species well. Especially considering that many factors affect germination and emergence of grass species. Using the same model for all six species allows a weed manager to interpret the same figure and understand how the species are behaving in relation to each other.

Barnyardgrass reached 10% cumulative emergence in similar time with green foxtail and shattercane, but before yellow foxtail, giant/yellow foxtail and large crabgrass (Table 3.1). The last species to reach 10% emergence was large crabgrass. Yellow, green, and giant/yellow foxtail, and shattercane reached 90% cumulative emergence in similar time to large crabgrass and barnyardgrass. However, large crabgrass reached 90% cumulative emergence before barnyardgrass, which was the last species to reach 90% cumulative emergence.

The duration of emergence was shortest for large crabgrass requiring 312 GDD from beginning to ending emergence (ED_{90}-ED_{10}), indicating that the window of emergence for this species was short compared to the other five grass species (Table 3.1). In order of increasing duration, yellow foxtail, giant/yellow foxtail, green foxtail, and shattercane. Myers et al. (2004) classified large crabgrass as a species having a long duration of emergence, which is opposed to the findings of this study. If emergence counts would have continued there would likely have been continued emergence observed from large crabgrass. Werle et al. (2014) had similar findings, that yellow foxtail had a shorter duration of emergence compared to giant and green foxtail in Iowa. Barnyardgrass had the longest duration of emergence in this study with 3,257 GDD, which indicated that it will continue to emerge throughout the growing season, but barnyardgrass did not have a long duration of emergence in the Iowa study (Werle et al. 2014). The grass species studied may require weed control at different times because they have different rates of emergence.

All grass weed species had reached mid-bloom and grain sorghum had reached visible flag leaf at time of biomass harvest on July 31, 2017. Weed biomass data in the high density treatments were collected from 25 plants m^{-2}, whereas the low density treatments were collected from 5 plants m^{-2}. Weed biomass, grain sorghum biomass, and grain sorghum heights were not different across species and within the same density (Table 3.2). This suggests that competition from grass species did not negatively impact grain sorghum biomass and height accumulation. Weed height varied among grass species, with shattercane the tallest across both densities and barnyardgrass the shortest grass in the high density. Barnyardgrass, large crabgrass, and green foxtail were the shortest grass species in the low density treatment. While giant/yellow foxtail was similar to green foxtail and yellow foxtail, yellow foxtail was the second tallest grass in the low density treatment.

According to Bradford (2002) imbibition of water by seeds requires a very low water potential because seeds are very dry. Therefore, ample moisture was received during the first seven weeks to create a soil moisture environment that facilitated grass seed germination (Table 3.3). Weeks eight, nine, ten, and twelve received little rainfall, however, precipitation received in week eleven stimulated a late flush of barnyardgrass and shattercane emergence (Figure 3.1). The mean 5 cm soil temperature at seeding was 13 C but was above 15 C at the first observation timing and increased throughout the 12 weeks (Table 3.3). Optimum giant foxtail germination occurs between soil temperatures of 15 to 30 C (Kegode et al. 1998; Fausey and Renner 1997). The optimum germination soil temperature for the remaining species has not been determined in previous research, however, they would likely be similar for the species with similar emergence timings.

Herbicide labels often list a maximum height for certain weed species at or below which control can be expected. The Zest™ label lists control of large crabgrass up to a maximum height of 5 cm, while barnyardgrass and green, yellow, and giant foxtail are listed as controlled up to 10 cm (Anonymous 2016). Shattercane is not listed as a weed that can be controlled by Zest™.

An understanding of when these grass species reach the listed heights will help guide POST applications. Shattercane was the first species to reach 5 and 10 cm height and would be the first species that needed to be controlled (Table 3.4 and Figure 3.2). Large crabgrass was predicted to reach 5 cm at a similar time as shattercane reached 10 cm height. Giant/yellow foxtail was the next second species to reach 10 cm height followed by yellow foxtail, green foxtail, large crabgrass and barnyard grass.

Five of the six grass species reached 90% emergence by 676 GDD after seeding (Table 3.1). Large crabgrass was the first species to reach maximum controllable height by 653 GDD. This indicates that implementing a control strategy by 653 GDD would control of 90% of the total emergence. Further, all species would still be under the maximum controllable height of herbicides (Table 3.4). Barnyardgrass would be the only species that continued to steadily emerge and need further control.

Weeds that emerge with the crop have been found to cause greater yield loss than weeds which emerge after the crop (Dieleman et al. 1995, Hock et al. 2006). Delayed planting has been found to maximize the weeds that are controlled prior to planting, thus reducing the crop-weed competition and achieving greater yields (Forcella et al. 1993). If grain sorghum producers can delay planting until June, then 90% of grass weed emergence for five of the six species can be controlled with a non-selective herbicide or tillage prior to planting and emergence of the grain sorghum.

Conclusion

Understanding emergence timing and duration of weed species is the cornerstone of biological knowledge necessary for a weed manager to exploit weaknesses and limit competition and seed production (Norsworthy et al. 2012). Knowing that 90% of grass weeds will have emerged by the end of May in Kansas allows the opportunity to delay planting and control all emerged weeds prior to planting. Planting grain sorghum into a weed-free field and implementing a weed management strategy prior to weed emergence, such as a preemergence herbicide, then controlling grass weeds through duration of emergence will limit crop competition and provide the best opportunity to attain maximum yield.

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Tables and Figures

Table 3.1 Parameter estimates for the 3-parameter regression model (Equation 3-2) used to estimate GDDs (and standard error) for 10, 50, and 90% emergence of six grass species. D is the upper limit, E is the GDD giving a 50% response between the upper and lower limits (inflection point), and the parameter B is the slope of the line at the inflection point.

Species	Parameter estimates (SE)			Predicted values (SE)		
	B	D	E_{50}	ED_{10}	ED_{90}	Duration (ED_{90}- ED_{10})
		%	----------------------------	GDD	--------------------------	
large crabgrass	-6.39 (0.92)	98 (1.9)	445 (11)	316 (19) c	628 (31) a	312
barnyardgrass	-4.50 (0.29)	111 (20.5)	791 (234)	182 (19) a	3439 (1964) b	3257
green foxtail	-4.12 (0.49)	99 (2.0)	361 (13)	212 (16) ab	615 (42) ab	403
yellow foxtail	-5.18 (0.72)	101 (1.9)	372 (12)	244 (18) b	569 (33) ab	325
giant/yellow foxtail	-4.80 (0.71)	101 (2.1)	397 (13)	251 (21) b	628 (43) ab	377
shattercane	-3.71 (0.46)	92 (2.2)	374 (15)	207 (16) ab	676 (60) ab	469

Table 3.2 Total emergence from the count and pull quadrats (with standard error), and weed and sorghum biomass and height (with standard error) for six grass species at high (~100 seeds) and low (~25 seeds) densities, and harvested from the growth and development quadrats when all grass species reached mid-bloom on July 31, 2017 in Kansas. Weed biomass for the high density is 25 plants and low density is 5 plants.

Density	Species	Total Emergence	Weed Biomass	Sorghum Biomass	Weed Height	Sorghum Height
		# 0.25 m^{-2}	g 0.25 m^{-2}	g m^{-1} row	cm	cm
High	large crabgrass	66 (9) a[a]	1505 (625) a	318 (56) a	77 (9) c	72 (5) a
	barnyardgrass	33 (9) b	1078 (461) a	378 (54) a	61 (6) d	84 (4) a
	green foxtail	31 (9) b	752 (163) a	331 (59) a	84 (5) c	84 (3) a
	yellow foxtail	52 (9) ab	1053 (538) a	331 (52) a	110 (2) b	75 (6) a
	giant/yellow foxtail	32 (10) b	1066 (534) a	338 (76) a	98 (5) bc	72 (4) a
	shattercane	62 (9) a	1467 (629) a	308 (52) a	241 (8) a	72 (4) a
Low	large crabgrass	35 (4) a	649 (269) a	415 (36) a	65 (5) d	82 (7) a
	barnyardgrass	15 (5) bc	1449 (485) a	387 (60) a	65 (5) d	78 (5) a
	green foxtail	16 (4) bc	752 (309) a	281 (64) a	78 (4) cd	75 (5) a
	yellow foxtail	24 (4) ab	1369 (717) a	313 (84) a	97 (7) b	80 (6) a
	giant/yellow foxtail	15 (4) bc	852 (634) a	346 (92) a	85 (10) bc	71 (7) a
	shattercane	9 (5) c	1073 (449) a	356 (41) a	233 (5) a	76 (6) a

[a] For each density and column, different lowercase letters identify significant differences among grass species at α=0.05.

Table 3.3 Growing degree day accumulation using long season grain sorghum formula (Equation 3-1), mean soil temperature at 5 cm depth, and rainfall by week starting April 11 and ending July 31, 2017.

Weeks after seeding	Calendar Date	Growing degree days	5 cm soil temperature	Rainfall
			C	mm
1	25-April	195	16	33
2	5-May	253	15	42
3	10-May	356	21	2
4	16-May	481	23	8
5	24-May	571	18	55
6	30-May	675	24	21
7	6-June	831	27	12
8	13-June	1019	29	0
9	21-June	1254	29	3
10	28-June	1406	27	4
11	5-July	1576	28	63
12	12-July	1799	31	0
Total	31-July	2388	-	275

Table 3.4 Parameter estimates for Equation 3-3 where Y is the height in cm, m is the slope of the line, x is the GDD from April 11, 2017, and y_0 is the intercept. Predicted GDD when grass weed species reach 5 and 10-cm height, and the R^2 value for each line fit.

