Influence of grain sorghum planting dates and Palmer amaranth emergence timings on competitive outcomes

by

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Abstract

Grain sorghum (*Sorghum bicolor* L.) is an important crop to Kansas agriculture, and Palmer amaranth (*Amaranthus palmeri* S. Wats.) is considered the most troublesome weed in grain sorghum. In 2019, field experiments were conducted near Manhattan and Hutchinson, Kansas to determine the influence of grain sorghum planting dates and Palmer amaranth emergence timings on competitive outcomes. Grain sorghum was planted on June 3 and July 1 at Manhattan and May 17 and June 17 at Hutchinson. Natural populations of Palmer amaranth were established at an early and late emergence timing relative to crop planting along with a weed-free treatment. Palmer amaranth was thinned and maintained at a target population of 4 plants m^{-1} of row. The growth stage and height of grain sorghum and Palmer amaranth were recorded weekly. Biweekly up to grain sorghum flag-leaf stage, two grain sorghum and two Palmer amaranth plants $plot^{-1}$ were harvested to measure leaf area and biomass. Grain sorghum was harvested to measure yield and seed weight. Late planted grain sorghum accumulated height, leaf area, and biomass more quickly than early planted grain sorghum on a time scale of days after planting (DAP) at both locations. On a scale of growing degree units (GDU), grain sorghum leaf area and biomass accumulation at Manhattan were similar across planting dates, while the late planting accumulated more height. In Hutchinson, grain sorghum leaf area accumulation was similar across plantings, while the late planting accumulated height and biomass more quickly on a GDU scale. Palmer amaranth density in both sites were less than desired and inconsistent, therefore, it was impossible to test the effects of Palmer amaranth emergence timing. In Manhattan, grain yields were similar across treatments, excluding the treatment with the highest Palmer amaranth density (1.5 plants m^{-1} of row), and seed weight was greater in the early planting than the late. In Hutchinson, grain sorghum yield was 37% less in the early planting

than the late planting, due to poor crop establishment in cool soil temperatures after planting, and poor pollination and grain fill during hot and dry conditions. Later planted grain sorghum grew faster than early planted grain sorghum, thus was more competitive against weed competition in early growth stages. This research demonstrated a potential tactic that a producer could implement to enhance early season competitiveness of grain sorghum against Palmer amaranth.

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Chapter 1 - Literature Review

Grain Sorghum Importance and Biology

Grain sorghum (*Sorghum bicolor* (L.) Moench) is an important crop for arid and semi-arid regions of the world that experience harsh climatic conditions. It is grown on over 40 million hectares worldwide (USDA-WAOB, 2020) and 2.07 million hectares in the United States (USDA-NASS, 2019). Kansas accounts for 52% of the area producing grain sorghum in the United States, with total production on 1.07 million hectares (USDA-NASS, 2019). Grain sorghum is a staple food crop in many countries of Africa and Asia (Prasad and Staggenborg, 2009). Of the 6.2 million metric tons used in the United States in 2018/2019, 57% of grain sorghum was used as feed for livestock, while the remaining 43% was used for human consumption, industrial products, or seed (USDA-WAOB, 2019). It is believed that sorghum originated in north-central Africa and it was introduced in the United States in the mid-1800s (Prasad and Staggenborg, 2009; Stahlman and Wicks, 2000).

Grain sorghum is a member of the *Poaceae,* or grass, family and is a determinant, short day, summer annual species (Prasad and Staggenborg, 2009). It is relatively slow growing in early vegetative stages compared to other crops (Vanderlip, 1993). The time to flowering is approximately two-thirds of the total time from planting to physiological maturity and maximum water use occurs during this stage, thus the stages immediately prior and up to the completion of flowering are most sensitive to water and heat stress (Assefa et al., 2010; Vanderlip, 1993). Physiological maturity is the point where maximum total dry weight has occurred and accounts for approximately one-third of the plant's life cycle (Vanderlip, 1993).

Grain sorghum has a C_4 photosynthetic pathway which allows the plant to be highly efficient in using water and light (Prasad and Staggenborg, 2009). Even when compared to other

C_4 species like corn (*Zea mays* L.), grain sorghum is more tolerant of heat and water stress (Allen and Musick, 1993; Assefa et al., 2010). Grain sorghum has an enhanced ability to scavenge water and nutrients due to an extensive root system (Assefa et al., 2010). It can maintain a higher rate of CO_2 exchange and minimize water loss better than other summer crops under drought stress. All these biological attributes explain why grain sorghum is highly adapted to hot and dry climates.

Grain Sorghum Planting Date

Grain sorghum is generally planted from April to July in the United States (Conley and Wiebold, 2003; Prasad and Staggenborg, 2009; Trostle et al., 2010). Across Kansas, planting date recommendations are dependent on the region (Shroyer et al., 1996). The southeast portion of the state has the longest planting date recommendation period, ranging from May 1 to June 25. The northwest region of the state has the shortest planting date recommendation period, ranging from May 15 to June 10. The recommendation for the remaining portions of the state are from May 15 to June 15. Within the last 60 years, average planting dates in Kansas have shifted from early June to late May (Assefa and Staggenborg, 2010).

The maturity group of the grain sorghum hybrid is also dependent on the planting date. The most appropriate maturity group maximizes the length of the growing season, while accounting for moisture availability (Prasad and Staggenborg, 2009). Long-season hybrids are typically preferred if there is sufficient time to fully mature before the first frost (Roozeboom and Fjell, 1998). In shorter growing seasons, hybrids that mature more quickly would be the better option. In regions of limited moisture, long-season hybrids can use all the available water before reaching maturity, thus short-season hybrids should be used (Trostle et al., 2010).

Grain sorghum has the ability to germinate within a wide range of temperatures, spanning from 5 to 48 C, but the ideal soil temperature for germination is 21 to 35 C (Prasad and Staggenborg, 2009), with an optimum temperature of 30 C (Conley and Wiebold, 2003). For satisfactory germination in the U.S. Great Plains, grain sorghum should not be planted until the soil temperature has reached an average of 15.5 C over a 5-day period (Trostle et al., 2010).

The planting date of grain sorghum influences its growth and development. Emergence occurs more slowly when planted earlier in the season (Allen and Musick, 1993). The length of time to reach each developmental stage shortens as the crop is planted later in the season (Martin and Vanderlip, 1997; Vanderlip, 1993). Increased tillering has been observed when grain sorghum was planted early in the season (Blum, 1972; Trostle et al., 2010). The water use distribution varies with different planting times, even though total water use is similar (Blum, 1972). Early planted grain sorghum used less water early in the season, leaving more water available during flowering and grain fill, compared to late planting.

Previous studies have reported the influence of grain sorghum planting date on yield with varying results. In Missouri, the highest yields were observed with a mid-May planting, but differences were very small and insignificant when planted anytime from late-April to late-June (Conley and Wiebold, 2003). In Kansas, dryland grain sorghum yields planted from late-May to late-June were not statistically different (M'Khaitir and Vanderlip, 1992). Over the past 60 years, increased grain sorghum yields in Kansas were not influenced by shifting the planting date from early-June to late-May (Assefa and Staggenborg, 2010). In Israel under dryland conditions, planting in late-March produced approximately an 18% increase in yield compared to late-April (Blum, 1972). In northern Texas, dryland grain sorghum yielded approximately 12.5% more when planted in late-May and mid-June compared to early-May (Allen & Musick, 1993) and yielded approximately 11 and 6% more when planted in early-June versus mid-May and late-June, respectively (Baumhardt et al., 2005). In Kansas under dryland conditions, optimum yields were observed in late-May planting, with decreases of 41, 38, and 38% for mid-April, early-May, and mid-June, respectively (Martin and Vanderlip, 1997).

Determining the best planting date for a given region must factor in environmental conditions and how those influence plant growth and development to maximize yield. When grain sorghum is planted before the soil has reached the optimum temperature, germination and establishment can be poor (Shroyer et al., 1998). If grain sorghum flowers during a hot and dry period, pollination and peduncle elongation can be detrimentally affected (Vanderlip, 1993). If grain sorghum is planted too late in the season, the crop could have inadequate time to mature before frost in the fall (Shroyer et al., 1998). All of these possible conditions lead to yield loss and must be weighed when deciding the best planting date for the location.

Weed Competition in Grain Sorghum

Weeds compete with crops for resources like water, nutrients, and light and can adversely affect yield, lower harvest quality and efficiency, and increase production costs (Stahlman and Wicks, 2000). The slow growth of grain sorghum in early vegetative stages decreases its competitive ability and allows weeds to establish more easily than other crops (Burnside and Wicks, 1967; Stahlman and Wicks, 2000). There are fewer chemical control options available for grain sorghum compared to other major field crops (Prasad and Staggenborg, 2009). Grain sorghum yield losses due to various weed species and mixtures generally range from 30 to 50% (Stahlman and Wicks, 2000) but can reach up to 60% (Moore et al., 2004), 62% (Burnside and Wicks, 1967), and 74% (Graham et al., 1988). According to a recent survey, grain sorghum yield loss due to weeds averaged 48% and valued over $500 million across the U.S. (Dille et al., 2020). Kansas yield loss due to weeds equaled 32.8% and valued over $200 million on an annual basis (Dille et al., 2020).

Palmer amaranth (*Amaranthus palmeri* S. Wats.) is the second most troublesome weed following *Urochloa* spp. and third most common weed following *Digitaria* spp. and *Urochloa* spp. in U.S. grain sorghum production (Van Wychen, 2017). Grain sorghum yield reductions of 31, 49, and 74% were observed from Palmer amaranth and smooth pigweed (*Amaranthus hybridus* L.) population at densities of 1, 4, and 12 plants m^{-2}, respectively (Graham et al., 1988). Palmer amaranth alone reduced grain sorghum yield up to 60% (Moore et al., 2004). Palmer amaranth is highly competitive due to its great height, aggressive rate of growth and development, and large amount of above and below ground biomass (Culpepper et al., 2010; Horak and Loughin, 2000). The growth rate and biomass of grain sorghum and Palmer amaranth roots were found to be comparable (Stahlman and Wicks, 2000). Palmer amaranth has allelopathic capabilities and can severely inhibit grain sorghum root growth (Menges, 1988). This weed species can also affect harvest efficiency by increasing grain moisture, foreign material, and sorghum seed loss through the combine (Moore et al., 2004).

Palmer amaranth is native to the southwestern United States and Mexico and was first documented in Kansas in 1895 (Culpepper et al., 2010). It is a dioecious, summer annual, C_4 weed that is a member of the *Amaranthaceae* family (Ward et al., 2013). Like grain sorghum, it is well adapted to high temperatures and moisture-limited environments. It has the ability to germinate within a wide range of soil temperatures, spanning from 14 to 48 C, but the optimum soil temperature for germination is 26 to 38 C (Guo and Al-Khatib, 2003; Keeley et al., 1987; Steckel et al., 2004; Wright et al., 1999). This allows an extended period of emergence throughout the year, spanning from early spring to late fall, but the peak emergence times are during warm and moist conditions from mid-May to late-July in the U.S. (Jha and Norsworthy, 2009; Keeley et al., 1987) Palmer amaranth seeds are small and require shallow depths for emergence (Keeley et al., 1987). Seed persistence is relatively short, with 20 and 5% viability reported after 1 and 3 years of burial, respectively and 15 and 4% viability after 1 and 3 years on the surface, respectively (Korres et al., 2018). Growth and development of Palmer amaranth was severely depressed when grown under cooler air temperatures and increased substantially as temperature increased to a day/night temperature regime of 34/30 C (Wright et al., 1999). It has very high fecundity, often producing as many as 200,000 to 600,000 seeds per plant with a potential of reaching one million seeds per plant (Keeley et al., 1987; Sellers et al., 2003). Palmer amaranth is highly productive because it is diaheliotropic (solar tracking) and photosynthesizes at a high rate (Ward et al., 2013).

Effect of Emergence Timing on Competitive Outcomes

The time of plant emergence has huge implications on its competitive ability. Forcella et al. (2000) deemed emergence as the single most significant factor in a plant's success. The competitive advantage of early emerging plants is primarily due to considerable resource capture (i.e. light, water, and nutrients) that robs later emerging plants (Stahlman and Wicks, 2000). A crop yield advantage has been observed when weeds have emerged after grain sorghum was well established (Wiese et al., 1964). Redroot pigweed (*Amaranthus retroflexus* L.) competition caused 40 and 10% yield loss when emerging at 1 and 3-leaf stage of grain sorghum (Knezevic et al., 1997). Yield losses were 62, 31, 3, 5, and 2% when various weed species emerged 0, 2, 4, 6, and 8 weeks after grain sorghum planting (Burnside and Wicks, 1967) and 20, 4, and 0% when various weed species emerged 2, 3, and 4 weeks after planting (Burnside and Wicks, 1969). Hence, the most critical time for weed control in grain sorghum is approximately a month after planting, and minimal yield loss occurs with subsequent weed emergence (Stahlman and Wicks, 2000).

Emergence timings also influence weed competitiveness. Later emerging Palmer amaranth grow faster (Horak and Loughin, 2000; Keeley et al., 1987; Spaunhorst et al., 2018). Palmer amaranth plants that emerge early have greater biomass and leaf area compared to later emerging plants (Horak and Loughin, 2000; Keeley et al., 1987) and increases in biomass of 164% have been reported (Spaunhorst et al., 2018). In competition with crops, Palmer amaranth accumulated less biomass when it emerged later relative to crop establishment, with reductions up to 73% (MacRae et al., 2013). Time to flowering was reduced when the weed emerged later in the season (Keeley et al., 1987; Spaunhorst et al., 2018). Later emerging Palmer amaranth also had lower fecundity, with reports of 77% (MacRae et al., 2013) and 113% (Spaunhorst et al., 2018) fewer seeds per plant compared to early emerging. Reductions of 50, 89, and 99% fewer seeds were observed when Palmer amaranth was established 6, 9, and 12 weeks after cotton (*Gossypium hirsutum* L.) planting (Webster and Grey, 2015). Palmer amaranth that emerged with a corn (*Zea mays* L.) crop produced 140,000 to 514,000 seeds m^{-2} of row, while those that emerged after corn establishment produced 1,800 to 91,000 seeds m^{-2} of row (Massinga et al., 2001).

Stahlman and Wicks (2000) stated the best weed control in grain sorghum occurs by integrating chemical and cultural practices to give grain sorghum an early competitive advantage. It is important in all crops to maximize weed control in multiple ways to optimize yield and limit the selection pressure on one specific management tactic, but it is arguably more important in grain sorghum production for three reasons. First, it is relatively less competitive and more susceptible to weed competition in early stages. Second, the crop is typically produced in locations with recurring extreme temperatures and drought conditions, and under weed competition, yield losses can be drastic. Finally, there are fewer chemical weed control options available compared to other crops, and it is more important to limit selection pressure and slow the development of resistant weed populations to the few herbicides that are available.