Species	Parameter estimates (SE)				
	m	y_0	R^2	Y=5 cm	Y=10 cm
	cm GDD^{-1}	cm		GDD	
large crabgrass	0.012 (0.0022)	-2.83 (1.13)	0.866	653	1069
barnyardgrass	0.006 (0.0015)	-0.46 (0.78)	0.78	910	1743
green foxtail	0.011 (0.0021)	-1.69 (1.12)	0.842	608	1063
yellow foxtail	0.011 (0.002)	-1.57 (1.05)	0.866	597	1052
giant/yellow foxtail	0.015 (0.002)	-3.12 (1.03)	0.92	541	875
shattercane	0.022 (0.0001)	-4.45 (0.01)	0.955	430	657

Growing Degree Days

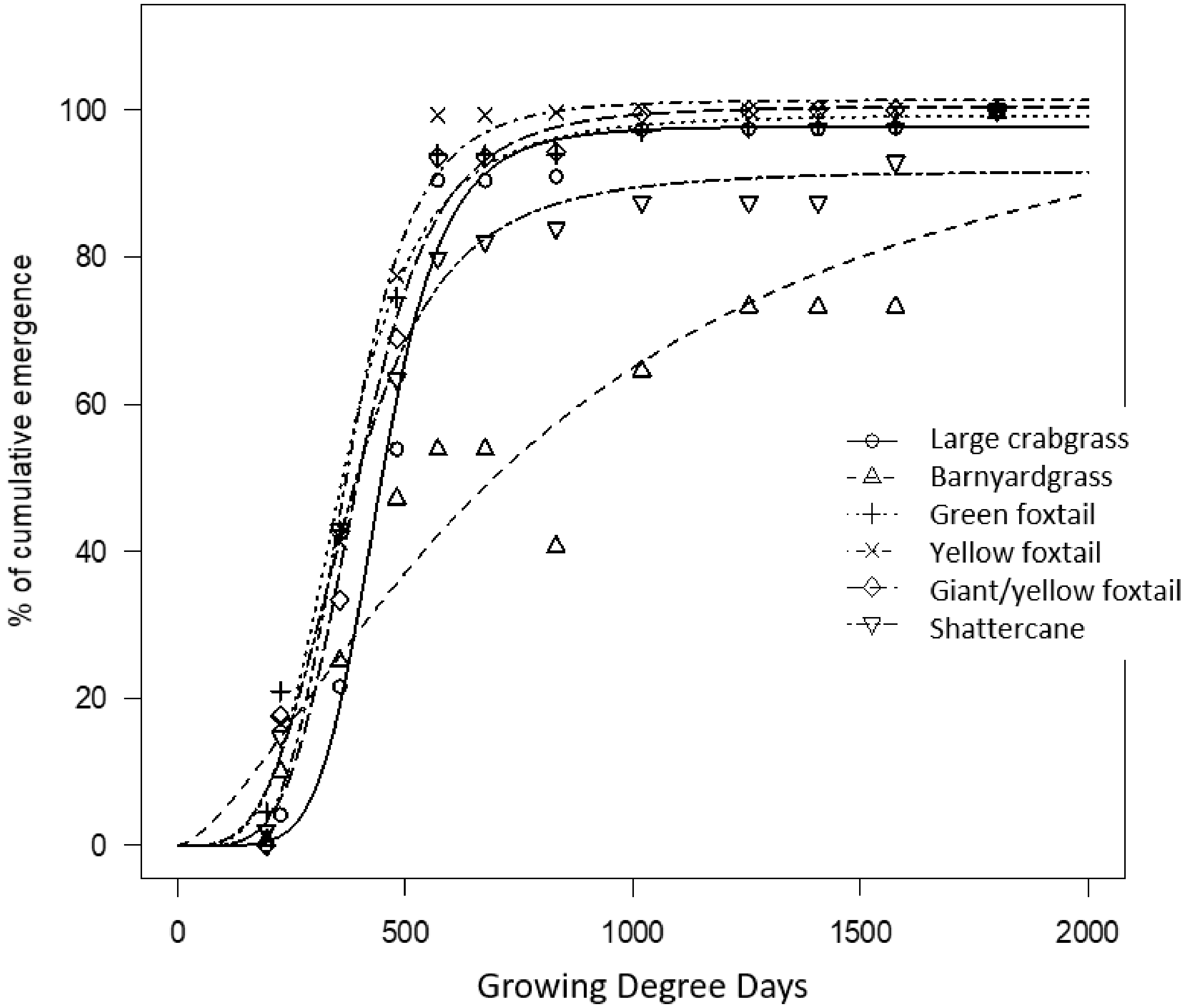

Figure 3.1 Percent cumulative emergence by growing degree days (GDD) from time of grass seeding on April 11 to July 31, 2017 for six grass species: large crabgrass (○), barnyardgrass (△), green foxtail (+), yellow foxtail (×), giant/yellow foxtail mix (◊), shattercane (▽) over time

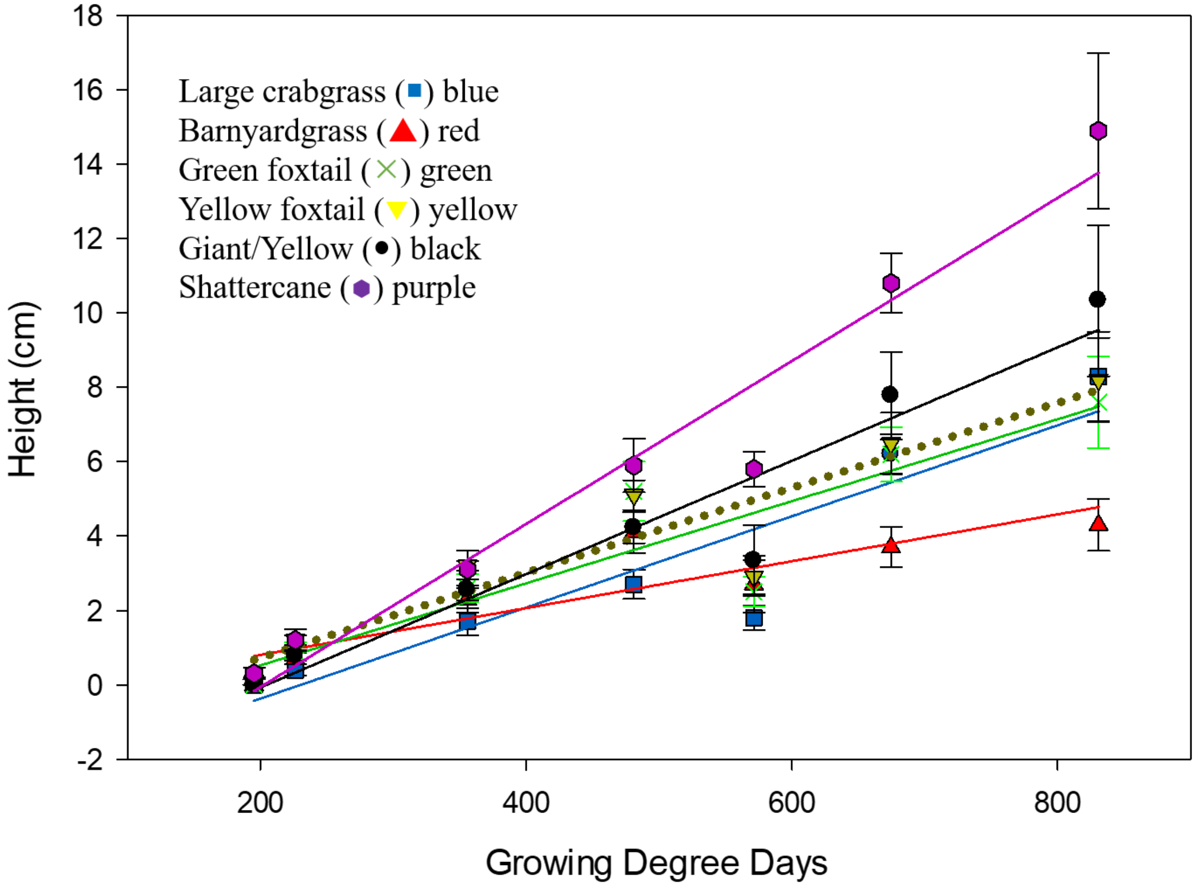

Figure 3.2 Grass weed height development from time of grass seeding on April 11 to June 6, 2017 (0 to 831 GDD). Points are means from cumulative emergence data from 10 replications and lines are predicted height based on Equation 3-3.

Chapter 4 - Herbicidal Control of Atrazine-Resistant Palmer amaranth (*Amaranthus palmeri*) in Double-Crop Grain Sorghum

Abstract

A common cropping practice in the southern plains region is double cropping; planting grain sorghum immediately after winter wheat harvest. In double-crop grain sorghum fields in Kansas, Palmer amaranth (*Amaranthus palmeri* S. Watson) is among the most troublesome weeds, especially if herbicide-resistant populations are present, and drive many weed management decisions. To evaluate control of atrazine-resistant and susceptible Palmer amaranth in double-crop grain sorghum a diversity of herbicide programs were assessed and included eight PRE only and six PRE followed by POST applications. Visual ratings of Palmer amaranth control were taken 3 and 8 weeks after planting. PRE treatments containing very long chain fatty acid-inhibiting herbicides provided 91% control of atrazine-resistant Palmer amaranth three weeks after planting. PRE followed by POST treatments provided greater control (71 to 93%) of both atrazine-resistant and susceptible Palmer amaranth 8 weeks after planting compared to PRE treatments alone (59 to 79%). These results demonstrated the value of residual herbicides controlling atrazine-resistant Palmer amaranth, as well as the value of an effective POST application following residual herbicides for controlling both atrazine-resistant and -susceptible Palmer amaranth in double-crop grain sorghum.

Introduction

Grain sorghum is the sixth most common crop in the United States being grown on 1.2 million hectares in 2016 (NASS 2017). As with all crop production, competition with weeds is among the top yield reducers for grain sorghum. Palmer amaranth (*Amaranthus palmeri* S.

Watson) was rated as the most troublesome weed by the Weed Science Society of America in a 2015 Survey (Van Wychen 2016), and is a problem weed in grain sorghum production in Kansas (Peterson 1999). No-till production is especially important for double-crop grain sorghum because soil moisture often is limited following a winter wheat crop, and the main tools for weed control in no-till crop production are herbicides. Grain sorghum has fewer options for chemical weed control compared to other major crops such as corn, soybeans, and cotton in the United States.

Palmer amaranth has been documented to be resistant to at least four different herbicide sites of action in Kansas (Heap 2018; Peterson 1999), which makes managing Palmer amaranth especially challenging. It is important that weeds do not germinate and grow up with the crop when managing herbicide-resistant weed species. In no-till, this is achieved by using soil-applied, preemergence (PRE) herbicides, which is an excellent way to implement WSSA's Best Management Practices #6 "Use multiple herbicide mechanisms of action that are effective against the most troublesome weeds or those most prone to herbicide resistance" (Norsworthy et al. 2012).

Different weed species have different emergence times and patterns across a given year. Some weeds like Palmer amaranth have extended emergence such that they continue to emerge throughout the growing season (Norsworthy et al. 2014). The difference in emergence timing of weed species influences the timing and duration needed for weed management. Weed management is also greatly influenced by crop planting date because of crop competition and shading (Jha and Norsworthy 2009). The recommended planting time for grain sorghum in Kansas is from the beginning of May through the end of June. Double-crop grain sorghum is typically planted in late June to early July after winter wheat harvest (Shroyer et al. 1996). These different planting dates influence what weed species will most likely emerge with grain sorghum and the competitive ability of grain sorghum.

Little research has been conducted for weed control in double-crop grain sorghum since the 1960s (Phillips 1969), when few herbicides were on the market and no-till crop production was not as feasible or widely accepted as today. This presents an opportunity to update data, knowledge, and share a valuable perspective to aid producers in making herbicidal weed control decisions for double-crop grain sorghum production.

Material and Methods

Field experiments were conducted near Manhattan and Hutchinson, KS in 2016 and 2017. Within 24 hours after winter wheat harvest, glyphosate (1542 g ae ha^{-1}) (RoundUp PowerMax, Monsanto Company, St. Louis, MO) and ammonium sulfate (1% v/v) (N-Pak, Winfield Solutions, St. Paul, MN) were applied over the entire plot area for control of emerged grasses. Two hours after glyphosate application, grain sorghum hybrid HG 48-B (Heartland Genetics, Beloit, KS) was planted at 123,500 seeds ha^{-1} into winter wheat stubble in rows spaced 76-cm apart with four rows per plot. The site near Hutchinson was planted on June 29, 2016 and June 22, 2017. The site near Manhattan was planted on June 30, 2016 and June 21, 2017. Treatments were arranged as a randomized complete block design with plot dimensions of 7.6 m long by 3 m wide and four replications.

Fourteen herbicide treatments and one non-treated check were evaluated, with multiple herbicidal products from several herbicide manufacturing companies (Table 4.1). Treatments consisted of eight PRE-only and six PRE followed by a postemergence (POST) application three weeks later (Table 4.2). Atrazine-resistant Palmer amaranth was present at the Hutchinson site, and atrazine-susceptible Palmer amaranth was present at the Manhattan site. Nine of the PRE treatments contained a very long chain fatty acid (VLCFA) -inhibiting herbicide, two with the addition of saflufenacil, and one with the addition of mesotrione. These nine treatments are the only treatments containing sites of action effectively controlling Palmer amaranth in a PRE application at Hutchinson. Immediately after planting, paraquat (933 g ha^{-1}) (Gramoxone SL 2.0, Syngenta Crop Protection, Greensboro, NC) and crop oil concentrate (1% v/v) (Prime oil, Winfield Solutions, St. Paul, MN) were applied over all plots for the control of emerged glyphosate-resistant broadleaf weeds and tank-mixed with PRE treatments. POST treatments were applied 3 WAP. All herbicide treatments were applied with a CO_2 backpack sprayer and a 1.9 m handheld boom equipped with AIXR 110015 nozzles (TeeJet Technologies, Wheaton, IL) at a volume of 140 L ha^{-1} at 220 kPa, and a speed of 4.8 km h^{-1}. Treatments were centered over the four crop rows, covering 1.9 m of the 3 m plot width.

One week after planting, 172 kg N ha^{-1} as urea (46-0-0) was applied with a hand spreader. In 2016, both sites received an insecticide application of flupyradifurone (Sivanto, Bayer CropScience, Research Triangle Park, NC) at mid-bloom to control a sugarcane aphid infestation.

Precipitation was measured and recorded by Kansas Mesonet (Weather Data Library, Kansas State University) located within 2.5 km of all sites. Palmer amaranth control was visually evaluated 3 and 8 weeks after planting (WAP) between the center two rows of each plot and recorded as percent control relative to the non-treated plots with 0% being no weed control and 99% as complete weed control. Weed height, density, and above ground biomass were recorded for each plot from 0.25 m^2 quadrats at grain sorghum physiological maturity in both 2016 and 2017. Biomass was bagged, dried at 65 C for one week, and dry weights were recorded. The center two rows of each plot were combine harvested at Manhattan in both years. Grain sorghum heads at Hutchinson were hand harvested from center two rows for 2 m in 2016 and the entire plot length was hand harvested in 2017. Collected heads were threshed with a plot combine to determine yield and grain moisture for Hutchinson. All grain yield data were adjusted to 14.5% moisture.

Weed control at 3 and 8 WAP, grain yield, weed biomass, weed height, and weed density were subjected to ANOVA using Mixed Procedure in Jmp Pro 12 (SAS Institute, Cary, NC) and means separated using Fisher’s Protected Least Significant Difference (LSD) at $\alpha=0.05$. Treatment was considered as a fixed effect and replication nested within year as a random effect. Density data were log transformed for Manhattan to meet assumptions of equal variance and back transformed for discussion. Biomass and height data were adjusted with the Kenward-Rogers procedure for both sites after no transformation improved the assumption of equal variance (Kenward and Rogers 1997). Sites were analyzed separately due to the presence of atrazine-resistant Palmer amaranth at Hutchinson and atrazine-susceptible Palmer amaranth at Manhattan. Data were pooled across years for each site after no year by treatment interaction was observed. Differences among groups of treatments were compared using orthogonal contrasts with significance at $\alpha = 0.05$ performed in JMP Pro 12. These comparisons included PRE vs. PRE fb POST, PRE with VLCFA-inhibiting herbicides vs. PRE with atrazine only, PRE with saflufenacil or mesotrione and VLCFA vs. PRE with only VLCFA, and POST with pyrasulfotole or dicamba vs. PRE with VLCFA-inhibiting herbicides.

Results and Discussion

Environmental Conditions

All sites received 17 mm or more precipitation from one rain event within 8 days after grain sorghum planting, providing sufficient soil moisture to activate PRE residual herbicides

(Table 4.3). All sites received 21 mm or more precipitation from one rain event within 14 days after POST application, providing sufficient soil moisture to activate POST residual herbicides. Precipitation for July and August 2016 was greater than the 30-year average at both sites and provided adequate moisture for production of double-crop grain sorghum, but in 2017, both sites received less than the 30-year average rainfall (Table 4.4). Hutchinson received less than half the 30-year average for July and August and this created a less than optimum growing environment where the grain sorghum was moisture stressed for extended periods of time (personal observation). Despite the moisture stress in 2017, the grain sorghum crop received enough moisture to produce grain.

Comparison of Herbicide Programs

Herbicide programs that included a PRE fb POST provided greater visual control of Palmer amaranth 8 WAP than PRE treatments alone at Manhattan (Table 4.5) and Hutchinson (Table 4.6). Palmer amaranth biomass, density, and height were reduced more with PRE fb POST treatments compared to PRE treatments alone at both Manhattan and Hutchinson.

PRE treatments containing VLCFA-inhibiting herbicides provided greater visual Palmer amaranth control 3 WAP compared to atrazine only PRE treatments at Hutchinson (Table 4.6). This demonstrated the effectiveness of a PRE application of VLCFA-inhibiting herbicides on atrazine-resistant Palmer amaranth. No differences in control 3 WAP of atrazine-susceptible Palmer amaranth were observed for this contrast at Manhattan (Table 4.5). A comparison of atrazine only PRE treatments showed greater Palmer amaranth control 8 WAP compared to programs containing VLCFA-inhibiting herbicides at Manhattan. Treatments including a POST herbicide provided weed control further into the growing season, likely because VLCFA-inhibiting herbicides degrade over time (Beestman and Deming 1974). For instance, a treatment that contained VLCFA-inhibiting herbicides applied PRE and POST had 99% Palmer amaranth control compared to the same herbicide applied PRE only with 80% control 8 WAP at Hutchinson (Table 4.7). This suggested that an effective residual herbicide can provide season-long control of Palmer amaranth when applied PRE and POST. Across sites and years, Palmer amaranth biomass and height were not different between PRE with VLCFA-inhibiting herbicides and atrazine only PRE treatments but weed density at Hutchinson was reduced with VLCFA-inhibiting herbicides.

PRE herbicide programs that contained a VLCFA-inhibiting herbicide plus either saflufenacil or mesotrione provided greater Palmer amaranth control 3 WAP than did PRE treatments containing a VLCFA-inhibiting herbicide and no saflufenacil or mesotrione at Manhattan (Table 4.5) but not at Hutchinson (Table 4.6). No difference in control between these treatment groups was observed 8 WAP at either site. Weed biomass, density, and height were not affected by the addition of saflufenacil or mesotrione to a PRE containing VLCFA-inhibiting herbicides. This is likely because the addition of another effective herbicide is not captured by the already high levels of control achieved by VLCFA-inhibiting herbicides.

Treatments with a POST that contained pyrasulfotole or dicamba provided greater Palmer amaranth control compared to any treatments that contained VLCFA-inhibiting herbicides 8 WAP at Manhattan (Table 4.5). Weed height was decreased at both sites but biomass was decreased at Manhattan only (Table 4.5 and Table 4.6). The emergence and growth of atrazine-resistant Palmer amaranth through atrazine only PRE treatments resulted in poor Palmer amaranth control with the POST treatments at Hutchinson. Dense weed populations have been shown to decrease efficacy of POST control by limiting weed coverage (Legleiter et al. 2018). Shultz et al. (2015) found PRE fb POST herbicide programs provided greater control of waterhemp (*Amaranthus rudis* J.D. Sauer) compared to POST only. This last contrast emphasized the level of control that effective POST herbicides can provide when preceded by an effective PRE treatment.

Multiple effective sites of action in herbicide programs

To control a weed, an herbicide containing an effective site of action must come into contact with plants through the soil (residual) or foliar tissues. The treatments in this study included both residual and foliar applied herbicide products and the number of effective sites of action differed across sites because of the presence of atrazine-resistant Palmer amaranth at Hutchinson and atrazine-susceptible Palmer amaranth at Manhattan (Table 4.2). Greater control was not observed with two effective sites of action compared to one effective site of action at Hutchinson (Table 4.2 and Table 4.8), likely due to the high efficacy of the VLCFA-inhibiting herbicides in those treatments. Previous research has shown that the use of at least 2.5 effective sites of action per application conferred the best control of troublesome weeds such as Palmer amaranth and delayed resistance evolution (Evans et al. 2015). Using multiple effective sites of action is described in Best Management Practice #6 “to reduce the likelihood of incurring herbicide resistance” (Norsworthy et al. 2012). Therefore, using multiple effective sites of action in each herbicide application will ensure the longevity of effective herbicides used in grain sorghum.

Grain Yield

The grain yields were not different for any of the orthogonal contrasts for treatments at Manhattan (Table 4.5) or Hutchinson (Table 4.6). Across treatments at Manhattan, three PRE only treatments achieved grain yields that were not different that the non-treated, while all other treatments achieved grain yields not different from each other but greater than the non-treated (Table 4.7). Across treatments at Hutchinson, eight treatments achieved grain yields that were not different from each other but greater than the remaining six treatments, that achieved grain yield not different from the non-treated (Table 4.8).

In this study, yield differences were difficult to attribute to specific herbicide programs. Many factors other than weed control likely contributed to variability in grain yield, such as soil fertility, soil moisture, and heat stress during grain sorghum flowering and grain fill. Palmer amaranth, if left uncontrolled can make a crop completely unharvestable, therefore, control of Palmer amaranth remains critical (Norsworthy et al. 2014). Grain sorghum producers should consider differences in weed control and choose the best herbicidal weed control program to limit weed interference with crop production.

Conclusion

No-till planting makes herbicidal weed control the primary method used in double-crop grain sorghum. This study did not show that the use of multiple effective sites of action provided greater Palmer amaranth control compared to one effective site of action per application. However, repeated use of a single site of action will lead to development of herbicide resistance at a more rapid rate compared multiple effective sites of action used in each application (Evans et al. 2015). The ‘triangle method’ should be used to preserve yield and the continued use of effective herbicides in double-crop grain sorghum. The three sides of the triangle, which cannot be broken, are: (1) plant into weed-free fields, (2) use overlapping residual herbicides PRE and POST, (3) use multiple effective sites of action with each application (Hay 2018, personal communication). The results of this study show that adequate weed control of atrazine-resistant and -susceptible Palmer amaranth can be achieved using effective residual herbicides, such as

VLCFA-inhibiting herbicides, as well as an effective POST application in double-crop grain sorghum.

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Tables and Figures

Table 4.1 Herbicide active ingredient, trade name, manufacturer and site.