With an overarching goal of providing grain sorghum an early competitive advantage, one tactic includes managing the weed to delay or completely prevent emergence. Palmer amaranth has been found to be less competitive when it emerged later in the season than earlier in corn, soybean (*Glycine max* (L.) Merr.), and cotton, but the level of competition as influenced by relative crop and weed emergence timings in grain sorghum has not been examined. Another tactic to provide grain sorghum an early competitive advantage includes shaping the conditions to induce a faster growth rate of grain sorghum. Growth rate is one indicator of competitiveness and grain sorghum has been found to grow faster when planted later in the season versus earlier. Several studies have been performed to examine grain sorghum planting dates with a goal of optimizing yield, however, only a limited number of studies have been performed to examine grain sorghum planting date with a goal of optimizing weed control. Therefore, the goal of this research was to examine the influence of grain sorghum planting date and Palmer amaranth emergence timing to optimize Palmer amaranth control and grain sorghum yield.

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Chapter 2 - Grain Sorghum Planting Dates and Palmer Amaranth Emergence Timings Influence on Competitive Outcomes

Abstract

Grain sorghum (*Sorghum bicolor* L.) is an important crop to Kansas agriculture, and Palmer amaranth (*Amaranthus palmeri* S. Wats.) is considered the most troublesome weed in grain sorghum. In 2019, field experiments were conducted near Manhattan and Hutchinson, Kansas to determine the influence of grain sorghum planting dates and Palmer amaranth emergence timings on competitive outcomes. Grain sorghum was planted on June 3 and July 1 at Manhattan and May 17 and June 17 at Hutchinson. Natural populations of Palmer amaranth were established at an early and late emergence timing relative to crop planting along with a weed-free treatment. Palmer amaranth was thinned and maintained at a target population of 4 plants m^{-1} of row. The growth stage and height of grain sorghum and Palmer amaranth were recorded weekly. Biweekly up to grain sorghum flag-leaf stage, two grain sorghum and two Palmer amaranth plants $plot^{-1}$ were harvested to measure leaf area and biomass. Grain sorghum was harvested to measure yield and seed weight. Late planted grain sorghum accumulated height, leaf area, and biomass more quickly than early planted grain sorghum on a time scale of days after planting (DAP) at both locations. On a scale of growing degree units (GDU), grain sorghum leaf area and biomass accumulation at Manhattan were similar across planting dates, while the late planting accumulated more height. In Hutchinson, grain sorghum leaf area accumulation was similar across plantings, while the late planting accumulated height and biomass more quickly on a GDU scale. Palmer amaranth density in both sites were less than desired and inconsistent, therefore, it was impossible to test the effects of Palmer amaranth emergence timing. In Manhattan, grain yields were similar across treatments, excluding the treatment with the highest

Palmer amaranth density (1.5 plants m^{-1} of row), and seed weight was greater in the early planting than the late. In Hutchinson, grain sorghum yield was 37% less in the early planting than the late planting, due to poor crop establishment in cool soil temperatures after planting, and poor pollination and grain fill during hot and dry conditions. Later planted grain sorghum grew faster than early planted grain sorghum, thus was more competitive against weed competition in early growth stages. This research demonstrated a potential tactic that a producer could implement to enhance early season competitiveness of grain sorghum against Palmer amaranth.

Introduction

Grain sorghum (*Sorghum bicolor* (L.) Moench) is important crop in arid and semi-arid regions of the world. Kansas accounts for 52% of the area producing grain sorghum in the United States, producing on 1.07 million hectares (USDA-NASS, 2019). It is adapted to hot and dry climates and is more tolerant of heat and moisture stress than other crops (Assefa et al., 2010). It is relatively slow growing in early vegetative stages compared to other crops (Vanderlip, 1993). It has been reported to grow more slowly when planted early in the growing season (Allen and Musick, 1993; Martin & Vanderlip, 1997). The slow growth of grain sorghum in early vegetative stages decreases its competitive ability and allows weeds to establish more easily than other crops (Burnside and Wicks, 1967; Stahlman and Wicks, 2000).

Palmer amaranth (*Amaranthus palmeri* L.) is the second most troublesome and third most common weed in grain sorghum production in the U.S. (Van Wychen, 2017). It has been reported that one Palmer amaranth plant per 15 m of row inflicted 3.5% yield loss in grain sorghum (Moore et al., 2004). Like grain sorghum, Palmer amaranth is well adapted to hot and dry conditions (Spaunhorst et al., 2018). It is highly competitive due to its tall height, fast growth rate, and large amount of above and below ground biomass (Culpepper et al., 2010; Horak and Loughin, 2000).

Numerous studies have found that grain sorghum was more competitive when weeds emerged later than crop establishment (Burnside and Wicks, 1967; Knezevic et al., 1997; Wiese et al., 1964). The most critical time period for weed control in grain sorghum is approximately the first 30 days after planting, and minimal yield loss occurs with subsequent weed emergence (Stahlman and Wicks, 2000). Palmer amaranth has been observed to have less leaf area, biomass, and fecundity when it emerged later in the season without competition or when in competition with crops (Horak and Loughin, 2000; MacRae et al., 2013; Massinga et al., 2001; Spaunhorst et al., 2018; Webster and Grey, 2015).

The best weed control in grain sorghum can be achieved by integrating chemical and cultural practices to provide grain sorghum an early competitive advantage (Stahlman and Wicks, 2000). Few studies have been performed to understand grain sorghum and Palmer amaranth interactions, especially in regards to emergence timing. Therefore, the objective of this research was to determine the influence of grain sorghum planting date and Palmer amaranth emergence timings on grain sorghum competition with Palmer amaranth at two Kansas locations in 2019.

Materials and Methods

Experiment Site and Establishment

In 2019, field studies were conducted at the Department of Agronomy experiment fields at Ashland Bottoms Research Farm near Manhattan, Kansas and at the South Central Experiment Field near Hutchinson, Kansas. The soil type at the Manhattan site was a Reading silt loam, with an organic matter of 3% and a soil pH of 6.1 (Web Soil Survey, 2020). The soil type at the

Hutchinson site was a Nalim loam type with an organic matter of 2% and a soil pH of 6.4 (Web Soil Survey, 2020). The Manhattan field was fertilized with 135 kg N ha^{-1} on April 18 and was field cultivated before planting grain sorghum on June 3 and July 1. The Hutchinson field was prepared with a disk before grain sorghum planting on May 17 and with a rototiller before planting on June 17. This field was fertilized with 52 kg N ha^{-1} on May 31. A medium early maturing grain sorghum hybrid, DK 37-07, was planted at a depth of 3.8 cm and at a population of 130,000 plants ha^{-1} with a 4-row plot planter at both locations.

The experimental design was a split-plot arrangement of treatments where the whole plot factor was two grain sorghum planting dates (early and late) and the subplot factor was three Palmer amaranth emergence timings (weed free, early, and late) with four replications (Table 2.1). The Manhattan location was a side-by-side arrangement of whole plots, while the Hutchinson location was a true split plot arrangement. The individual plots were 9.15 m long by 3.05 m wide. Palmer amaranth was established from a naturally occurring population in the weed seedbank, thinned to a target population of four plants m^{-1} of row, marked with colored stakes, and maintained throughout the season. Weed control included hand-weeding and various herbicide applications (Table 2.2).

Data Collection

Grain sorghum stand was determined once the crop was adequately established by counting the number of plants in a meter of row four times per plot and calculating the average. Each week, height of grain sorghum to the tip of the uppermost developed leaf and height of Palmer amaranth to the uppermost developed leaf were recorded. Grain sorghum growth stage defined by Vanderlip (1993) was recorded each week up to bloom stage. Palmer amaranth stage was recorded weekly and was defined by the number of main branches, followed by flower initiation and flowering stages. Leaf area and leaf and stem biomass were measured three times at biweekly intervals up to grain sorghum flag-leaf stage (GS Stage 4); two grain sorghum plants and two Palmer amaranth plants per plot were measured. Leaf and stem tissue were separated, and leaf area was measured with LI-3100C Area Meter (LI-COR, 4647 Superior St. Lincoln, Nebraska 68504-5000) and bagged separately. All samples were oven dried at 50 C for at least 72 hours, and biomass was measured. To minimize the effect of destructive measurements, each plot was separated perpendicularly to reserve half for destructive measurements and half for grain sorghum yield.

Palmer amaranth stands were recorded at the end of the season by counting each plant in the center two rows in the yield section of the plot. Grain sorghum in Hutchinson was harvested by hand on October 10 from the center two rows of the plot for a total of area of 2 m by 1.5 m. Samples were dried at 50 C for 72 hours, threshed in a stationary thresher, and the grain sorghum seed was weighed. Grain sorghum plots in Manhattan were harvested with a modified plot combine from the center two rows of each plot for a total area of 4.5 m by 1.5 m on September 30 and October 25 for the early planting and late planting, respectively. Grain sorghum yields were adjusted to 12.5% moisture. One hundred seed weight was determined by averaging the weight of three samples of 100 grain sorghum seeds.

Data on daily precipitation, air temperature (minimum and maximum), and soil temperature during the study period were retrieved from the Kansas Mesonet (2020), where the weather parameters for Manhattan and Hutchinson locations were retrieved from the Ashland Bottoms and Hutchinson 10SW stations, respectively. The observed, normal, and departure values for precipitation and temperature in Riley (Manhattan) and Reno (Hutchinson) Counties were retrieved from Kansas Office of the State Climatologist (2020). Growing degree units (GDU) were calculated with the following equation:

$$GDU = \Sigma\ ([T_{max} + T_{min}] / 2) - T_b \qquad [1]$$

where T_{max} is daily maximum air temperature (C), T_{min} is daily minimum air temperature (C), and T_b is base temperature of sorghum (10 C). If T_{min} was less than 10 C, T_{min} was set to 10 C. If T_{max} exceeded 38 C, it was set to 38 C.

Data Analysis

Data on grain sorghum stand, height, leaf area, total biomass, leaf biomass, stem biomass, yield, and seed weight, in addition to Palmer amaranth height, leaf area, total biomass, leaf biomass, and stem biomass were subjected to an analysis of variance (ANOVA) using Procedure GLIMMIX in SAS 9.4 (SAS Institute Inc., 100 SAS Campus Drive Cary, NC 27513-2414, USA). Location, grain sorghum planting date, and Palmer amaranth emergence timing were modeled as fixed effects, and replication as a random effect. The Satterthwaite degrees of freedom method was used, and means were separated using the least square means method.

Grain sorghum growth stage, height, leaf area, total biomass, leaf biomass, and stem biomass were modeled across days after planting (DAP) or growing degree units (GDU) in Sigma Plot 12.3 (Systat Software Inc., 2107 North First Street, Suite 360 San Jose, CA 95131, USA). Grain sorghum growth stage for each location was modeled with a linear regression:

$$y = y0 + ax \qquad [2]$$

where y is the growth stage, x is DAP or GDU, $y0$ is the growth stage when x is 0, and a is the slope. Grain sorghum height for each location and leaf area, leaf biomass, stem biomass, and total biomass at Manhattan were modeled with a three-parameter sigmoid regression:

$$y = \frac{a}{1+e^{\frac{(-x-x0)}{b}}} \qquad [3]$$

where *y* is height, leaf area, leaf biomass, stem biomass, or total biomass, *x* is DAP or GDU, *a* is the maximum of *y* converged on 100%, *b* is the slope at the inflection point, and *x0* is *x* at 50% of *y*. Grain sorghum leaf area, leaf biomass, stem biomass, and total biomass at Hutchinson were modeled with a three-parameter exponential growth regression:

$$y = y0 + ae^{bx} \qquad [4]$$

where *y* is height, leaf area, leaf biomass, stem biomass, or total biomass, *x* is DAP or GDU, *a* is the maximum of *y* converged on 100%, *b* is the slope at the inflection point, and *y0* is *y* when *x* is zero. Differences in the regression lines for the early and late planting were compared using a pairwise F-test ($\alpha = 0.05$); when no differences were detected within a location, the data were pooled across planting date treatments.

Results and Discussion

Palmer Amaranth Emergence

Palmer amaranth populations that emerged in both sites were less than the desired target of 4 plants m^{-1} of row and inconsistent in growth, therefore it was not possible to accurately test the effects of Palmer amaranth emergence timing. Palmer amaranth data are presented only to demonstrate its relative competitiveness to the grain sorghum crop. Early planted plots in Manhattan averaged 0.7 and 0.1 plants m^{-1} of row for the early and late Palmer amaranth emergence, respectively (Table 2.3). The late planted plots averaged 1.5 and 0.6 plants m^{-1} of row for the early and late Palmer amaranth emergence, respectively. The early planted plots in Hutchinson averaged 2.8 and 2.0 Palmer amaranth plants m^{-1} of row for early and late emergence, respectively, while the late planted plots averaged 3.1 and 0.4 plants m^{-1} of row, for early and late emergence, respectively.

Weather Conditions

Manhattan received 629 and 698 mm of precipitation for the early and late planting, respectively from March 1 through grain sorghum flag-leaf stage (Figure 2.1). Compared to the 30-year average precipitation, Manhattan had above average precipitation in May, June, and August, and precipitation similar to the average in July, September, and October (Table 2.4). Total precipitation from March 1 through harvest equaled 907 and 976 mm in Manhattan for the early and late plantings, respectively.

The early and late planting in Manhattan accumulated 736 and 670 growing degree units (GDU), respectively from time of planting to grain sorghum flag-leaf stage, a difference of 66 GDU (Figure 2.2). The total cumulative GDU from planting to harvest was 1720 and 1476 GDU for early and late planting, respectively. Compared to the 30-year average GDU accumulation, Manhattan had a normal amount of GDUs in May and June, less than average in July and August, and above average in September and October (Table 2.4)

Hutchinson received 526 mm of precipitation for both planting timings from March 1 through grain sorghum flag-leaf stage (Figure 2.1). Compared to the 30-year average precipitation, the Hutchinson site received above average precipitation in May, June, and August, and less than average precipitation in July, September, and October (Table 2.5). Total precipitation from March 1 to harvest equaled 716 mm in Hutchinson.

The early and late planting in Hutchinson accumulated 666 and 588 GDU, respectively from planting to flag-leaf stage, a difference of 78 GDU (Figure 2.2). The cumulative GDU from planting to harvest was 2045 and 1726 GDU for the early and late planting, respectively. Compared to the 30-year average cumulative GDU, Hutchinson had above average GDU accumulation in May, June, July, September, and October (Table 2.5).

Grain Sorghum Stands

Grain sorghum stands in Manhattan were similar across planting dates, averaging 10.2 plants m^{-1} of row. The grain sorghum stand in Hutchison was different across planting dates averaging 5.5 and 8.2 plants m^{-1} of row for the early and late planting, respectively (Table 2.6). The reduced stands in Hutchinson likely occurred because of lower soil temperatures immediately following planting, especially in the early planting (Figure 2.3).

Grain Sorghum Growth Stage

In Manhattan, the late planted grain sorghum progressed more quickly through growth stages than the early planted grain sorghum reaching the flag-leaf stage approximately 5 days sooner when compared on a scale of DAP (Figure 2.4). The late planted grain sorghum also progressed more quickly through growth stages when compared over a scale of GDU. Regression parameters are presented in Table 2.7.