Active Ingredient	Trade Name	Rate	Manufacturer	Location
		g ai/ae ha^{-1}		
S-metolachlor + mesotrione + atrazine	Lumax	2031 + 203 + 762	Syngenta Crop Protection, LLC	Greensboro, NC
dimethenamid-P + saflufenacil	Verdict	1267 + 50	BASF Corporation	Research Triangle Park, NC
acetochlor + atrazine	Degree Xtra	2814 + 1396	Monsanto Company	St. Louis, MO
S- metolachlor + atrazine	Bicep II Magnum	1421 + 1835	Syngenta Crop Protection, LLC	Greensboro, NC
dimethenamid-P	Outlook	1105	BASF Corporation	Research Triangle Park, NC
bromoxynil	Buctril	421	Bayer CropScience	Research Triangle Park, NC
bromoxynil + pyrasulfotole	Huskie	246 + 44	Bayer CropScience	Research Triangle Park, NC
dicamba	Clarity	281	BASF Corporation	Research Triangle Park, NC
atrazine	Aatrex	1123 or 562 or 1684	Syngenta Crop Protection, LLC	Greensboro, NC

Table 4.2 Effective sites of action on atrazine-susceptible Palmer amaranth at Manhattan and atrazine-resistant Palmer amaranth at Hutchinson for each application for herbicide treatments of soil residual and foliar control.

Treatments			Manhattan		Hutchinson	
	Rate	Timing	Residual	Foliar	Residual	Foliar
Non-treated	g ai/ae* ha^{-1}					
dimethenamid-P	1105	PRE	1	-	1	-
dimethenamid-P + saflufenacil	1267 + 50	PRE	2	-	2	-
dimethenamid-P + saflufenacil + atrazine	1067 + 50 +1123	PRE	3	-	2	-
S- metolachlor + atrazine	1421 + 1835	PRE	2	-	1	-
S- metolachlor + saflufenacil + atrazine	1424 + 1835 +50	PRE	3	-	2	-
S-metolachlor + mesotrione + atrazine	2031 + 203 + 762	PRE	3	-	2	-
acetochlor + atrazine	2814 + 1396	PRE	2	-	1	-
atrazine	1684	PRE	1	-	0	-
dimethenamid-P + atrazine fb dimethenamid-P + atrazine	579 + 1123 fb 528 + 562	PRE fb POST	2	1	1	0
acetochlor + atrazine fb acetochlor + atrazine	2814 + 1396 fb 1291 + 641	PRE fb POST	2	1	1	0
atrazine fb bromoxynil + atrazine	1123 fb 421 + 562	PRE fb POST	1	2	0	1
atrazine fb bromoxynil + pyrasulfotole + atrazine	1123 fb 246 + 44 + 562	PRE fb POST	1	3	0	2
atrazine fb dicamba + atrazine	1123 fb 281* +562	PRE fb POST	1	2	0	1
atrazine fb atrazine	1123 fb 562	PRE fb POST	1	1	0	0

Abbreviations: PRE, preemergence; POST, postemergence; fb, followed by;

Table 4.3 Rainfall (mm) by week after PRE application date at Manhattan and Hutchinson in 2016 and 2017.

		Date of Application		Rainfall								
				Weeks after PRE application								
Site	Year	PRE	POST	1	2	3	4	5	6	7	8	Total
				mm								
Manhattan	2016	June 30	July 21	44	67	0	28	16	34	19	46	254
	2017	June 22	July 18	4	63	0	0	31	3	97	35	232
Hutchinson	2016	June 29	July 20	56	11	21	13	27	51	55	0	234
	2017	June 22	July 22	0	19	0	8	7	8	43	5	91

Table 4.4 Rainfall totals (mm) for the months of July and August and the 30-year average at Manhattan and Hutchinson in 2016 and 2017.

	Manhattan			Hutchinson		
Month	2016	2017	30-year	2016	2017	30-year
	mm					
July	155	34	112	128	24	96
August	186	155	112	205	55	80
July and August	341	188	224	333	79	175

Table 4.5 Orthogonal contrasts of treatments on visual Palmer amaranth control at 3 and 8 weeks after planting (WAP), and on Palmer amaranth biomass, density, height, and grain yield in double-crop grain sorghum at Manhattan averaged across 2016 and 2017.

Orthogonal Contrasts	Treatments in Contrast	3 WAP	8 WAP	Grain Yield	Weed Biomass	Weed Density	Weed Height
	# vs. #	% Visual Control		kg ha^{-1}	g m^{-2}	no. m^{-2}	cm
PRE alone **vs**. PRE fb POST	8 vs. 6	-	79 vs. 93 ****	5886 vs. 6126 NS	52 vs. 16 ***	1.15 vs. 0.52 *	68 vs. 20 ****
PRE with VLCFA **vs**. Atrazine PRE	9 vs. 5	90 vs. 93 NS	84 vs. 92 ***	5970 vs. 6022 NS	32 vs. 45 NS	1.09 vs. 0.51 NS	47 vs. 48 NS
PRE with saflufenacil or mesotrione + VLCFA **vs**. PRE with VLCFA and no saflufenacil or mesotrione	4 vs. 5	94 vs. 88 *	85 vs. 83 NS	5803 vs. 6104 NS	30 vs. 33 NS	0.93 vs. 1.21 NS	49 vs. 46 NS
POST with either pyrasulfotole or dicamba **vs**. PRE with VLCFA	2 vs. 9	-	98 vs. 84 ****	6035 vs. 5970 NS	2 vs. 32 *	0.20 vs. 1.09 NS	13 vs. 47 ***

[a] Abbreviations: WAP, weeks after planting; PRE, preemergence; POST, postemergence; fb, followed by; VLCFA, very long chain fatty acid inhibiting herbicides; NS, not significant.

[b] Means of contrast difference: *P = 0.1 to 0.05, **P = 0.05 to 0.01, ***P= 0.01 to 0.0001, ****P <0.0001 levels.

Table 4.6 Orthogonal contrasts of treatments on visual Palmer amaranth control at 3 and 8 weeks after planting (WAP) and on Palmer amaranth biomass, density, height, and grain yield in double-crop grain sorghum at Hutchinson averaged across 2016 and 2017.

Orthogonal Contrasts	Treatments in Contrast	3 WAP	8 WAP	Grain Yield	Weed Biomass	Weed Density	Weed Height
	# vs. #	% Visual Control		kg ha^{-1}	g m^{-2}	no. m^{-2}	cm
PRE alone **vs**. PRE fb POST	8 vs. 6	-	59 vs. 71 ***	4130 vs. 4329 NS	91 vs. 60 *	3.1 vs. 4.6 NS	62 vs. 51 NS
PRE with VLCFA **vs**. Atrazine PRE	9 vs. 5	91 vs. 54 ****	66 vs. 61 NS	4250 vs. 4173 NS	75 vs. 82 NS	2.4 vs. 6.1 **	55 vs. 63 NS
PRE with saflufenacil or mesotrione + VLCFA **vs**. PRE with VLCFA and no saflufenacil or mesotrione	4 vs. 5	93 vs. 89 NS	70 vs. 64 NS	4297 vs. 4213 NS	88 vs. 65 NS	3.1 vs. 1.9 NS	48 vs. 60 NS
POST with either pyrasulfotole or dicamba **vs**. PRE with VLCFA	2 vs 9	-	76 vs. 66 NS	4382 vs. 4250 NS	63 vs. 75 NS	10.5 vs. 2.4 NS	36 vs. 55 **

[a] Abbreviations: WAT, weeks after planting; PRE, preemergence; POST, postemergence; fb, followed by; VLCFA, very long chain fatty acid inhibiting herbicides; NS, not significant.

[b] Means of contrast difference: *P = 0.1 to 0.05, **P = 0.05 to 0.01, ***P= 0.01 to 0.0001, ****P <0.0001 levels.

Table 4.7 Herbicide treatments, rates, and timing of application with least square means of visual Palmer amaranth control ratings at three and eight weeks after planting (WAP), weed biomass, weed density, and weed height taken at physiological maturity growth stage; and grain yield for double-crop grain sorghum at Manhattan in 2016 and 2017.

Treatments	Rate	Timing	Palmer amaranth					Grain Sorghum
			3 WAP	8 WAP	Biomass	Density	Height	Grain Yield
	g ai/ae* ha^{-1}		% Control		g m^{-2}	no. m^{-2}	cm	kg ha^{-1}
Non-treated			0	0	191 a	10.93 a	132 a	4678 d
dimethenamid-P	1105	PRE	50 d	33 d	97 b-d	2.84 b	118 a	5780 a-c
dimethenamid-P + saflufenacil	1267 + 50	PRE	78 c	56 c	112 bc	2.26 bc	120 a	6470 a
dimethenamid-P + saflufenacil + atrazine	1067 + 50 +1123	PRE	99 a	97 a	3 e	0.27 e	22 cd	5010 cd
S- metolachlor + atrazine	1421 + 1835	PRE	95 a	86 a	42 de	0.27 e	93 ab	6350 ab
S- metolachlor + saflufenacil + atrazine	1424 + 50 + 1835	PRE	98 a	89 a	6 e	0.21 e	44 cd	6260 ab
S-metolachlor + mesotrione + atrazine	2031 + 203 + 762	PRE	99 a	99 a	1 e	0 e	11 cd	5470 b-d
acetochlor + atrazine	2814 + 1396	PRE	99 a	99 a	25 e	0.92 b-e	19 cd	6320 ab
atrazine	1684	PRE	82 bc	72 b	131 ab	1.45 b-d	119 a	5438 b-d
dimethenamid-P + atrazine fb dimethenamid-P + atrazine	579 + 1123 fb 528 + 562	PRE fb POST	97 a	96 a	0 e	0 e	0 d	5100 ab
acetochlor + atrazine fb acetochlor + atrazine	2814 + 1396 fb 1291 + 641	PRE fb POST	99 a	99 a	0 e	0 e	0 d	6090 ab
atrazine fb bromoxynil + atrazine	1123 fb 421 + 562	PRE fb POST	94 ab	98 a	32 e	0.38 de	41 cd	6120 ab
atrazine fb bromoxynil + pyrasulfotole + atrazine	1123 fb 246 + 44 + 562	PRE fb POST	98 a	99 a	1 e	0.07 e	14 cd	6110 ab
atrazine fb dicamba + atrazine	1123 fb 281* +562	PRE fb POST	97 a	98 a	2 e	0.32 c-e	11 cd	5960 a-c
atrazine fb atrazine	1123 fb 562	PRE fb POST	93 ab	91 a	58 c-e	0.33 e	53 bc	6480 a

Abbreviations: PRE, preemergence; POST, postemergence; fb, followed by

[a] Means followed by the same letter within a column are not statistically different according to Fisher’s Protected LSD (α=0.05)

Table 4.8 Herbicide treatments, rates, and timing of application with least square means of visual Palmer amaranth control ratings at three and eight weeks after planting (WAP), weed biomass, weed density, and weed height taken at physiological maturity growth stage; and grain yield for double-crop grain sorghum at Hutchinson in 2016 and 2017.

Treatments	Rate	Timing	Palmer amaranth					Grain Sorghum
			3 WAP	8 WAP	Biomass	Density	Height	Grain Yield
	g ai/ae* ha^{-1}		% Control		g m^{-2}	no. m^{-2}	cm	kg ha^{-1}
Non-treated			0	0	147 a	13.5 a	83 ab	3180 e
dimethenamid-P	1105	PRE	84 a	48 d-f	90 a-d	3.0 b-d	84 ab	3970 a-e
dimethenamid-P + saflufenacil	1267 + 50	PRE	88 a	61 b-e	123 ab	3.3 cd	47 c-e	4400 a-d
dimethenamid-P + saflufenacil + atrazine	1067 + 50 +1123	PRE	92 a	55 c-e	103 a-d	5.0 cd	64 a-d	3860 b-e
S- metolachlor + atrazine	1421 + 1835	PRE	86 a	38 ef	108 a-c	6.2 a-d	80 a-c	3860 b-e
S- metolachlor + saflufenacil + atrazine	1424 + 50 + 1835	PRE	95 a	74 a-c	79 a-e	2.6 d	44 de	4660 a-c
S-metolachlor + mesotrione + atrazine	2031 + 203 + 762	PRE	97 a	89 a	45 b-e	2.0 d	39 de	4260 a-d
acetochlor + atrazine	2814 + 1396	PRE	96 a	80 ab	42 c-e	2.3 d	43 de	4600 a-c
atrazine	1684	PRE	48 b	29 f	141 a	10.5 ab	96 a	3520 de
dimethenamid-P + atrazine fb dimethenamid-P + atrazine	579 + 1123 fb 528 + 562	PRE fb POST	85 a	65 a-d	60 b-e	4.0 cd	71 a-d	4330 a-d
acetochlor + atrazine fb acetochlor + atrazine	2814 + 1396 fb 1291 + 641	PRE fb POST	95 a	88 a	27 de	1.3 d	20 ef	4310 a-d
atrazine fb bromoxynil + atrazine	1123 fb 421 + 562	PRE fb POST	58 b	75 a-c	40 c-e	1.7 d	59 b-d	4890 a
atrazine fb bromoxynil + pyrasulfotole + atrazine	1123 fb 246 + 44 + 562	PRE fb POST	59 b	65 a-d	118 a-c	8.3 a-c	75 a-d	3930 a-e
atrazine fb dicamba + atrazine	1123 fb 281* +562	PRE fb POST	50 b	87 a	7 e	0.0 d	0 f	4840 ab
atrazine fb atrazine	1123 fb 562	PRE fb POST	54 b	48 d-f	105 a-c	4.2 cd	86 ab	3690 c-e

Abbreviations: PRE, preemergence; POST, postemergence; fb, followed by

[a]Means followed by the same letter within a column are not statistically different according to Fisher's Protected LSD (α=0.05)

Appendix A - Supplemental Data

Table A.1 Sorghum leaves, stems, heads dry biomass from 2-plants, and ratio for total dry biomass m^{-2} at Hays, KS in 2016.

Plot No.	Leaves	Stems	Heads	2-plt Biomass	Ratio	Total Biomass
		g m-row^{-1}		g		g m^{-2}
101	90.0	340.0	65.0	4.1	495.0	2040.0
102	79.0	230.0	52.0	5.0	361.0	1817.2
103	80.0	.	54.0	7.3	134.0	976.4
104	87.0	221.0	41.0	3.0	349.0	1051.8
105	94.0	300.0	64.0	4.3	458.0	1957.3
106	100.0	350.0	58.0	3.6	508.0	1840.4
107	80.0	245.0	58.0	3.9	383.0	1505.0
108	75.0	217.0	52.0	5.2	344.0	1791.1
109	90.0	225.0	51.0	4.2	366.0	1525.0
110	83.0	271.0	55.0	3.4	409.0	1400.6
111	90.0	295.0	73.0	4.5	458.0	2066.3
201	76.0	260.0	51.0	4.0	387.0	1552.0
202	85.0	232.0	61.0	3.5	378.0	1308.0
203	84.0	227.0	62.0	3.4	373.0	1253.3
204	74.0	204.0	56.0	5.1	334.0	1690.3
205	8.0	260.0	37.0	4.5	305.0	1357.3
206	93.0	299.0	65.0	4.3	457.0	1964.3
207	113.0	317.0	69.0	3.9	499.0	1943.5
208	93.0	285.0	75.0	3.9	453.0	1742.3
209	86.0	225.0	65.0	4.3	376.0	1612.6
210	91.0	263.0	60.0	3.9	414.0	1613.3
211	91.0	287.0	56.0	5.4	434.0	2363.0
301	72.0	242.0	61.0	5.2	375.0	1959.1
302	95.0	326.0	69.0	3.9	490.0	1907.9
303	84.0	193.0	68.0	4.1	345.0	1403.9
304	82.0	236.0	62.0	5.1	380.0	1937.7

305	83.0	273.0	56.0	4.4	412.0	1817.5
306	93.0	288.0	64.0	4.3	445.0	1899.6
307	82.0	198.0	56.0	3.6	336.0	1211.4
308	80.0	270.0	57.0	3.2	407.0	1305.9
309	88.0	226.0	51.0	3.6	365.0	1302.2
310	88.0	277.0	.	4.5	365.0	1633.0
311	87.0	296.0	72.0	2.3	455.0	1031.3
401	78.0	237.0	61.0	5.1	376.0	1903.8
402	80.0	247.0	68.0	3.9	395.0	1547.1
403	90.0	310.0	74.0	4.4	474.0	2102.6
404	79.0	289.0	63.0	3.5	431.0	1508.5
405	90.0	280.0	67.0	4.9	437.0	2147.0
406	97.0	334.0	76.0	3.5	507.0	1749.2
407	86.0	292.0	66.0	3.9	444.0	1745.2
408	83.0	290.0	65.0	3.9	438.0	1713.9
409	90.0	305.0	77.0	4.1	472.0	1929.8
410	75.0	193.0	53.0	5.6	321.0	1791.3
411	89.0	305.0	65.0	4.2	459.0	1928.3

Table A.2 Sorghum leaves, stems, heads dry biomass from 2-plants, and ratio for total dry biomass m^{-2} at Manhattan, KS in 2016.

Plot No.	Leaves	Stems	Heads	2-plt Biomass	Ratio	Total Biomass
		g m-row^{-1}		g		g m^{-2}
101	90.9	197.1	62.4	350.4	3.5	1221.5
102	79.4	186.6	63.2	329.2	2.0	666.0
103	93.5	191.7	65.4	350.6	3.2	1110.9
104	92.0	212.0	68.4	372.4	3.1	1169.8
105	73.8	166.5	68.0	308.3	3.9	1214.6
106	74.7	183.8	58.0	316.5	4.6	1451.4
107	88.0	203.9	62.2	354.1	3.1	1092.2
108	82.9	200.3	66.1	349.3	3.5	1228.0
109	82.8	200.4	64.7	347.9	3.3	1135.5
110	90.6	180.7	78.3	349.6	2.6	909.0
111	106.7	224.4	73.1	404.2	3.1	1253.9
201	77.5	192.4	64.0	333.9	4.6	1521.1
202	75.3	172.3	62.0	309.6	4.5	1396.1
203	71.7	160.1	51.0	282.8	3.6	1023.1
204	87.9	178.0	64.1	330.0	3.3	1089.0
205	100.9	238.8	73.8	413.5	2.9	1211.7
206	82.8	198.8	61.6	343.2	4.4	1512.5
207	84.0	200.0	66.5	350.5	3.4	1184.4
208	98.1	237.8	70.1	406.0	3.0	1221.9
209	90.5	176.0	62.3	328.8	2.8	919.8
210	87.4	206.2	66.8	360.4	3.9	1407.7

211	93.1	218.8	66.2	378.1	3.2	1199.5
301	84.3	215.3	65.3	364.9	3.0	1106.5
302	85.9	211.3	66.8	364.0	3.0	1108.7
303	89.4	206.4	70.0	365.8	3.9	1430.3
304	83.4	198.0	73.2	354.6	2.7	956.2
305	79.3	173.6	59.1	312.0	4.1	1264.3
306	82.7	182.6	70.9	336.2	3.9	1298.2
307	84.8	189.1	98.7	372.6	4.5	1672.4
308	63.1	139.0	56.9	259.0	3.5	906.5
309	72.9	144.2	62.9	280.0	5.5	1542.2
310	77.4	179.1	64.0	320.5	4.4	1410.2
311	84.9	179.1	60.6	324.6	5.2	1699.9
401	88.7	193.7	65.9	348.3	2.8	988.3
402	88.3	197.7	69.1	355.1	3.6	1293.6
403	71.1	171.6	58.0	300.7	2.3	678.7
404	85.4	188.9	61.1	335.4	3.6	1193.4
405	77.5	177.7	58.9	314.1	4.0	1260.8
406	87.6	202.7	60.4	350.7	3.3	1172.9
407	76.1	164.6	64.7	305.4	3.6	1098.2
408	90.3	199.2	69.9	359.4	2.3	843.7
409	77.2	130.6	55.7	263.5	3.3	869.3
410	70.2	143.6	59.6	273.4	3.8	1033.8
411	86.9	166.5	64.9	318.3	2.5	810.8

Table A.3 Sorghum leaves, stems, heads dry biomass from 2-plants, and ratio for total dry biomass m^{-2} at Hays, KS in 2017.

Plot No.	Leaves	Stems	Heads	2-plt Biomass	Ratio	Total Biomass
		g m-row^{-1}		g		g m^{-2}
101	77.6	212.8	59.2	349.6	6.0	2088.2
102	94.0	391.3	75.4	560.7	4.6	2553.0
103	89.1	300.0	73.6	462.7	2.9	1362.7
104	94.3	279.9	72.9	447.1	4.5	2012.0
105	79.3	331.1	55.0	465.4	3.2	1485.8
106	79.1	228.3	65.4	372.8	4.0	1505.5
107	91.9	237.7	75.4	405.0	3.5	1399.8
108	93.6	303.0	79.4	476.0	3.5	1682.3
109	85.8	325.7	73.1	484.6	4.6	2229.6
110	83.3	275.0	62.9	421.2	4.2	1749.4
111	92.5	341.6	65.7	499.8	3.5	1732.9
201	82.0	273.8	70.8	426.6	3.9	1673.1
202	90.3	317.8	86.7	494.8	4.8	2389.5
203	102.2	294.7	71.9	468.8	3.5	1640.4
204	93.6	384.1	89.4	567.1	4.7	2677.5
205	93.3	421.1	66.4	580.8	3.8	2187.0
206	103.9	338.7	80.0	522.6	2.2	1125.2
207	87.1	328.9	82.2	498.2	3.1	1547.2
208	95.1	371.2	89.9	556.2	3.2	1768.5
209	92.1	349.1	83.7	524.9	2.5	1298.0
210	87.0	305.7	65.2	457.9	4.1	1855.1

211	98.6	316.8	83.6	499.0	2.6	1300.8
301	90.7	295.5	78.2	464.4	3.2	1464.2
302	90.0	380.4	77.1	547.5	3.4	1846.3
303	82.9	280.9	64.1	427.9	3.5	1478.9
304	99.9	299.9	76.4	476.2	2.9	1381.2
305	96.1	268.4	63.8	428.3	4.5	1918.3
306	95.1	416.5	87.2	598.8	3.8	2273.1
307	94.1	414.3	83.7	592.1	2.5	1490.5
308	85.7	220.7	74.1	380.5	3.2	1201.1
309	91.6	332.1	77.2	500.9	3.9	1951.5
310	94.1	266.2	74.0	434.3	2.8	1214.8
311	83.8	306.1	76.1	466.0	4.5	2119.1
401	88.4	251.9	70.7	411.0	3.3	1361.9
402	88.5	305.6	76.0	470.1	3.4	1593.6
403	96.1	429.8	82.0	607.9	2.7	1654.2
404	81.1	203.6	61.8	346.5	5.4	1887.2
405	97.5	350.6	80.9	529.0	2.4	1258.9
406	89.5	332.5	71.6	493.6	3.1	1508.4
407	92.6	309.8	71.9	474.3	2.4	1153.1
408	92.8	330.4	81.9	505.1	3.2	1622.1
409	88.5	295.1	77.0	460.6	2.7	1240.1
410	96.1	440.6	87.2	623.9	3.9	2416.5
411	94.2	377.8	81.5	553.5	2.9	1601.8

Table A.4 Sorghum leaves, stems, heads dry biomass from 2-plants, and ratio for total dry biomass m^{-2} at Manhattan, KS in 2017.