In Hutchinson, late planted grain sorghum progressed more quickly through growth stages than the early planted when compared on a scale of DAP, reaching flag-leaf stage approximately 20 days sooner (Figure 2.5). The same pattern was observed over a GDU time scale, although to a much lesser extent than the DAP scale. Regression parameters are presented in Table 2.7.

Grain Sorghum and Palmer Amaranth Height

Growth parameters like height, leaf area, and biomass are indicators of competitiveness (Horak and Loughin, 2000). Plants that are taller, or have greater leaf area or biomass have captured more resources than surrounding plants and have a competitive advantage to capture further resources (Graham et al., 1988).

In Manhattan, grain sorghum plants grew taller more quickly when planted late than when planted early based on DAP and GDU scales (Figure 2.6). Regression parameters are presented in Table 2.8. At flag-leaf stage, the late planted grain sorghum was 123.5 cm and the early planted grain sorghum was 5% shorter (Table 2.9). In Manhattan, Palmer amaranth that established in the early planting were extremely short by grain sorghum flag-leaf stage (Table 2.10). Within the late planting, the early emerged Palmer amaranth was 129 cm, reaching above the crop canopy, and the late emerged was approximately 60% as tall as the crop canopy at flag-leaf stage.

In Hutchinson, grain sorghum plants grew taller more quickly when planted late than when planted early on a DAP scale, reaching 100 cm approximately 20 days sooner (Figure 2.7). The same pattern was observed on a GDU scale, but to a lesser extent. Regression parameters are presented in Table 2.8. At flag-leaf stage, the early planted grain sorghum was 6% taller than the late planted (Table 2.6). In Hutchinson, the Palmer amaranth that established in the early planting was approximately 49% and 22% as tall as the height of the crop canopy for early and late emergence, respectively by grain sorghum flag-leaf stage (Table 2.10). In the late planting, the early emerging Palmer amaranth was 91% as tall as the crop canopy, while the late emerging was extremely short.

Late planted grain sorghum gained height more quickly than early planted in both locations on a DAP and GDU scale, therefore, the late planted grain sorghum was more competitive than the early planted. This difference in competitiveness was observed more when compared on a DAP scale, and once compared on a GDU scale the difference in growth rate was less, but still occurred. Planting date and heat units influenced height accumulation, thus also influenced competition. The final height of the late planted grain sorghum was taller than the early planted in Manhattan, even with the greater Palmer amaranth density in the late planting. Precipitation could have also been the factor at play in Manhattan because the late planting received almost 70 mm of additional rain than the early planting by grain sorghum flag-leaf stage. In Hutchinson, early planted grain sorghum was taller than late planted.

Palmer amaranth was predominately shorter than the grain sorghum canopy indicating less competitive plants in this study. Others have observed Palmer amaranth that emerged with the grain sorghum crop grew taller than the canopy, reaching up to 140 cm and 173 g $plant^{-1}$ of biomass and caused drastic yield loss, from 31 to 74% (Graham et al., 1988).

Grain Sorghum and Palmer Amaranth Leaf Area

Grain sorghum leaf area accumulated more quickly when planted later than earlier in Manhattan on a DAP scale (Figure 2.8). Leaf area accumulation was similar across plantings on GDU scale. Regression parameters are presented in Table 2.11. At grain sorghum flag-leaf stage, leaf area was similar between planting dates. In Manhattan at grain sorghum flag-leaf stage, the Palmer amaranth within the early planting had almost no leaf area, reaching only 8 and 15 cm^2 $plant^{-1}$ for the early and late emergence, respectively (Table 2.10). The early emerging Palmer amaranth in the late planting reached 1262 cm^2 $plant^{-1}$, or approximately 37% of the grain sorghum leaf area, while the late emerging Palmer amaranth reached 3% of the grain sorghum leaf area.

Grain sorghum leaf area accumulated more quickly when planted later than earlier in Hutchinson on a DAP scale, reaching 2000 cm^2 $plant^{-1}$ approximately 10 days sooner (Figure 2.9). Leaf area accumulation was similar across plantings on a GDU scale. Regression parameters are presented in Table 2.12. At grain sorghum flag-leaf stage, the early planted grain sorghum had 34% greater leaf area than the late planted (Table 2.6). In Hutchinson at grain sorghum flag-leaf stage, the Palmer amaranth leaf area within the early planting was 13% and 2% of the grain sorghum leaf area for early and late emergence, respectively (Table 2.10). The early emerging Palmer amaranth in the late planting reached 797 cm^2 $plant^{-1}$, or 35% of the grain sorghum leaf area, and the late emerging Palmer amaranth leaf area was minuscule.

At both locations, later planted grain sorghum accumulated leaf area more quickly than early planted on a DAP scale, but not on a GDU scale, therefore later planted grain sorghum was more competitive only on a DAP scale. Similar results were observed where late planted grain sorghum accumulated leaf area index (LAI) more quickly over a DAP scale (Blum, 1972). Heat units influenced the accumulation rate of leaf area, while planting date influenced competitiveness.

Grain Sorghum and Palmer Amaranth Biomass

In Manhattan, the late planted grain sorghum gained total biomass more quickly than the early planted on a DAP scale, reaching 20 g $plant^{-1}$ approximately 5 days sooner (Figure 2.10). In contrast, the total biomass accumulation rate was similar on a GDU scale. The late planted grain sorghum gained leaf biomass more quickly than the early planted on a DAP scale, but was similar on a GDU scale (Figure 2.11). Both plantings had a similar rate of stem biomass accumulation on a DAP and GDU scale (Figure 2.12). Total and leaf biomass followed the same pattern of accumulation while stem biomass accumulation was different, which indicated that the leaf component was a greater contributor to the total biomass accumulation rate than the stem component. At grain sorghum flag-leaf stage, grain sorghum total biomass was 12% greater in the early planting than the late (Table 2.19). Leaf biomass was not significant, but stem biomass was 25% more in the early planting than the late planting (Table 2.19). At flag-leaf stage, stem biomass appeared to be a larger contributor to total biomass versus leaf biomass. In Manhattan at grain sorghum flag-leaf stage, Palmer amaranth biomass in the early planting was minimal (Table 2.10). In the late planting, early emerging Palmer amaranth biomass was 14 g plant^{-1}, or 44% of grain sorghum biomass, while the late emerging Palmer amaranth was minuscule.

In Hutchinson, the late planted grain sorghum gained total biomass more quickly than the early planted on a DAP scale, reaching 20 g plant^{-1} approximately 18 days sooner, and the same pattern was observed on a GDU scale, but to a lesser degree (Figure 2.13). Leaf biomass followed the same pattern in that the late planted grain sorghum gained more quickly than the early planted on both DAP and GDU scales (Figure 2.14). Stem biomass accumulated more quickly by the late planting than early planting on a DAP scale, but was similar on a GDU scale (Figure 2.15). Leaf biomass was a greater contributor to total biomass over time than stem biomass at this location. At grain sorghum flag-leaf stage, the early planted grain sorghum had 29% more total biomass than the late planted (Table 2.6). Additionally, grain sorghum in the late Palmer amaranth emergence treatments had the greatest total biomass, followed by the weed-free treatments, and lastly by the early emergence that was 28% less than the late emergence. Grain sorghum leaf biomass was 27% greater in the early emergence than the late emergence (Table 2.6). Palmer amaranth emergence timing influenced grain sorghum leaf biomass, where it was greatest in the late emergence treatment, followed by the weed free, and lastly by the early emergence, which was 27% less than the late. Stem biomass was only significant by planting date, and was 34% greater in the early planting than the late (Table 2.6). At flag-leaf stage, leaf biomass appeared to be a larger contributor to total biomass versus stem biomass at that location. In Hutchinson at grain sorghum flag-leaf stage, Palmer amaranth biomass in the early planting was miniscule (Table 2.10). In the late planting, early emerging Palmer amaranth biomass was

14 g plant^{-1}, or 44% of the grain sorghum biomass, while the late emerging Palmer amaranth biomass was minimal.

At both locations, late planted grain sorghum accumulated biomass more quickly than early planted on a DAP scale, but not on a GDU scale, therefore late planted grain sorghum was more competitive only on a DAP scale. Heat units influenced the accumulation rate of biomass, while planting date influenced competitiveness. Total biomass at flag-leaf stage was greater in the early planting than the late planting at both locations. Similar trends have been reported that early planted grain sorghum had greater final biomass of 36.5 g plant^{-1} than late planted with 30.4 g plant^{-1} (Blum, 1972). Leaf biomass was the greater contributor from planting up to flag-leaf, but at flag-leaf stage, stem biomass appeared to be the greater contribution factor, which is consistent with the typical growth and development of grain sorghum (Vanderlip, 1993). During early growth, leaf biomass would be a much greater indicator of competitiveness because the plant is putting the majority of its resources into leaf matter.

Grain Sorghum Yield and Seed Weight

Grain sorghum yield at Manhattan had a significant planting date by Palmer amaranth emergence interaction (Table 2.13). The yields for all treatments were similar, except for the late planted early Palmer amaranth emergence treatment with a 17% yield decrease. This was expected because a higher density of Palmer amaranth, 1.5 plants m^{-1} of row, was present (Table 2.3). Consequently, planting date did not influence competition in terms of total grain yield. This could have implications on a planting date decision if a yield reduction does not occur with planting in early July. Although one must consider the additional 339 mm of precipitation that occurred above the normal during that growing season and understand that trend could be different in years with more typical precipitation amounts (Table 2.4). Grain sorghum seed weight, a component of yield, had a planting date by Palmer amaranth emergence interaction in Manhattan (Table 2.13). Within the early planted treatments, the greatest seed weight occurred in the weed free treatment, followed by early emergence, and lastly by late emergence, where seed weight was 5% less than the weed free. Within the late planted treatments, seed weight was similar across emergence treatments. Seed weight was greater in the early planting than the late planting. Similar trends have been reported where early planted grain sorghum produced heavier seeds than late planted due to a longer period of grain fill under warmer temperatures (Blum, 1972). Martin and Vanderlip (1997) observed that test weights of grain sorghum of medium maturing hybrids were reduced by approximately 36% when planted in mid-July versus mid-June in Kansas.

Planting date affected grain sorghum yield in Hutchinson, where the early planted grain sorghum had a 37% decrease in yield from the late planted grain sorghum (Table 2.6). The yield reduction in the early planted grain sorghum was primarily due to various environmental factors. First, cool soil temperatures immediately following planting led to fewer plants per area (Figure 2.3). Secondly, high temperatures and drought-like conditions occurred immediately prior and throughout anthesis of the early planted treatments (Figure 2.1). Heat and moisture stress negatively affect pollination effort, and choosing planting dates to avoid times of high temperature and drought-like conditions are common (Assefa et al., 2010). Additionally, Palmer amaranth emergence affected yield, where yields were similar in the weed free and late emergence treatments, but were 25% less in the early emergence treatment (Table 2.6). In the early and late plantings, the early Palmer amaranth emergence had higher Palmer amaranth densities, so greater yield loss was expected. However, the early emergence densities were not significantly different from the late emergence densities in the early planting, so the yield decrease could also be influenced by the time of emergence. Many studies have shown a greater yield loss with early emerging weeds compared to late emerging weeds (Burnside and Wicks, 1967, 1969; Knezevic et al., 1997; MacRae et al., 2013; Massinga et al., 2001; Wiese et al., 1964). Grain sorghum seed weight in Hutchinson was 6% greater in the late planted grain sorghum than early planted (Table 2.6). Seed weight was similar in the weed free and late weed emergence treatments, while the early emergence treatment was 10% less. The seed weight component of yield was greater in the late planted grain sorghum than the early and was likely due to the drought conditions during the beginning stages of grain fill (Figure 2.1). Vanderlip (1993) reported that moisture stress during grain fill would result in light weight grain.

Conclusions and Implications

A clear trend was evident that late planted grain sorghum grew and developed more quickly than early planted with regards to the calendar date. When factoring in heat units, leaf area and biomass accumulation were similar between planting dates, while stage development and height accumulation were still more rapid in the late planting.

At a later stage of growth, the early planted grain sorghum was taller and had greater leaf area and biomass than late planted, thus was more competitive at that point in time. Weeds compete with crops throughout the entire season, however the critical time for weed control in grain sorghum is within the early vegetative stages, where the crop is small, slow growing, and less able to capture resources (Graham et al., 1988; Stahlman and Wicks, 2000). Therefore, early season growth patterns rather than later are more relevant to evaluating grain sorghum competitive ability with weeds.

Although unable to accurately test in the current study, countless studies have demonstrated the negative effects of later emergence compared to emergence at crop planting on weed competition and specifically Palmer amaranth competition (Burnside and Wicks, 1967, 1969; Forcella et al. 2000; Horak and Loughin, 2000; Keeley et al., 1987; Knezevic et al., 1997; MacRae et al., 2013; Massinga et al., 2001; Spaunhorst et al., 2018; Stahlman and Wicks, 2000; Webster and Grey, 2015; Wiese et al., 1964).

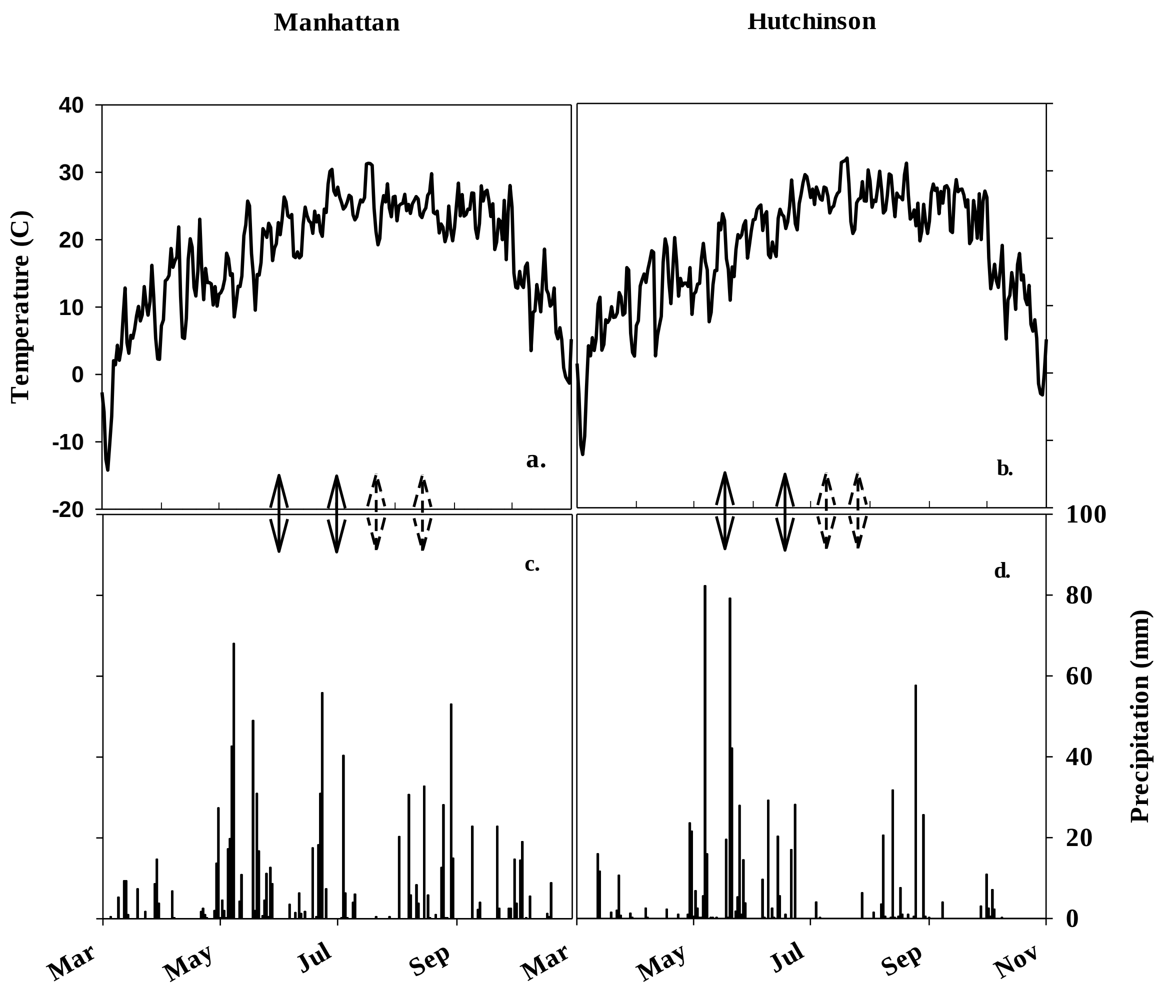
The topic of this study has significant implications for producers. Grain sorghum that is planted earlier has greater competitive ability in late stages of growth, but during the critical time for weed control in early vegetative stages, later planted grain sorghum is more competitive. The same trend is observed in Palmer amaranth, where early emerged plants have greater final leaf area, biomass, and fecundity, but it grows more quickly when emergence is delayed. Consequently, these principles must be applied in combination to maximize crop competitiveness. This could be implemented by delaying grain sorghum planting and subsequently delaying Palmer amaranth emergence until the crop is adequately established. Although the current study could not accurately assess this, the hypothesis remains that the effect of delaying grain sorghum planting and Palmer amaranth emergence is greater than the effect of only delaying Palmer amaranth emergence regarding grain sorghum competition.

The optimum planting date for grain sorghum is greatly dependent on the specific system in which it is produced, and planting date would be a zero-input cost method that could easily be manipulated. By delaying planting, the risk of avoiding heat and moisture stress during flowering stage is lessened, but the risk of inadequate time to mature before frost in the fall in increased. Shorter maturity hybrids can combat the issue of maturity before frost, in addition to providing a more favorable water use distribution in moisture limited regions. But shorter maturing hybrids typically yield less than longer maturity hybrids. A producer must consider each factor and determine the top limiting factors in their system.

Delaying Palmer amaranth emergence would also have implications for the cropping system. Delaying emergence would allow early flushes to emerge and be controlled before the crop was planted, lessening the weed pressure on the crop and lessening the number of seeds in the soil seedbank. Before the rise of preemergent herbicides, this was a common practice in weed management (Stahlman and Wicks, 2000). Weeds that emerged later would be less competitive, thus easier to control. If Palmer amaranth emerged after a month of grain sorghum growth, yield reductions would be minimal, and a producer must weigh the cost of control against the potential gain. If the producer chose to forego control of late emerging weeds, they must still consider the seed that would be added to the weed seedbank and provide weed pressure in the following years. While later emerging Palmer amaranth has been documented to producer fewer seeds, total production can still be substantial. Some researchers have called for a zero seed-tolerance policy to eliminate the spread of herbicide resistant Palmer amaranth populations (Barber et al., 2015). The dynamics of late emerging Palmer amaranth seed production must be further examined to understand the overarching effects of delaying emergence.

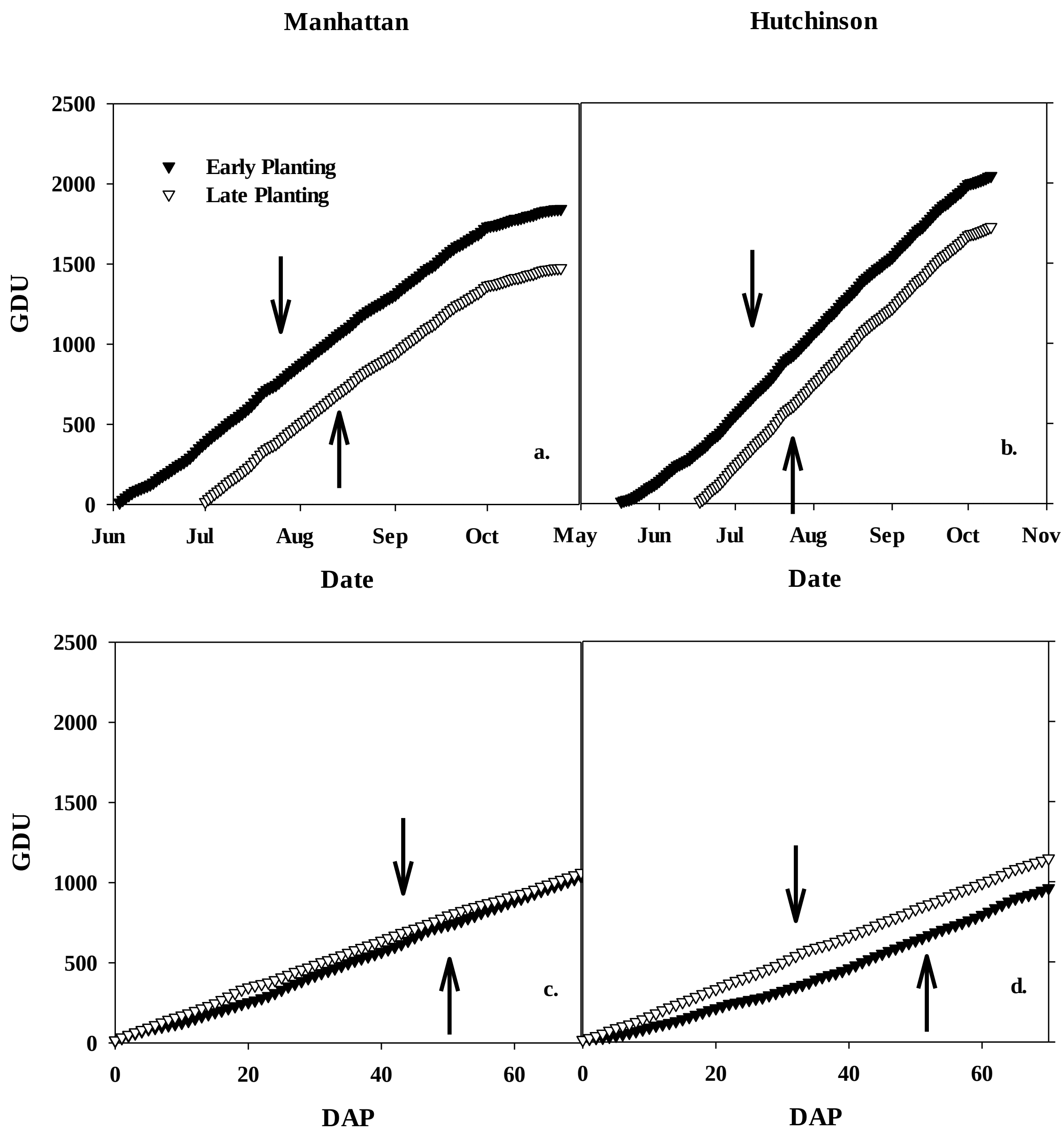
Figures and Table

Figure 2.1 Mean air temperature (C) at Manhattan (a.) and Hutchinson (b.) and precipitation (mm) at Manhattan (c.) and Hutchinson (d.) in 2019



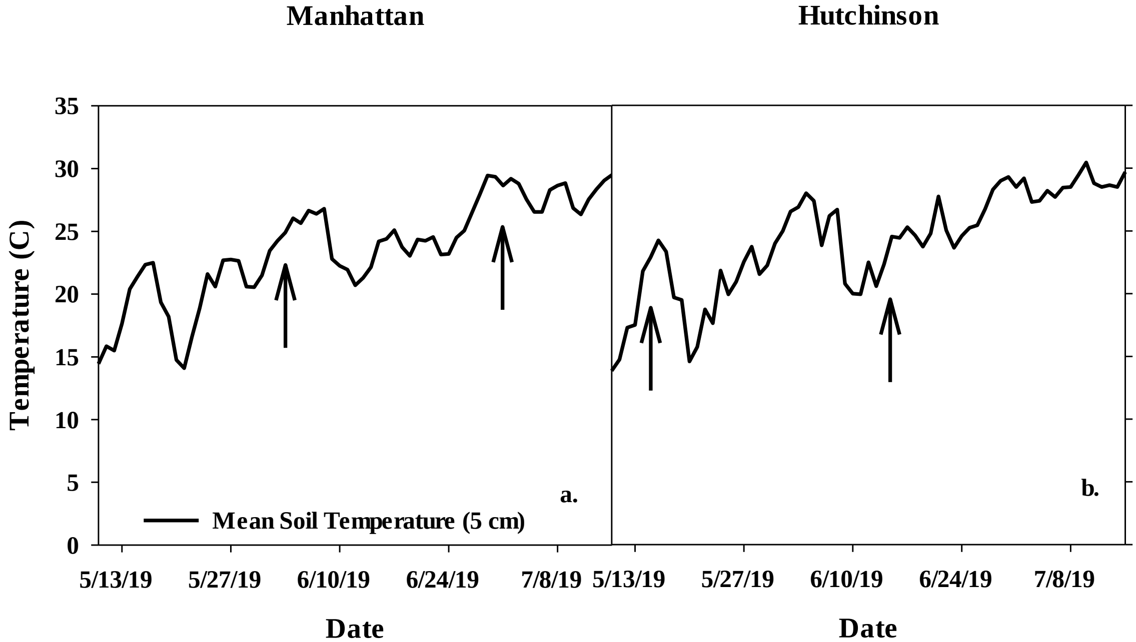
- Solid arrows signify the date of planting for the early and late planting
- Checked arrows signify the date of grain sorghum flag leaf stage (GS Stage 4) for the early and late planting

Figure 2.2 Cumulative growing degree units (GDU) over calendar date at Manhattan (a.) and Hutchinson (b.) and over days after grain sorghum planting (DAP) at Manhattan (c.) and Hutchinson (d.) in 2019



- Arrows signify the date of grain sorghum flag leaf stage (GS Stage 4) for the early and late planting

Figure 2.3 Mean soil temperature (C at 5 cm depth) during grain sorghum planting dates at Manhattan (a.) and Hutchinson (b.) Kansas in 2019



- ➢ Arrows signify the date of planting for the early and late planting

Figure 2.4 Grain sorghum growth stage (based on Vanderlip, 1993) over calendar date, days after planting (DAP), and growing degree units (GDU) at Manhattan, Kansas in 2019. Regression parameters presented in Table 2.7.

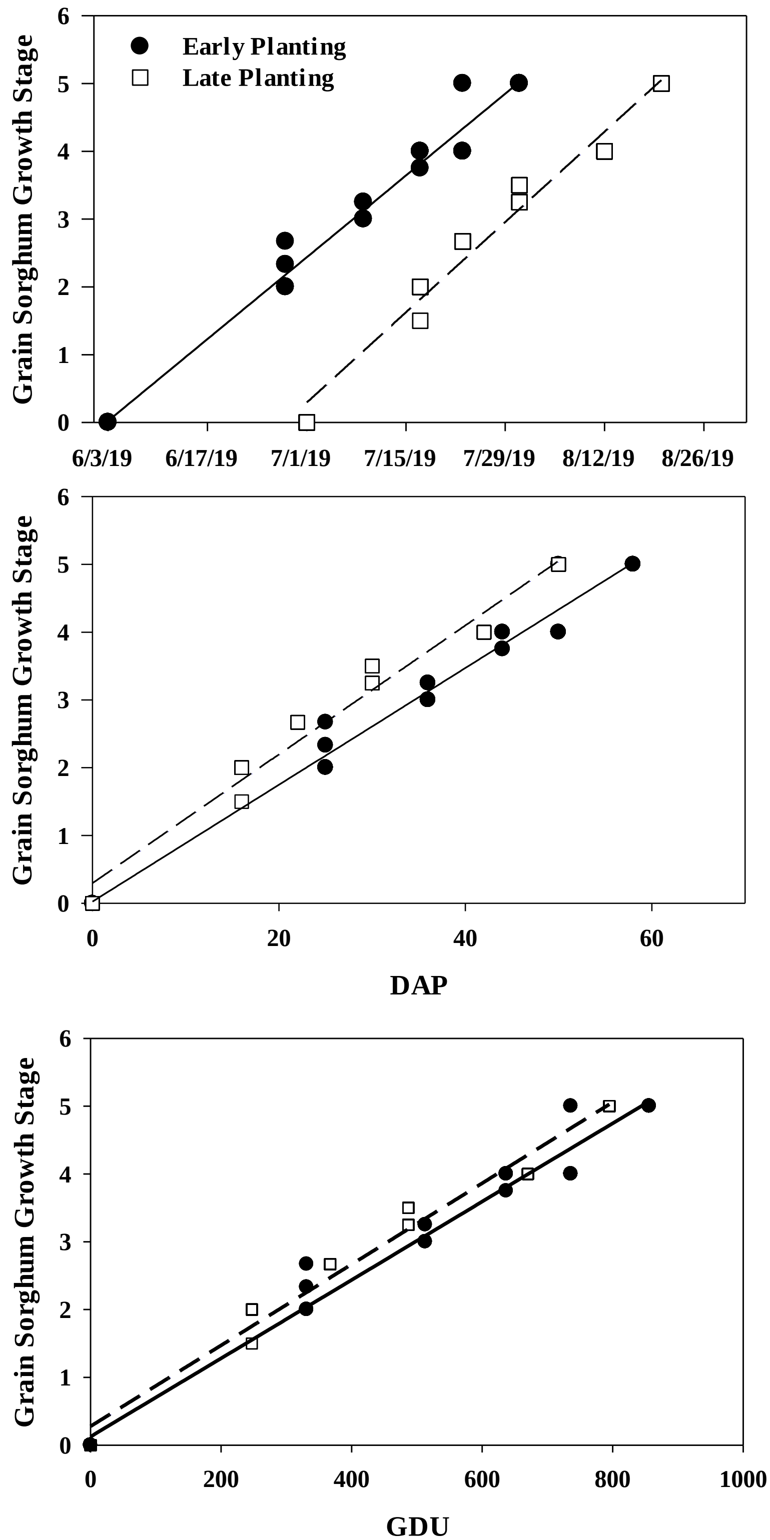


Figure 2.5 Grain sorghum growth stage (based on Vanderlip, 1993) over calendar date, days after planting (DAP), and growing degree units (GDU) at Hutchinson, Kansas in 2019. Regression parameters presented in Table 2.7.