Plot No.	Leaves	Stems	Heads	2-plt Biomass	Ratio	Total Biomass
		g m-row^{-1}		g		g m^{-2}
101	94.2	249.1	78.0	421.3	4.2	1748.8
102	99.8	258.8	79.2	437.8	4.3	1903.2
103	94.9	331.4	86.2	512.5	3.6	1830.9
104	97.4	329.8	86.7	513.9	3.4	1721.8
105	90.7	223.5	74.3	388.5	5.3	2045.9
106	91.7	274.5	72.2	438.4	7.1	3097.7
107	97.4	236.0	75.8	409.2	4.9	2023.1
108	104.0	308.0	75.5	487.5	6.1	2972.4
109	96.2	282.7	78.4	457.3	5.3	2414.3
110	97.9	286.5	78.8	463.2	5.1	2378.9
111	88.1	210.1	71.6	369.8	4.1	1533.7
201	92.0	250.3	81.9	424.2	4.4	1856.2
202	92.7	250.9	76.7	420.3	3.5	1451.2
203	97.8	233.0	74.7	405.5	3.0	1227.5
204	102.6	307.1	83.0	492.7	3.8	1853.3
205	106.6	317.9	80.0	504.5	4.6	2341.7
206	101.9	284.4	85.3	471.6	3.9	1835.3
207	105.4	183.7	84.3	373.4	3.6	1333.1
208	101.0	285.7	86.3	473.0	4.1	1950.6
209	90.7	236.1	73.7	400.5	6.2	2495.3
210	95.9	305.1	75.8	476.8	10.9	5179.9

211	88.2	209.6	71.7	369.5	5.3	1972.8
301	90.3	247.0	77.4	414.7	5.2	2165.0
302	104.4	314.1	81.3	499.8	3.6	1795.7
303	82.5	197.9	70.4	350.8	6.4	2232.4
304	98.2	271.5	77.4	447.1	4.5	1991.8
305	101.2	241.8	82.9	425.9	4.9	2107.6
306	95.7	252.2	81.7	429.6	4.6	1983.0
307	98.9	275.3	77.7	451.9	5.5	2492.1
308	103.1	352.1	91.8	547.0	3.5	1888.0
309	103.7	275.9	75.5	455.1	3.9	1791.5
310	89.6	238.8	73.4	401.8	4.5	1826.5
311	92.7	238.9	71.7	403.3	6.6	2666.8
401	98.9	273.9	75.8	448.6	5.0	2241.7
402	93.4	272.9	73.5	439.8	3.9	1735.7
403	89.7	219.2	69.5	378.4	7.5	2821.5
404	95.5	266.3	77.3	439.1	5.1	2233.9
405	101.9	334.0	81.1	517.0	4.6	2397.3
406	104.8	278.9	82.2	465.9	5.6	2619.5
407	88.4	253.3	72.7	414.4	5.2	2144.0
408	103.3	28.3	86.6	218.2	3.7	807.8
409	85.3	230.4	68.2	383.9	5.6	2145.1
410	101.8	301.4	82.8	486.0	3.8	1867.8
411	92.8	207.6	71.8	372.2	5.2	1923.0

Table A.5 Sorghum leaves, stems, heads dry biomass from 2-plants, and ratio for total dry biomass m^{-2} at Hutchinson, KS in 2017.

Plot No.	Leaves	Stems	Heads	2-plt Biomass	Ratio	Total Biomass
		g m-row^{-1}		g		g m^{-2}
101	78.3	176.7	71.1	326.1	4.4	1449.6
102	80.7	195.4	82.0	358.1	2.4	870.5
103	74.0	148.0	70.2	292.2	3.7	1090.1
104	74.1	136.0	68.4	278.5	3.9	1096.9
105	87.4	235.9	80.4	403.7	3.1	1269.7
106	83.4	492.0	74.9	650.3	3.0	1958.8
107	78.9	149.7	68.9	297.5	4.8	1442.8
108	78.1	182.9	78.3	339.3	3.6	1216.6
109	73.6	167.8	69.2	310.6	3.8	1180.1
110	42.3	144.9	59.9	247.1	2.7	665.0
111	74.0	194.0	69.7	337.7	3.5	1178.8
201	77.2	188.2	75.7	341.1	3.7	1259.2
202	73.6	179.9	65.8	319.3	4.6	1478.1
203	81.5	209.9	78.8	370.2	3.3	1217.5
204	75.0	204.8	69.0	348.8	4.5	1564.4
205	72.2	143.7	65.2	281.1	5.0	1400.9
206	84.5	204.1	78.7	367.3	3.4	1237.7
207	80.8	195.8	71.6	348.2	3.9	1367.0
208	88.3	245.1	80.6	414.0	3.0	1235.1
209	84.7	295.8	77.6	458.1	3.1	1425.6
210	80.9	213.0	73.5	367.4	3.5	1284.8

211	88.3	197.5	71.5	357.3	4.3	1545.9
301	76.4	171.6	75.5	323.5	4.4	1422.7
302	88.1	190.1	77.6	355.8	4.3	1517.2
303	83.9	234.0	80.0	397.9	3.6	1421.6
304	85.5	170.6	75.0	331.1	3.3	1094.8
305	79.2	238.0	79.2	396.4	3.2	1260.4
306	79.5	177.3	74.6	331.4	4.6	1522.6
307	88.3	228.5	82.4	399.2	3.7	1472.2
308	82.0	190.9	80.2	353.1	2.4	848.5
309	82.9	161.7	72.9	317.5	4.3	1355.7
310	78.9	157.9	69.1	305.9	4.9	1513.8
311	78.3	173.0	72.5	323.8	3.2	1024.2
401	85.7	159.3	64.5	309.5	3.7	1159.8
402	76.8	137.4	67.8	282.0	5.0	1398.4
403	82.9	225.2	80.9	389.0	3.0	1167.0
404	78.6	148.9	75.7	303.2	4.7	1424.4
405	79.9	188.2	82.9	351.0	3.7	1302.8
406	88.9	229.0	80.6	398.5	4.7	1878.2
407	83.3	183.7	71.1	338.1	4.4	1495.5
408	79.0	168.2	72.3	319.5	4.0	1275.1
409	80.3	177.3	70.8	328.4	4.0	1328.3
410	86.9	224.8	75.5	387.2	3.9	1513.5
411	82.5	211.0	72.7	366.2	4.0	1451.4

Table A.6 Grain sorghum biomass (with standard error) for all treatments at Hays and Manhattan KS in 2016 and 2017, and Hutchinson, KS in 2017. Biomass collected at grain sorghum mid-bloom.

Treatment	Hays		Manhattan		Hutchinson
	2016	2017	2016	2017	2017
			g m^{-2}		
PRE (*S*-metolachlor + Atrazine)	2250 (213) ab	2650 (291) b	1560 (34) a	2680 (199) ab	1910 (33) ab
Weedy All Season	1840 (244) b	2350 (125) b	1530 (242) b	2810 (413) ab	1340 (164) c
Weed-Free until 2 Weeks	2300 (98) ab	1930 (166) b	1460 (170) ab	3120 (324) ab	1810 (84) ab
Weed-Free until 3 Weeks	2600 (179) a	2080 (105) b	1580 (134) ab	3200 (358) ab	2140 (259) a
Weed-Free until 5 Weeks	2460 (111) a	2110 (423) b	1500 (165) ab	2700 (80) a	1790 (62) ab
Weed-Free until 7 Weeks	2350 (222) ab	2080 (116) b	1550 (176) b	2350 (110) b	1580 (180) bc
Weed-Free All Season	2320 (320) ab	2440 (192) ab	1620 (40) b	2450 (295) b	1750 (116) b
Weedy until 2 Weeks	2370 (157) ab	2590 (328) a	1420 (178) ab	3070 (253) ab	1600 (29) bc
Weedy until 3 Weeks	2150 (124) ab	1880 (236) b	1560 (256) ab	2690 (121) ab	1670 (184) bc
Weedy until 5 Weeks	1850 (240) b	2290 (123) b	1560 (231) a	1310 (460) b	1780 (140) ab
Weedy until 7 Weeks	1870 (85) b	2270 (259) b	1760 (125) b	2310 (155) b	1870 (35) ab