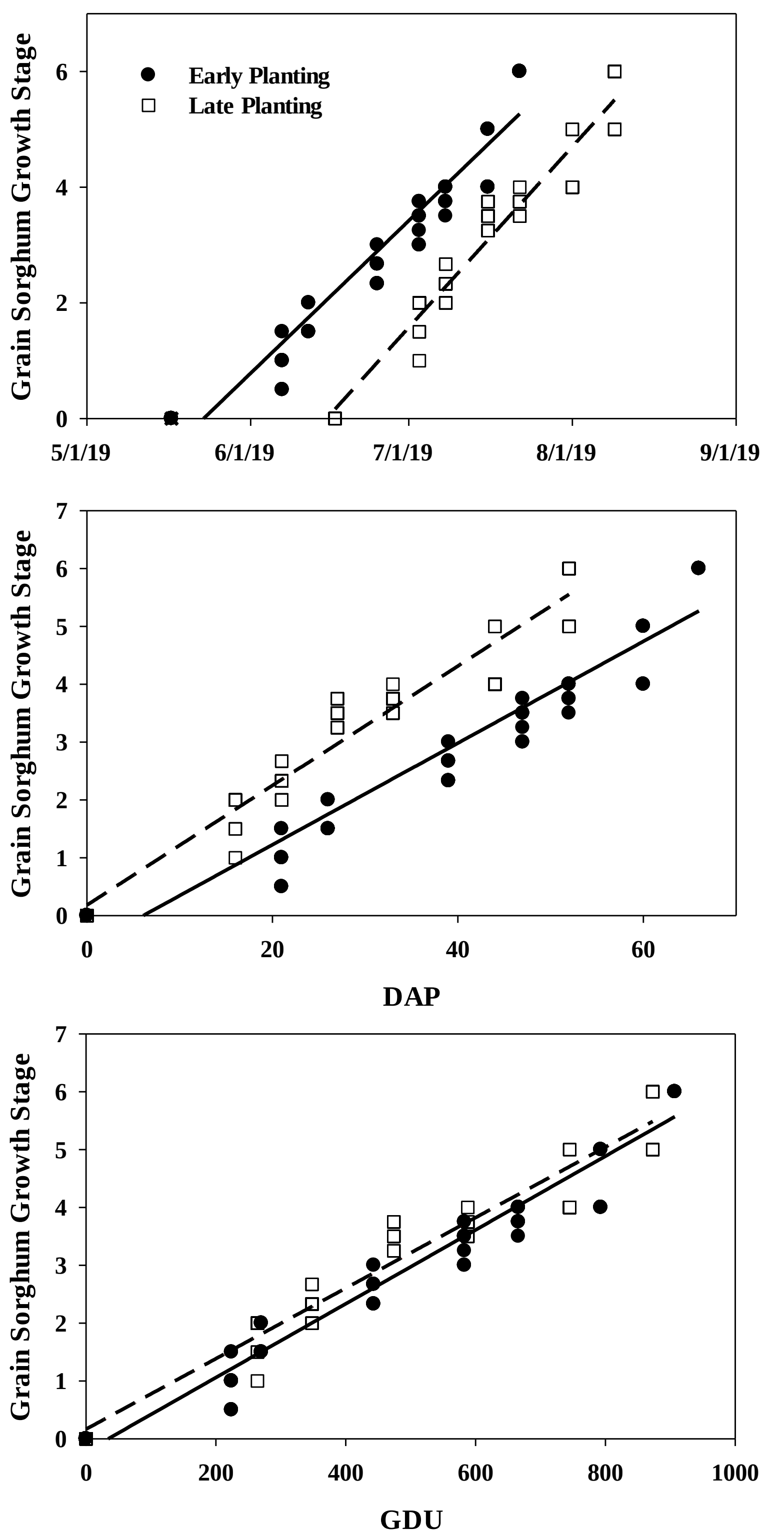


Figure 2.6 Grain sorghum height (cm) over calendar date, days after planting (DAP), and growing degree units (GDU) at Manhattan, Kansas in 2019. Regression parameters presented in Table 2.8.

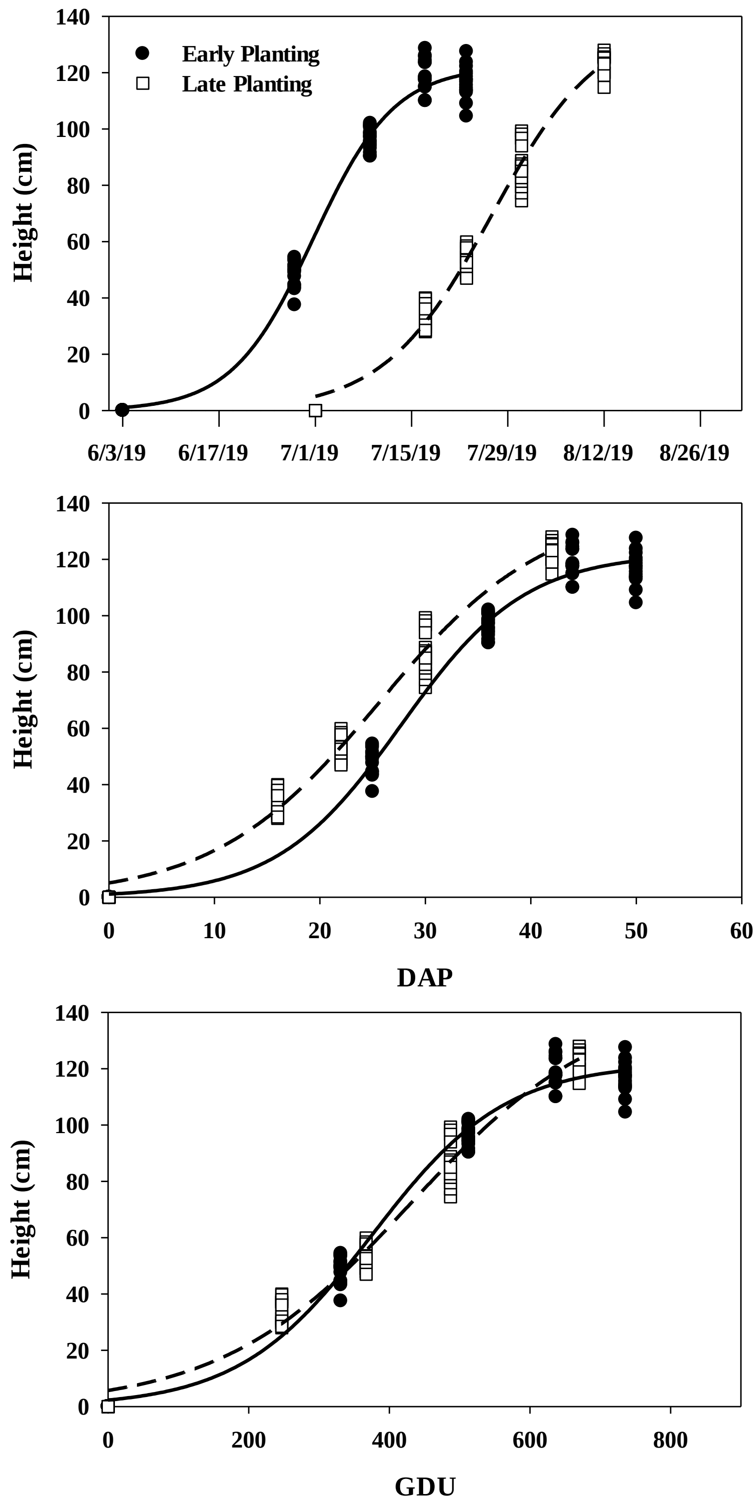


Figure 2.7 Grain sorghum height (cm) over calendar date, days after planting (DAP), and growing degree units (GDU) at Hutchinson, Kansas in 2019. Regression parameters presented in Table 2.8.

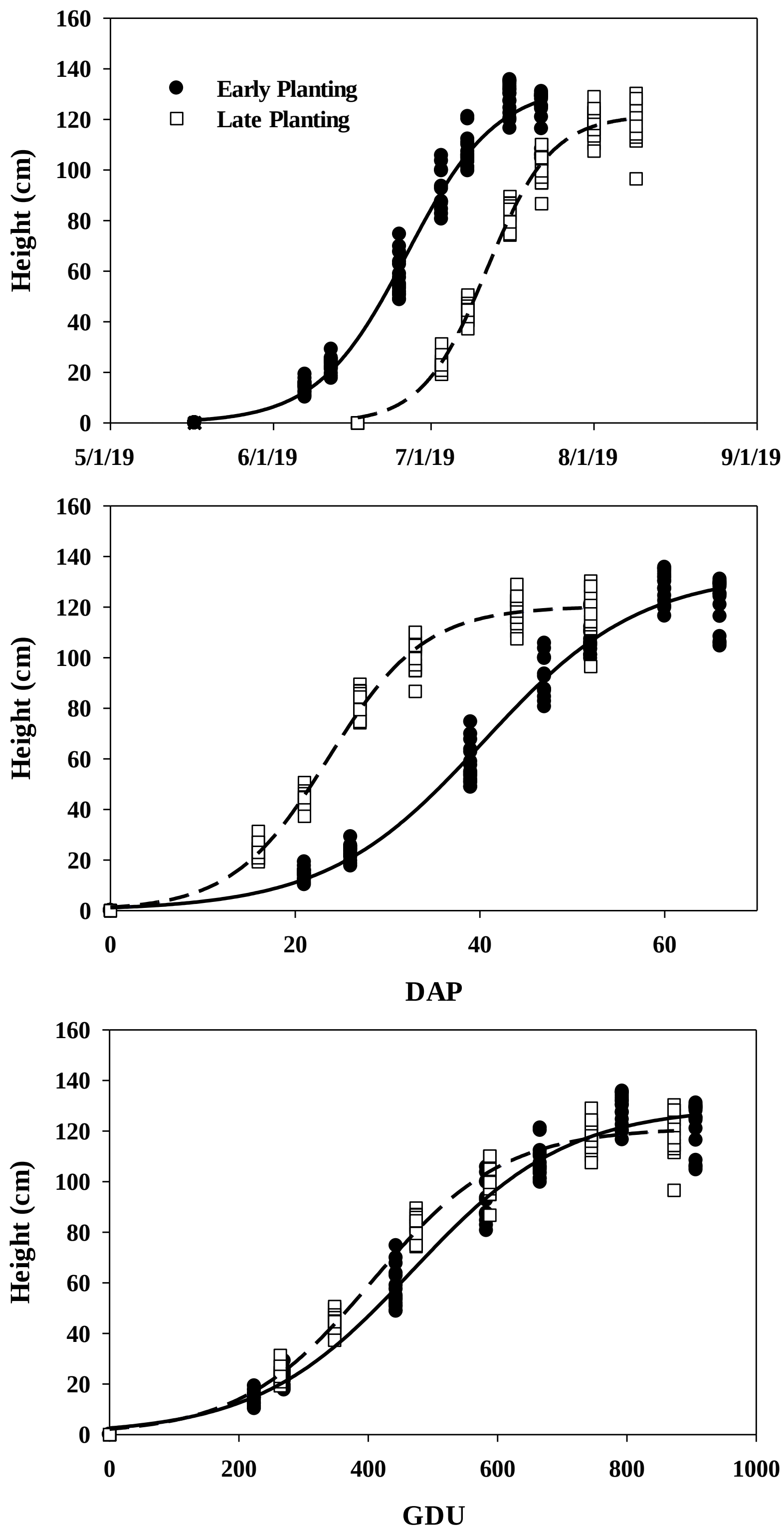


Figure 2.8 Grain sorghum leaf area (cm² plant⁻¹) over calendar date, days after planting (DAP), and growing degree units (GDU) at Manhattan, Kansas in 2019. Regression parameters presented in Table 2.11.

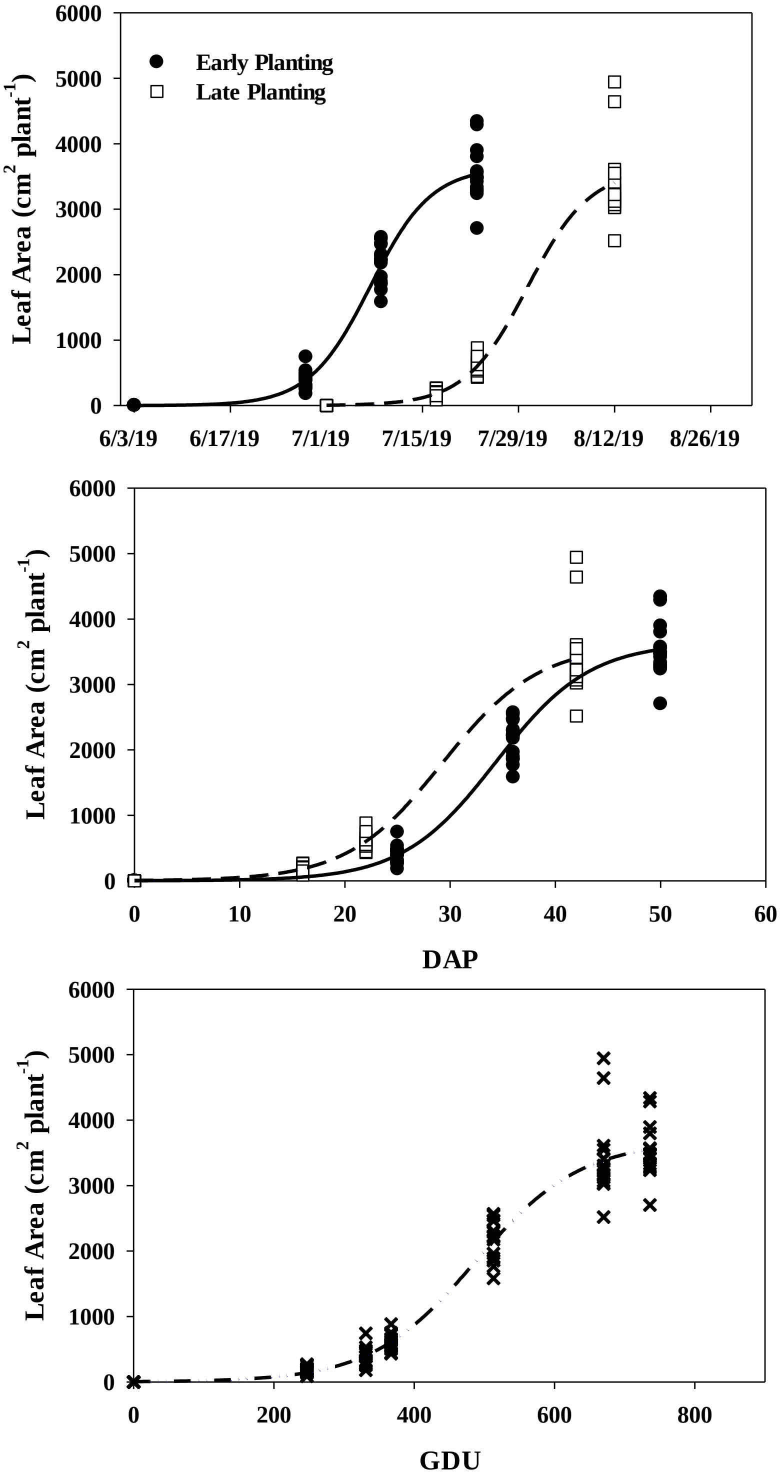


Figure 2.9 Grain sorghum leaf area (cm^2 plant^{-1}) over calendar date, days after planting (DAP), and growing degree units (GDU) at Hutchinson, Kansas in 2019. Regression parameters presented in Table 2.12.