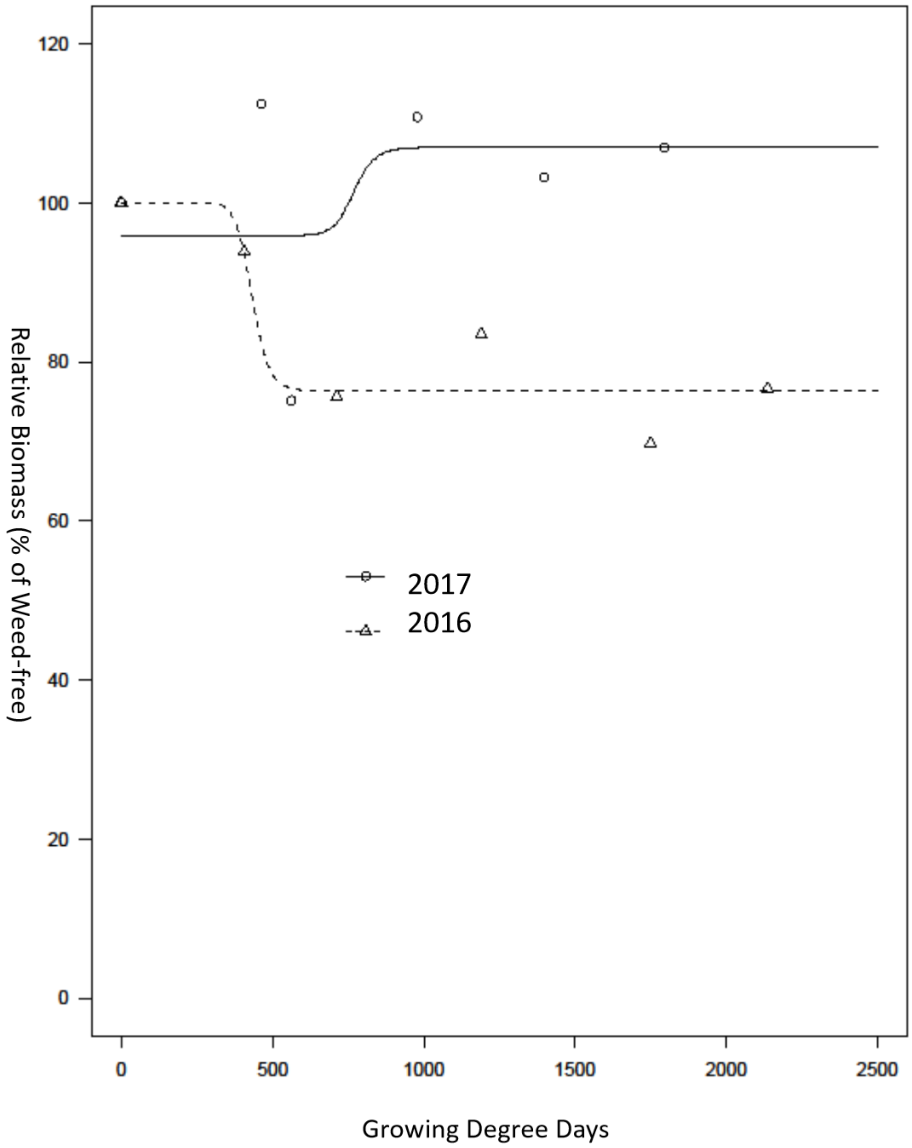

Figure A.1 Relative grain sorghum biomass (%) at mid-bloom growth stage as a function of increasing duration of weed interference (GDD) at Hays, KS in 2016 (Δ) and 2017 (o). Lines were predicted from fitting Equation 2-2 and line 1 represents 2017 and line 4 represents 2016.

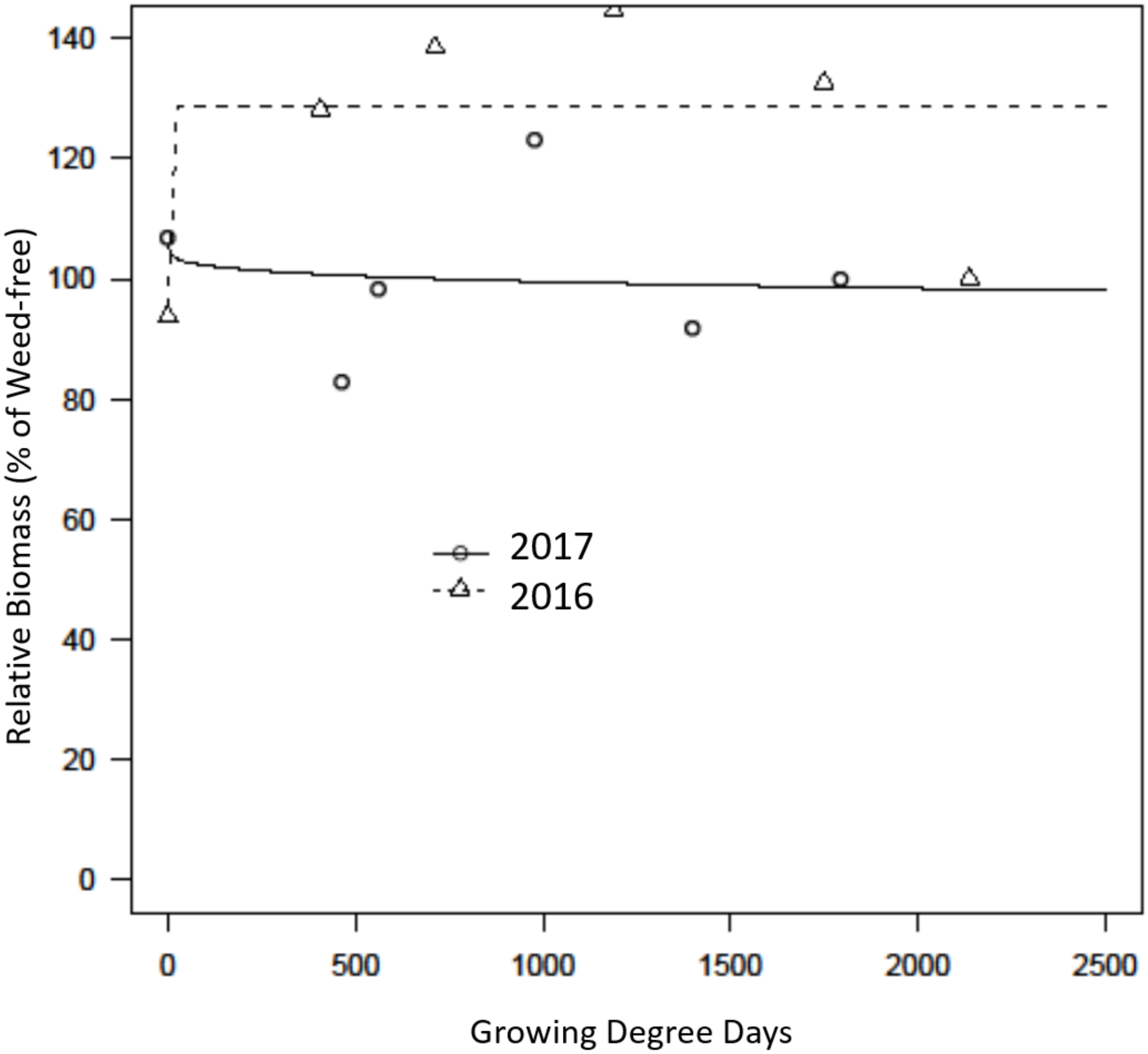

Figure A.2 Relative grain sorghum biomass (%) at mid-bloom stage as a function of increasing weed-free period at Hays, KS in 2016 (Δ) and 2017 (o). Lines were predicted from fitting Equation 2-2 to weed-free treatments and Line 1 represents 2017 and line 4 represents 2016.

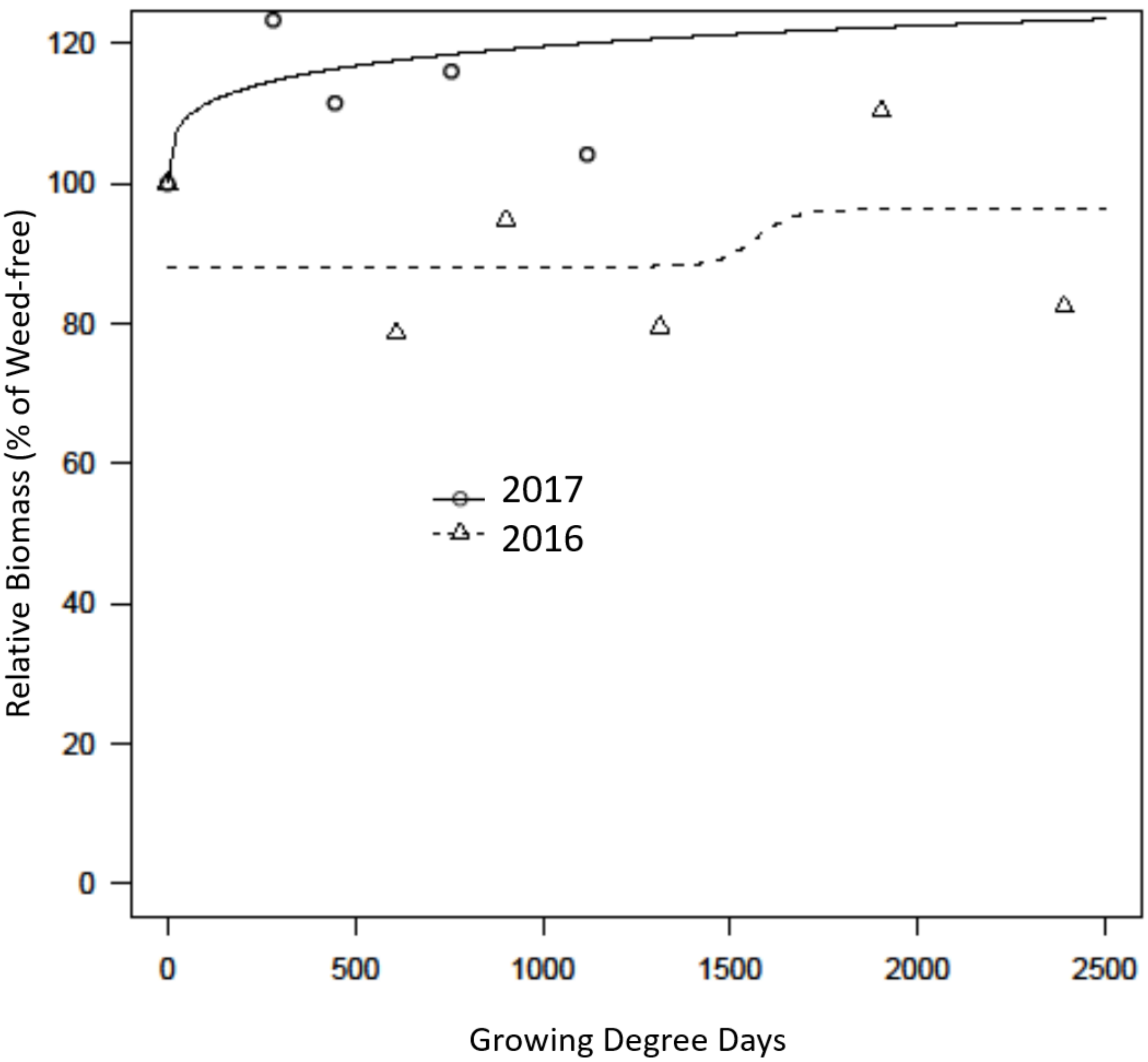

Figure A.3 Relative grain sorghum biomass (%) at mid-bloom growth stage as a function of increasing duration of weed interference at Manhattan, KS in 2016 (Δ) and 2017 (o). Lines were predicted from fitting Equation 2-2 to weedy treatments. Line 2 represents Manhattan 2017 and line 5 represents Manhattan 2016.

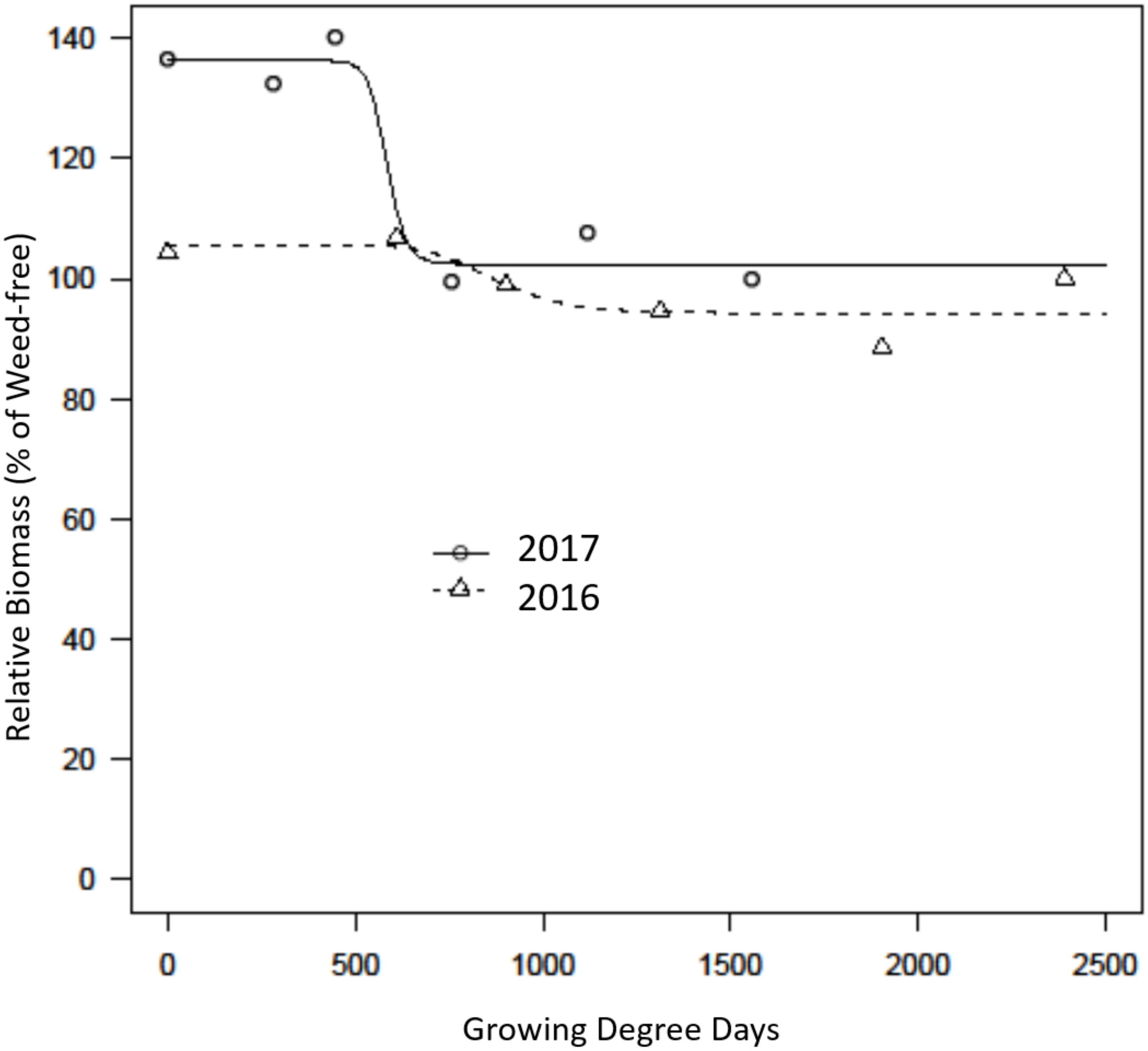

Figure A.4 Relative grain sorghum biomass (%) at mid-bloom growth stage as a function of increasing weed-free period at Manhattan, KS in 2016 (Δ) and 2017 (o). Lines were predicted from fitting Equation 2-2 to weed-free treatments, and line 2 represents 2017 and line 5 represents 2016.

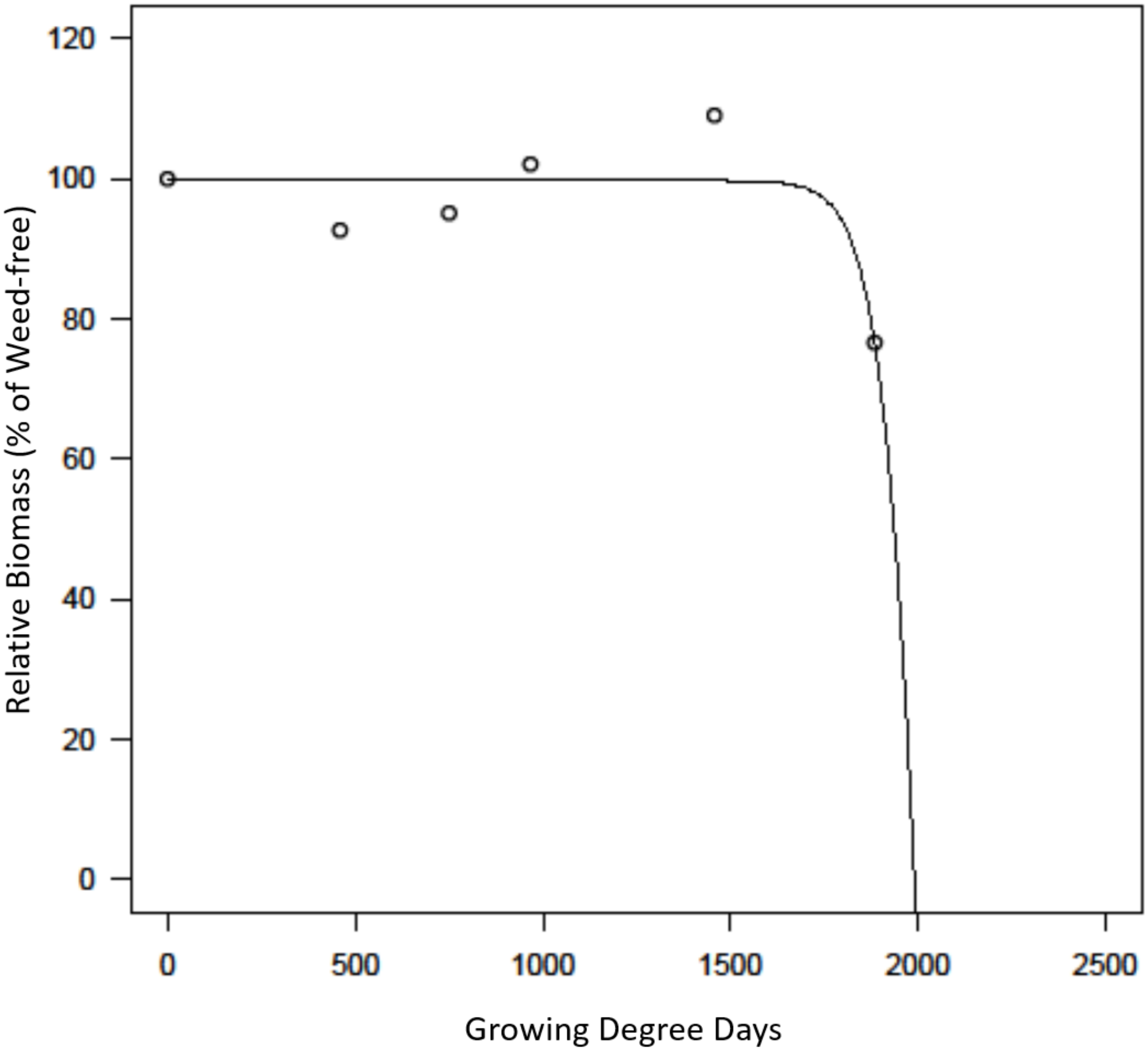

Figure A.5 Relative grain sorghum biomass (%) at mid-bloom growth stage as a function of increasing duration of weed interference at Hutchinson, KS in 2017 (o). Line was predicted based on fitting Equation 2-2 to weedy treatments.

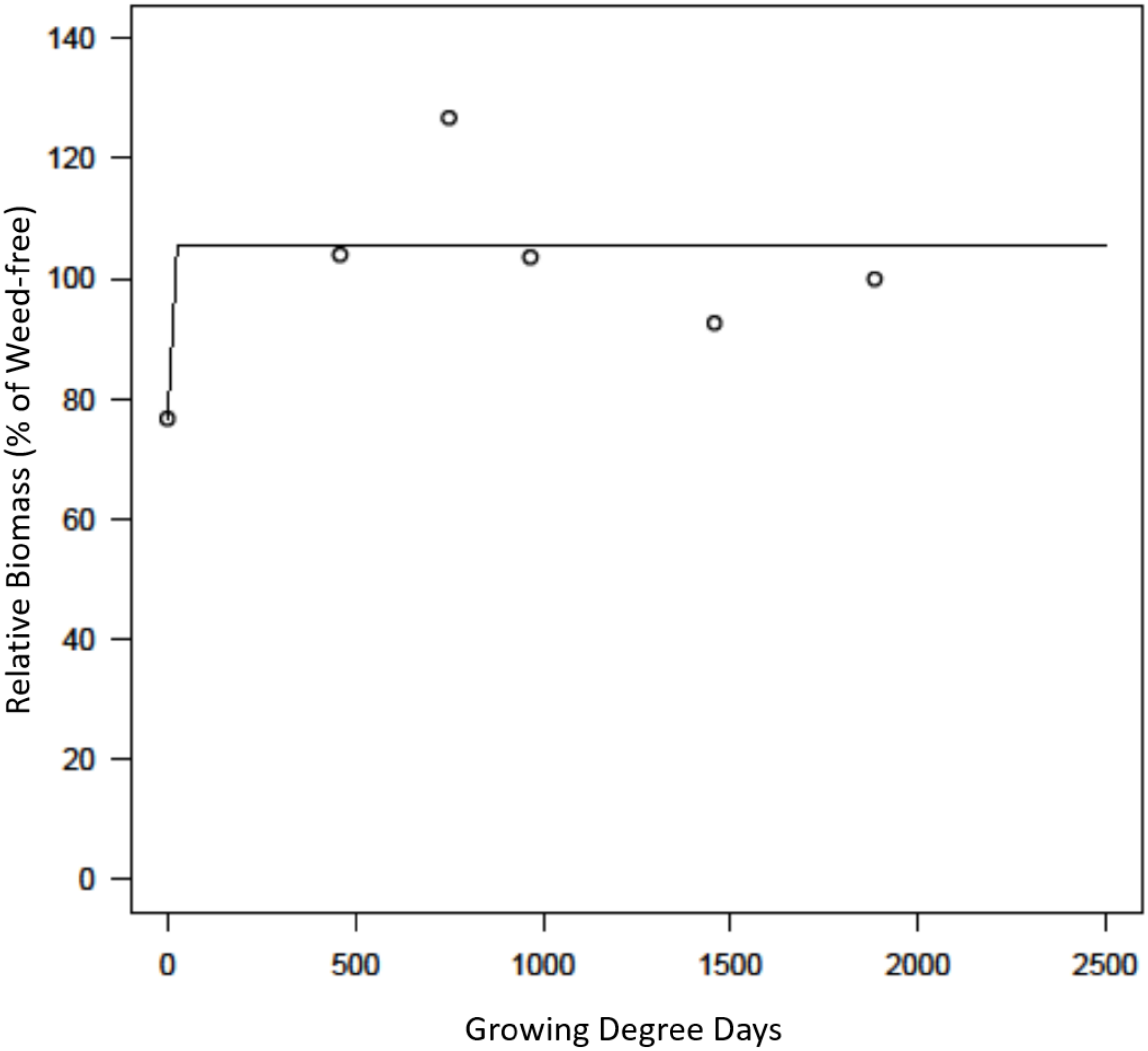

Figure A.6 Relative grain sorghum biomass (%) at mid-bloom growth stage as a function of increasing weed-free period at Hutchinson in 2017 (o). Line was predicted by fitting Equation 2-2 to weed-free treatments.