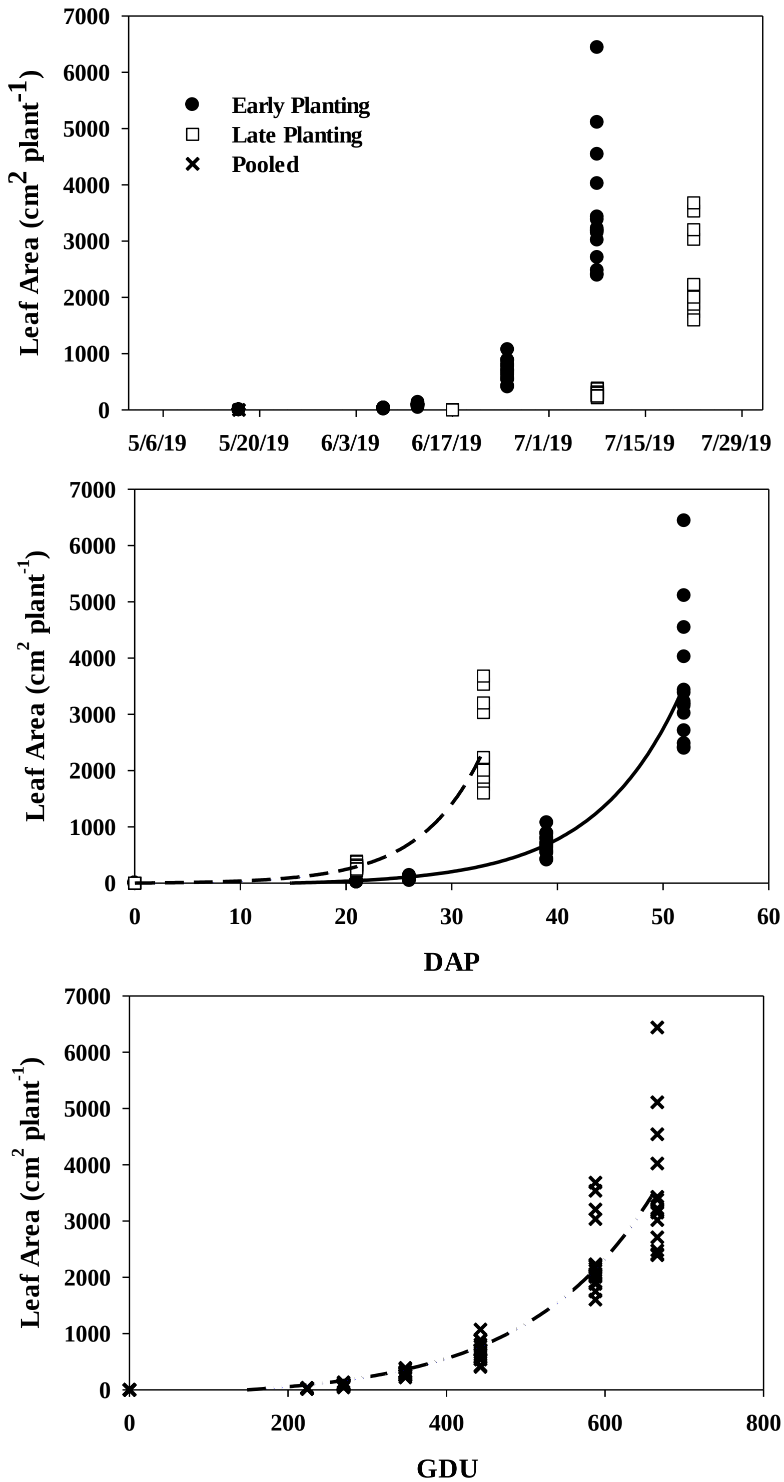


Figure 2.10 Grain sorghum total biomass (g plant^{-1}) over calendar date, days after planting (DAP), and growing degree units (GDU) at Manhattan, Kansas in 2019. Regression parameters presented in Table 2.11.

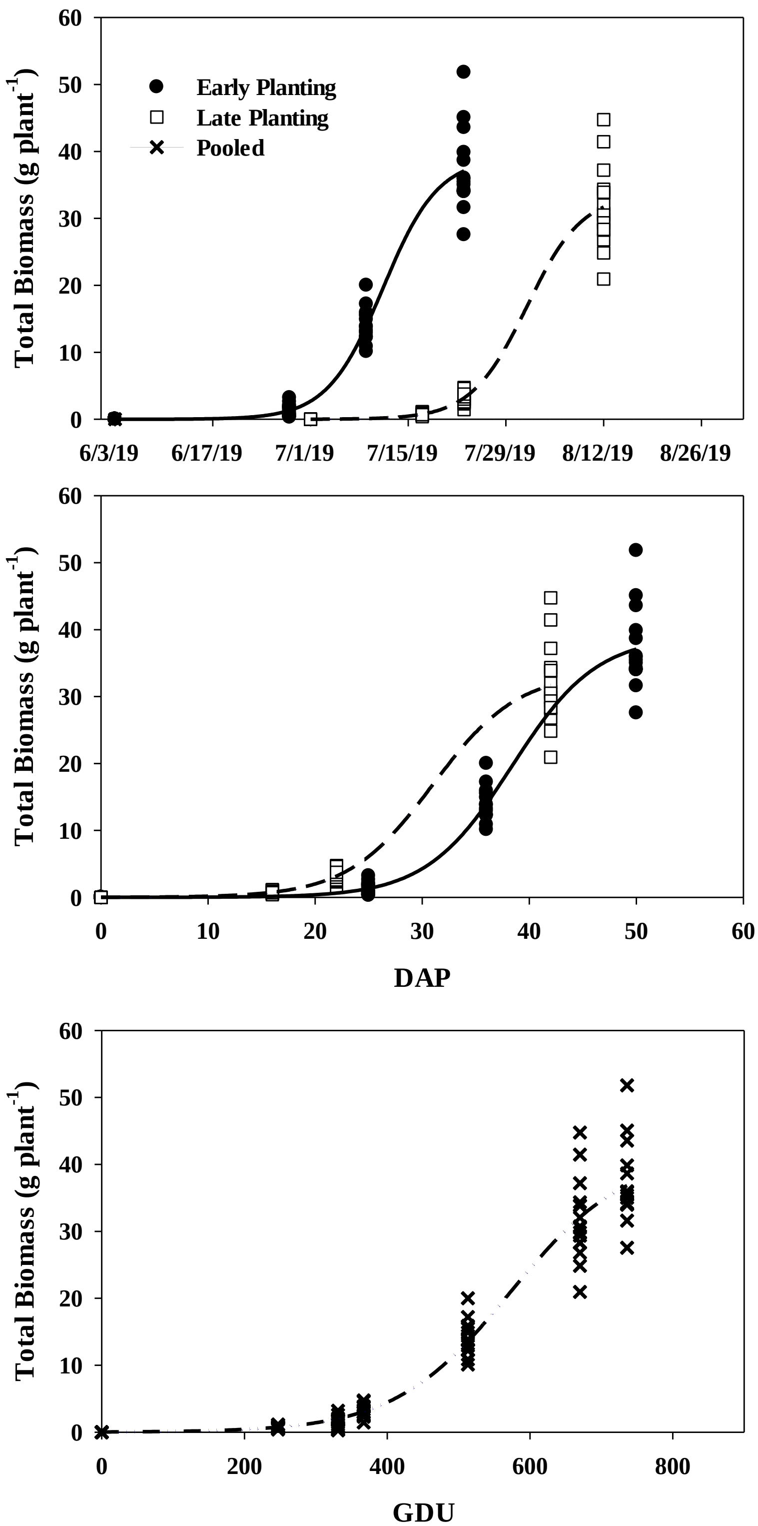


Figure 2.11 Grain sorghum leaf biomass (g plant-1) over calendar date, days after planting (DAP), and growing degree units (GDU) at Manhattan, Kansas in 2019. Regression parameters presented in Table 2.11.

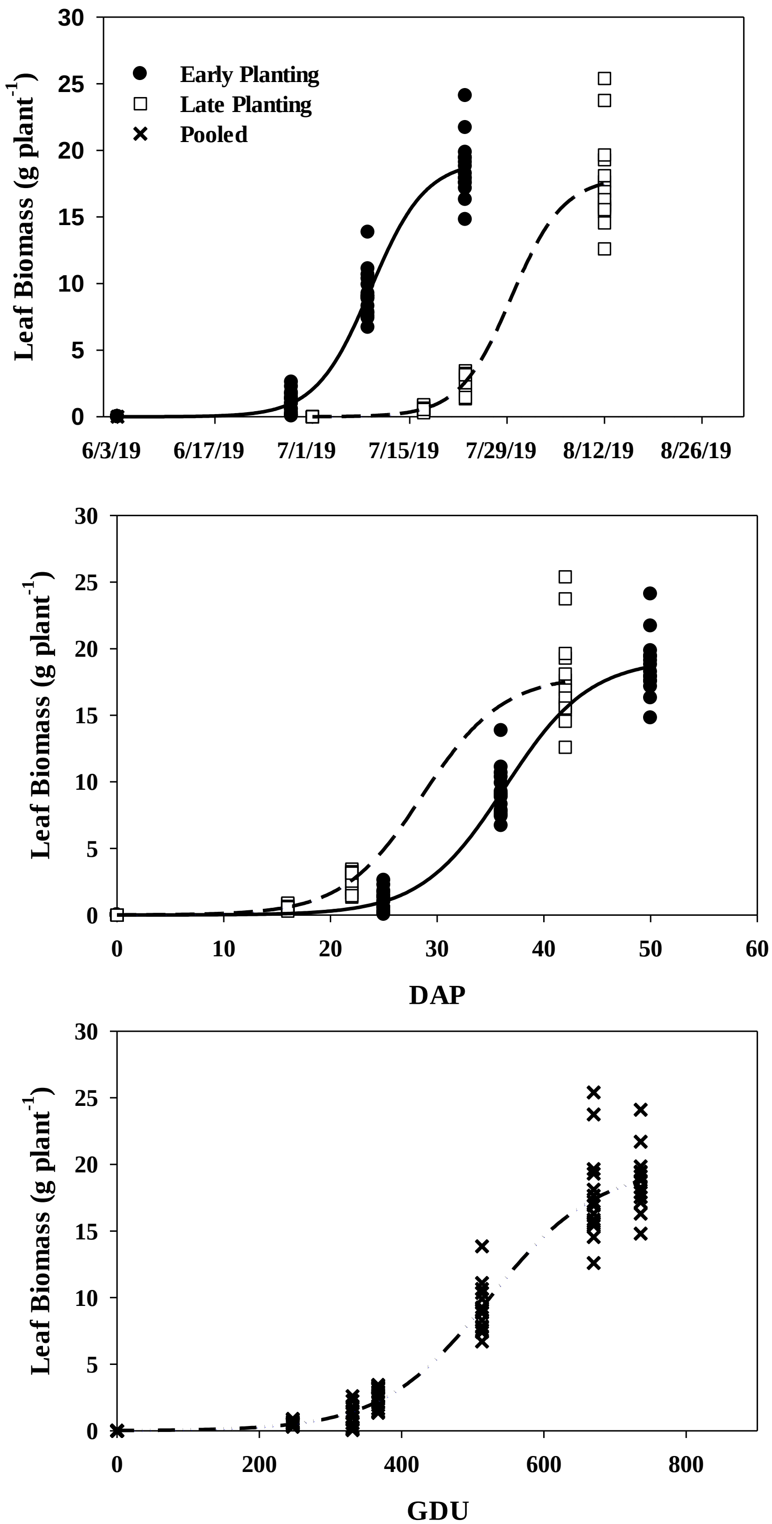


Figure 2.12 Grain sorghum stem biomass (g plant^{-1}) over calendar date, days after planting (DAP), and growing degree units (GDU) at Manhattan, Kansas in 2019. Regression parameters presented in Table 2.11.

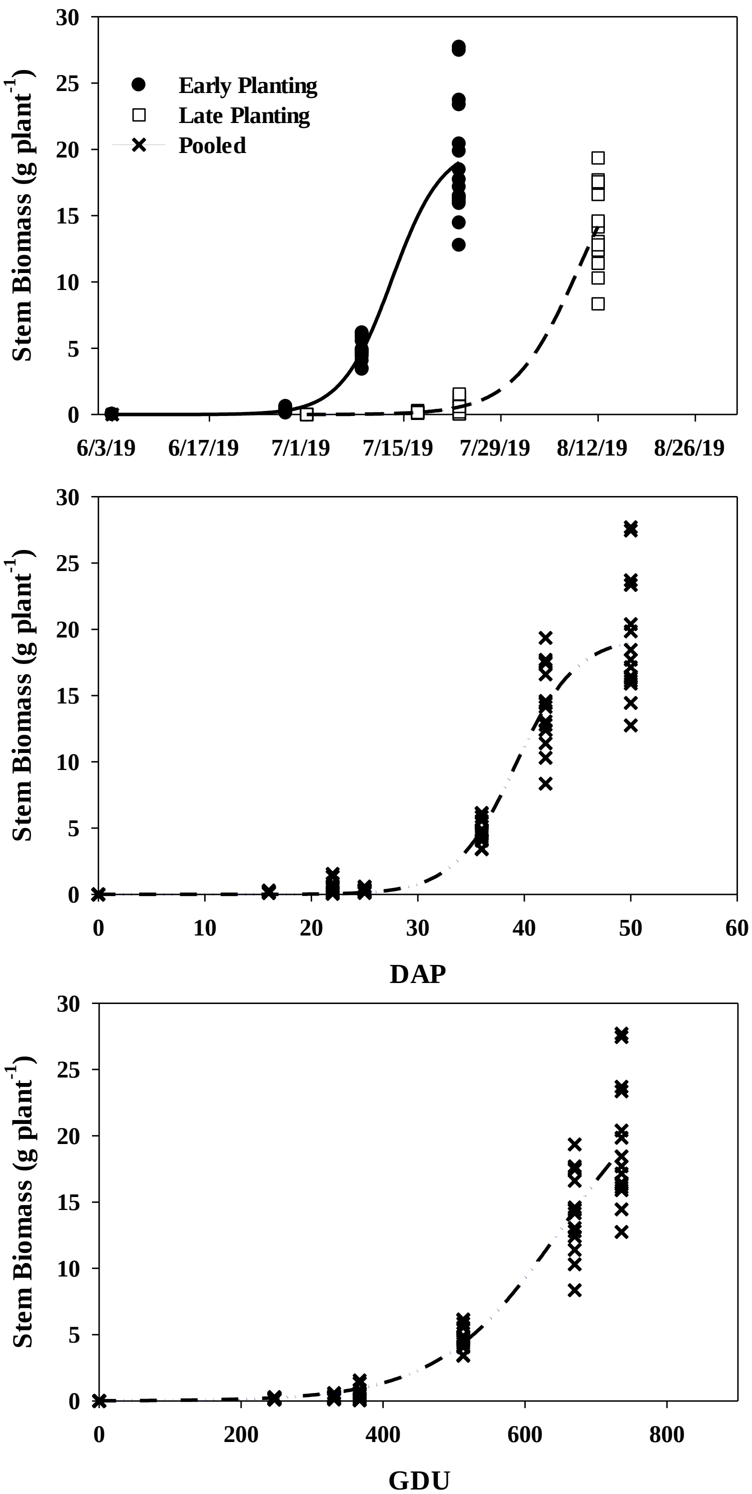


Figure 2.13 Grain sorghum total biomass (g plant^{-1}) over calendar date, days after planting (DAP), and growing degree units (GDU) at Hutchinson, Kansas in 2019. Regression parameters presented in Table 2.12.

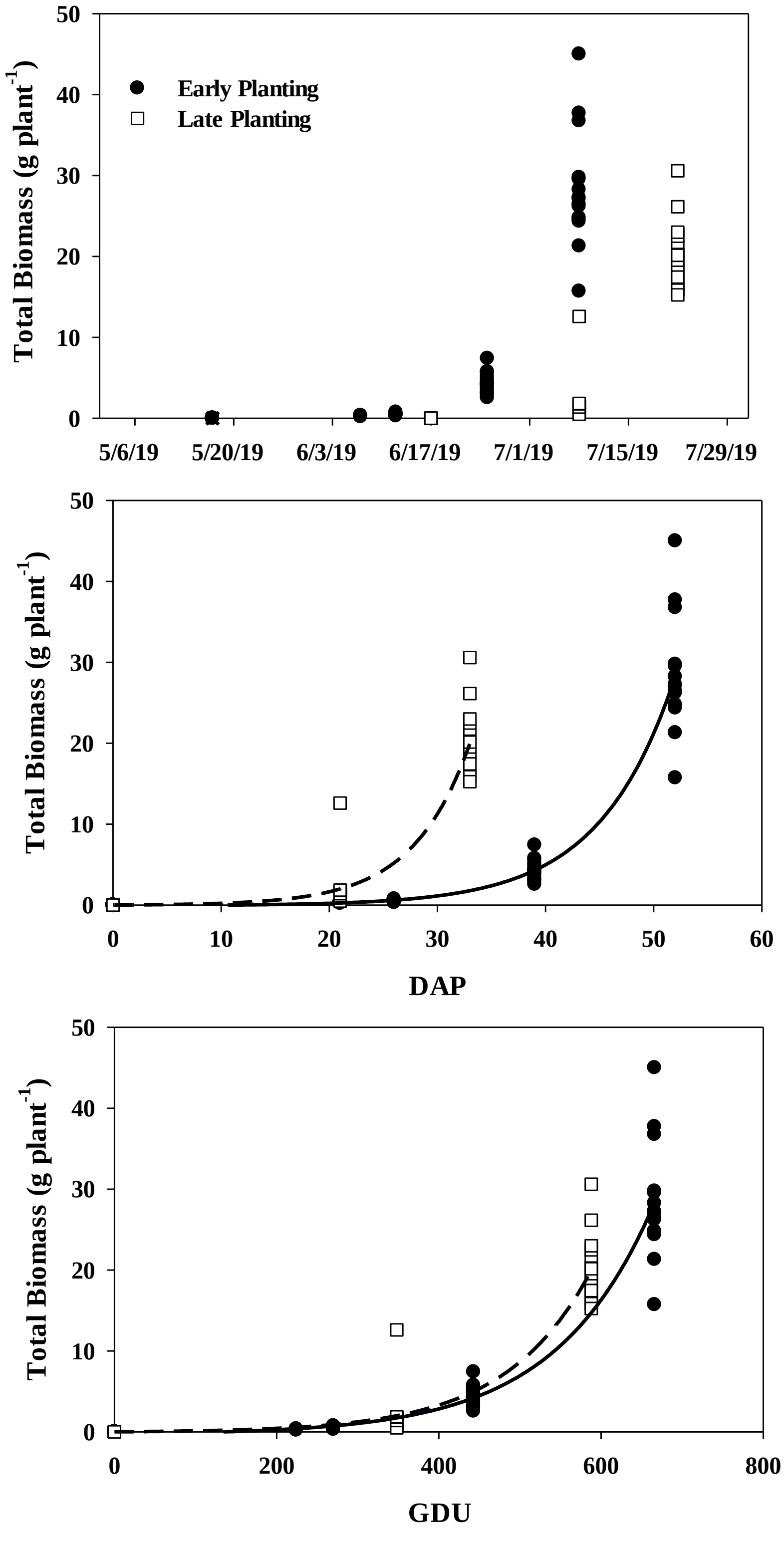


Figure 2.14 Grain sorghum leaf biomass (g plant^{-1}) over calendar date, days after planting (DAP), and growing degree units (GDU) at Hutchinson, Kansas in 2019. Regression parameters presented in Table 2.12.

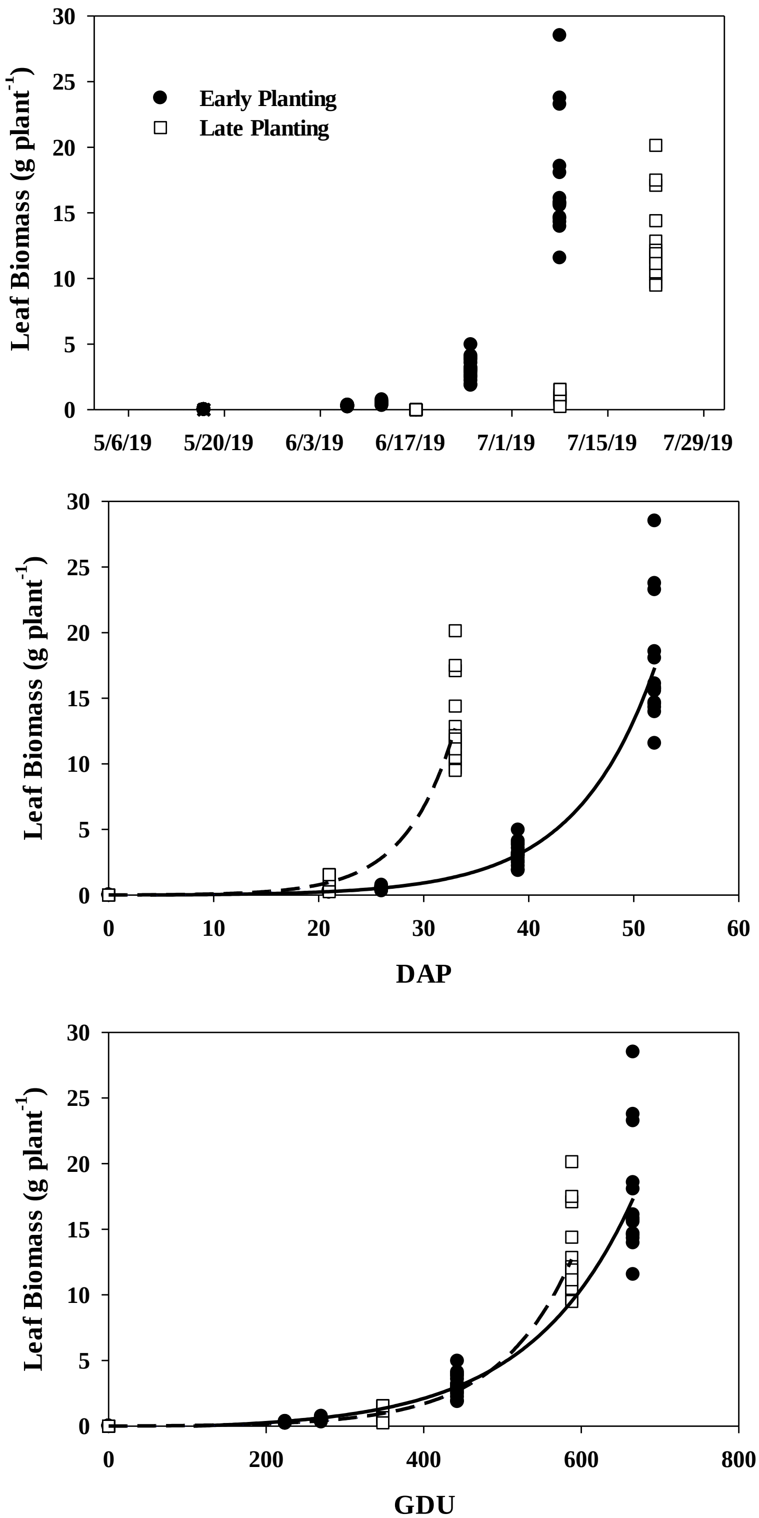


Figure 2.15 Grain sorghum stem biomass (g plant^{-1}) over calendar date, days after planting (DAP), and growing degree units (GDU) at Hutchinson, Kansas in 2019. Regression parameters presented in Table 2.12.

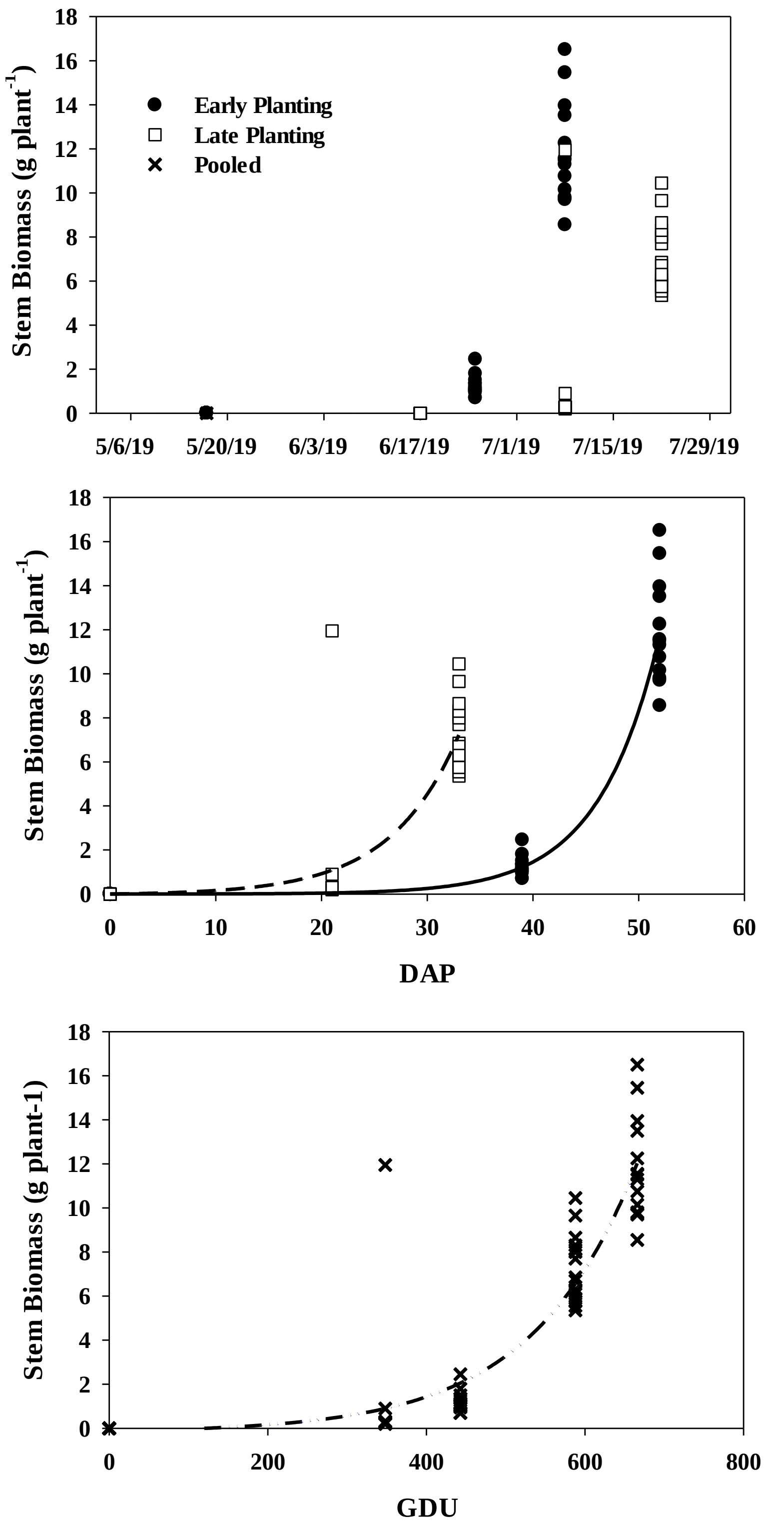


Table 2.1 Grain sorghum planting dates and Palmer amaranth emergence at days after grain sorghum planting (DAP) at Manhattan and Hutchinson, Kansas in 2019.

	Grain Sorghum		Palmer Amaranth	
Location	Treatment	Planting Date	Treatment	Emergence (DAP)
Manhattan	Early	June 3	Weed-Free	0
			Early	30
			Late	-
	Late	July 1	Weed-Free	0
			Early	10
			Late	15
Hutchinson	Early	May 17	Weed-Free	0
			Early	15
			Late	30
	Late	June 17	Weed-Free	0
			Early	15
			Late	30

- Hyphen (-) = emergence date not recorded

Table 2.2 Herbicide application products and dates in Manhattan and Hutchinson, Kansas in 2019.

Location	Planting Date	Palmer Amaranth Emergence	Herbicide Application	Application Date
Manhattan	Early	Weed-Free	Degree Xtra [a]	July 2
		Early	Warrant [b]	July 2
		Late	-	-
	Late	Weed-Free	Degree Xtra	July 2
		Early	-	-
		Late	-	-
Hutchinson	Early	Weed-Free	Huskie [c] & Degree Xtra Degree Xtra	June 10 July 3
		Early	Huskie & Warrant [d]	June 10
		Late	Huskie Warrant	June 10 July 3
	Late	Weed-Free	Huskie & Degree Xtra Degree Xtra	June 10 July 3
		Early	Huskie & Warrant	June 10
		Late	Huskie	June 10

a. 1895 g ha^{-1} acetochlor and 942 g ha^{-1} atrazine (Bayer, 800 N. Lindbergh Blvd. St. Louis, MO 63141)

b. 2100 g ha^{-1} acetochlor (Bayer, 800 N. Lindbergh Blvd. St. Louis, MO 63141)

c. 37 g ha^{-1} pyrasulfotole and 208 g ha^{-1} bromoxynil (Bayer, 800 N. Lindbergh Blvd. St. Louis, MO 63141) with 110 g ha^{-1} of ammonium sulfate (AMS)

d. Emerged Palmer amaranth plants were covered with plastic cups during Huskie and Warrant application to prevent injury in early Palmer amaranth plots at Hutchinson

Table 2.3 Palmer amaranth stand (plants m^{-1} of row) at Manhattan and Hutchinson, Kansas in 2019.

Location	Planting Date	Palmer Amaranth Emergence	Stand
			plants m^{-1} of row
Manhattan	Early	Early	0.7 cd
		Late	0.1 d
	Late	Early	1.5 bc
		Late	0.6 cd
Hutchinson	Early	Early	2.8 a
		Late	2.0 ab
	Late	Early	3.1 a
		Late	0.4 cd

- Different letters in column represent significance by least squares mean separation at $\alpha = 0.05$ across both locations

Table 2.4 Observed, normal, and departure values for precipitation, temperature, and cumulative growing degree units in Riley County, Kansas in 2019 (Manhattan).

	Precipitation (mm)			Temperature (C)			Growing Degree Units (GDU)		
Month	Observed	Normal	Departure	Observed	Normal	Departure	Observed	Normal	Departure
Mar.	57	61	-4	3	6	-3	46	57	-11
Apr.	52	76	-24	13	12	1	218	198	21
May	313	117	196	16	18	-1	443	440	3
June	157	127	30	23	23	0	835	834	1
July	97	107	-10	26	26	0	1322	1334	-12
Aug.	242	99	143	25	25	0	1764	1801	-37
Sept.	75	79	-4	24	20	4	2186	2101	85
Oct.	75	64	12	11	13	-2	2315	2256	59

Table 2.5 Observed, normal, and departure values for precipitation, temperature, and cumulative growing degree units in Reno County, Kansas in 2019 (Hutchinson).

	Precipitation (mm)			Temperature (C)			Growing Degree Units (GDU)		
Month	Observed	Normal	Departure	Observed	Normal	Departure	Observed	Normal	Departure
Mar.	48	66	-18	5	7	-3	55	56	-1
Apr.	40	64	-23	13	13	0	223	193	30
May	348	109	239	16	18	-2	450	440	10
June	123	112	11	23	24	-1	855	845	10
July	28	91	-64	27	27	0	1366	1353	12
Aug.	141	86	61	26	26	0	1844	1841	3
Sept.	15	64	-49	25	21	4	2297	2159	138
Oct.	34	64	-29	12	14	-2	2445	2327	118

Table 2.6 Grain sorghum stand, height, leaf area, total biomass, leaf biomass, stem biomass at Hutchinson, Kansas in 2019.

		Stand	Height	Leaf Area	Total Biomass	Leaf Biomass	Stem Biomass	Yield	Seed Weight
		plants m^{-1} of row	cm	cm^2 $plant^{-1}$	g $plant^{-1}$	g $plant^{-1}$	g $plant^{-1}$	kg ha^{-1}	g 100 $seeds^{-1}$
Planting Date	Early	5.5 (0.3) b	108.2 (2.0) a	3477.5 (236.1) a	28.3 (1.5) a	17.3 (1.0) a	10.9 (0.8) a	3790 (320) b	2.26 (0.07) b
	Late	8.2 (0.3) a	101.2 (1.9) b	2301.8 (221.8) b	20.0 (1.4) b	12.7 (0.9) b	7.2 (0.8) b	5970 (320) a	2.40 (0.07) a
Palmer Amaranth Emergence	Weed Free	-	-	-	23.7 (1.3) ab	14.8 (0.9) ab	-	5170 (320) a	2.39 (0.07) a
	Early	-	-	-	20.4 (2.0) b	12.6 (1.4) b	-	4070 (360) b	2.19 (0.08) b
	Late	-	-	-	28.2 (1.9) a	17.7 (1.3) a	-	5400 (360) a	2.43 (0.08) a

- Height, leaf area, total biomass, leaf biomass, and stem biomass measurements at grain sorghum flag-leaf stage
- Standard error denoted in parentheses
- Different letters in column represent significance by least squares mean separation at $\alpha = 0.05$
- Hyphen (-) = not significant

Table 2.7 Regression parameters (based on Equation 2) for grain sorghum growth stage at Manhattan and Hutchinson, Kansas in 2019.

Location	Time Scale	Planting Date	Parameter Estimates		
			y0	*a*	R^2
Manhattan	DAP	Early	0.03 (0.05)	0.09 (0.001)	0.98
		Late	0.30 (0.05)	0.10 (0.002)	0.97
	GDU	Early	0.13 (0.05)	0.006 (9.04e-5)	0.98
		Late	0.28 (0.04)	0.006 (8.79e-5)	0.98
Hutchinson	DAP	Early	-0.53 (0.09)	0.09 (0.002)	0.94
		Late	0.18 (0.08)	0.10 (0.002)	0.94
	GDU	Early	-0.22 (0.06)	0.006 (0.0001)	0.97
		Late	0.17 (0.07)	0.006 (0.0001)	0.95

- Standard error denoted in parentheses

Table 2.8 Regression parameters (based on Equation 3) for grain sorghum height (cm) at Manhattan and Hutchinson, Kansas in 2019.

Location	Time Scale	Planting Date	Parameter Estimates			
			a	*b*	*x0*	R^2
Manhattan	DAP	Early	122.2 (1.6)	5.9 (0.3)	27.7 (0.3)	0.988
		Late	138.5 (3.2)	7.8 (0.4)	25.6 (0.5)	0.986
	GDU	Early	122.1 (1.6)	95.1 (5.2)	375.5 (5.0)	0.987
		Late	144.6 (4.4)	135.3 (6.9)	431.2 (11.0)	0.984
Hutchinson	DAP	Early	133.8 (2.3)	8.5 (0.4)	40.4 (0.5)	0.978
		Late	120.3 (1.0)	5.2 (0.2)	23.6 (0.2)	0.986
	GDU	Early	129.6 (1.8)	120.0 (5.0)	468.2 (6.8)	0.979
		Late	121.3 (1.2)	101.3 (3.6)	406.0 (4.0)	0.986

- Standard error denoted in parentheses

Table 2.9 Grain sorghum height, total biomass, leaf biomass, and stem biomass at Manhattan, Kansas in 2019.

		Height	Total Biomass	Leaf Biomass	Stem Biomass
		cm	g $plant^{-1}$	g $plant^{-1}$	g $plant^{-1}$
Planting Date	Early	117.3 (1.3) b	37.0 (1.4) a	-	19.6 (1.0) a
	Late	123.5 (1.3) a	32.5 (1.4) b	-	14.7 (1.0) b
Palmer Amaranth Emergence	Weed Free	-	32.2 (1.3) b	17.2 (0.7) b	15.0 (0.9) b
	Early	-	32.2 (1.9) b	17.6 (1.0) ab	16.8 (1.3) ab
	Late	-	39.9 (1.9) a	20.3 (0.9) a	19.6 (1.3) a

- Height, leaf area, total biomass, leaf biomass, and stem biomass measurements at grain sorghum flag-leaf stage
- Standard error denoted in parentheses
- Different letters in column represent significance by least squares mean separation at α = 0.05
- Hyphen (-) = not significant

Table 2.10 Palmer amaranth height, leaf area, and total biomass at grain sorghum flag leaf stage at Manhattan and Hutchinson, Kansas in 2019.

Location	Planting Date	Palmer Amaranth Emergence	Height	Leaf Area	Total Biomass
			cm	cm^2 $plant^{-1}$	g $plant^{-1}$
Manhattan	Early	Early	-	8.3 (251.0)	0.1 (3.3)
		Late	-	15.0 (435.0)	1.1 (4.0)
	Late	Early	129.5 (13.8)	1261.7 (251.0)	14.3 (3.3)
		Late	72.1 (13.8)	133 (308.0)	1.6 (3.9)
Hutchinson	Early	Early	53.1 (6.2)	464.8 (95.4)	3.1 (1.3)
		Late	23.5 (5.8)	75.9 (95.4)	0.7 (2.1)
	Late	Early	91.7 (5.8)	796.7 (82.6)	12.9 (1.1)
		Late	-	-	-

- Standard error denoted in parentheses
- Hyphen (-) = unable to record

Table 2.11 Regression parameters (based on Equation 3) for grain sorghum leaf area, total biomass, leaf biomass, and stem biomass at Manhattan, Kansas in 2019.

	Time Scale	Planting Date	Parameter Estimates			
			a	*b*	*x0*	R^2
Leaf Area (cm^2 $plant^{-1}$)	DAP	Early	3643.6 (82.3)	4.5 (0.4)	34.4 (0.4)	0.969
		Late	3611.8 (379.0)	4.6 (1.6)	29.3 (3.5)	0.954
	GDU	Pooled	3680.6 (81.5)	74.8 (4.9)	487.6 (7.1)	0.963
Total Biomass (g $plant^{-1}$)	DAP	Early	39.1 (2.1)	3.9 (1.0)	38.4 (1.0)	0.956
		Late	33.7 (7.7)	4.0 (2.8)	31.0 (7.6)	0.952
	GDU	Pooled	41.7 (2.3)	81.2 (7.7)	572.4 (14.8)	0.955
Leaf Biomass (g $plant^{-1}$)	DAP	Early	19.2 (0.5)	3.9 (0.6)	36.4 (0.4)	0.964
		Late	18.0 (1.4)	3.8 (1.8)	28.7 (3.7)	0.95
	GDU	Pooled	19.8 (0.6)	134.6 (11.0)	942.1 (16.2)	0.958
Stem Biomass (g $plant^{-1}$)	DAP	Pooled	19.5 (0.6)	2.9 (0.3)	39.2 (0.4)	0.933
	GDU	Pooled	26.1 (3.5)	86.9 (10.6)	652.3 (28.2)	0.933

- Standard error denoted in parentheses

Table 2.12 Regression parameters (based on Equation 4) for grain sorghum leaf area, total biomass, leaf biomass, and stem biomass at Hutchinson, Kansas in 2019.

	Time Scale	Planting Date	Parameter Estimates			
			y0	*a*	*b*	R^2
Leaf Area (cm^2 $plant^{-1}$)	DAP	Early	-36.5 (91.8)	6.0 (5.3)	0.1 (0.02)	0.883
		Late	-8.1 (99.8)	8.1 (10.0)	0.2 (0.03)	0.890
	GDU	Pooled	-142.2 (84.2)	55.6 (22.1)	0.006 (0.0006)	0.880
Total Biomass (g $plant^{-1}$)	DAP	Early	-0.07 (0.5)	0.02 (0.01)	0.1 (0.02)	0.924
		Late	-0.04 (0.8)	0.04 (0.05)	0.2 (0.04)	0.907
	GDU	Early	-0.4 (0.6)	0.1 (0.08)	0.008 (0.001)	0.924
		Late	-0.08 (0.8)	0.08 (0.1)	0.01 (0.002)	0.907
Leaf Biomass (g $plant^{-1}$)	DAP	Early	-0.03 (0.4)	0.02 (0.01)	0.1 (0.02)	0.967
		Late	-0.01 (0.5)	0.01 (0.02)	0.2 (0.05)	0.915
	GDU	Early	-0.3 (0.4)	0.1 (0.07)	0.008 (0.001)	0.916
		Late	-0.02 (0.5)	0.02 (0.04)	0.01 (0.003)	0.915
Stem Biomass (g $plant^{-1}$)	DAP	Early	-0.001 (0.3)	0.001 (0.002)	0.2 (0.03)	0.941
		Late	-0.04 (0.5)	0.04 (0.08)	0.2 (0.1)	0.738
	GDU	Pooled	-0.2 (0.3)	0.08 (0.04)	0.008 (0.0008)	0.868

➢ Standard error denoted in parentheses

Table 2.13 Interactions for grain sorghum yield and seed weight at Manhattan, Kansas in 2019.

Planting Date	Palmer Amaranth Emergence	Yield	Seed Weight
		kg ha^{-1}	g 100 $seeds^{-1}$
Early	Weed Free	8910 (210) a	2.91 (0.03) a
	Early	8870 (290) a	2.84 (0.04) ab
	Late	8920 (290) a	2.75 (0.04) b
Late	Weed Free	8480 (210) a	2.55 (0.03) c
	Early	7374 (290) b	2.48 (0.04) c
	Late	8798 (290) a	2.56 (0.04) c

- Standard error denoted in parentheses
- Different letters in column represent significance by least squares mean separation at $\alpha = 0.05$

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Appendix A

Appendix Table 0.1 Analysis of variance for grain sorghum stand, height, leaf area, total biomass, leaf biomass, stem biomass, yield, and seed weight at Manhattan, Kansas in 2019.

	Stand	Height	Leaf Area	Total Biomass	Leaf Biomass	Stem Biomass	Yield	Seed Weight
	plants m^{-1} of row	cm	cm^2 $plant^{-1}$	g $plant^{-1}$	g $plant^{-1}$	g $plant^{-1}$	kg ha^{-1}	g 100 $seeds^{-1}$
Planting Date (PD)	NS	*	NS	*	NS	*	*	*
Palmer Amaranth Emergence (PAE)	NS	NS	NS	*	*	*	*	*
PD x PAE	NS	NS	NS	NS	NS	NS	*	*

- Asterisk (*) = significant
- NS = not significant

Appendix Table 0.2 Analysis of variance for grain sorghum stand, height, leaf area, total biomass, leaf biomass, stem biomass, yield, and seed weight at Hutchinson, Kansas in 2019.

	Stand	Height	Leaf Area	Total Biomass	Leaf Biomass	Stem Biomass	Yield	Seed Weight
	plants m^{-1} of row	cm	cm^2 $plant^{-1}$	g $plant^{-1}$	g $plant^{-1}$	g $plant^{-1}$	kg ha^{-1}	g 100 $seeds^{-1}$
Planting Date (PD)	*	NS	NS	*	NS	*	*	*
Palmer Amaranth Emergence (PAE)	NS	*	NS	NS	NS	NS	*	*
PD x PAE	NS	NS	NS	NS	NS	NS	NS	NS

- Asterisk (*) = significant
- NS = not significant

Appendix Table 0.3 Analysis of variance for Palmer amaranth height, leaf area, total biomass, leaf biomass, and stem biomass at Manhattan, Kansas in 2019.

	Height	Leaf Area	Total Biomass	Leaf Biomass	Stem Biomass
	cm	cm^2 $plant^{-1}$	g $plant^{-1}$	g $plant^{-1}$	g $plant^{-1}$
Planting Date (PD)	-	NS	NS	NS	NS
Palmer Amaranth Emergence (PAE)	*	NS	NS	NS	NS
PD x PAE	-	NS	NS	NS	-

- Asterisk (*) = significant
- NS = not significant
- Hyphen (-) = not able to calculate

Appendix Table 0.4 Analysis of variance for Palmer amaranth height, leaf area, total biomass, leaf biomass, and stem biomass at Hutchinson, Kansas in 2019.

	Height	Leaf Area	Total Biomass	Leaf Biomass	Stem Biomass
	cm	cm^2 $plant^{-1}$	g $plant^{-1}$	g $plant^{-1}$	g $plant^{-1}$
Planting Date (PD)	NS	*	*	*	*
Palmer Amaranth Emergence (PAE)	*	*	NS	*	NS
PD x PAE	-	-	-	-	-

- Asterisk (*) = significant
- NS = not significant
- Hyphen (-) = not able to calculate