CRITICAL DURATION OF GRASS WEED INTERFERENCE IN GRAIN SORGHUM

by

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Abstract

The availability of ALS-inhibitor herbicide-resistant grain sorghum hybrids will provide an opportunity to control grass weeds post-emergence with the ALS-inhibiting herbicide nicosulfuron (Zest™). More information on impact of grass weeds on sorghum yield are needed to optimize the application of nicosulfuron. The research objectives were to evaluate the impact of time of grass weed removal on grain sorghum yield when grown in different crop row spacing and seeding rates and to determine the critical duration of grass weed competition. Field studies were conducted in 2014 and 2015 at the KSU Agricultural Research Center at Hays, KS and the KSU Department of Agronomy Research Farm near Manhattan, KS. Four main treatments were grain sorghum row spacing of 25 and 76 cm at Hays or 20 and 76 cm at Manhattan, and two seeding rates of 125,000 and 150,000 seed ha^{-1}. Within each main plot, seven treatments were established including: weed-free all season using pre-emergence herbicides, weed-free all season by hand, weedy for 2, 3, 4, and 5 weeks after crop emergence in 2014 or weedy for 2, 4, 6, and 8 weeks after crop emergence in 2015, and weedy all season. The main grass weeds were giant, green, and yellow foxtail species, large crabgrass, and barnyardgrass. Grass weed biomass increased through the season at both locations in 2014 and in Manhattan in 2015. Hays 2014 grain sorghum aboveground stem and leaf biomass across row spacing and seeding rates decreased as weed removal time was delayed through the growing season. Grain sorghum yield decreased with increasing duration of grass weed competition in both years in Manhattan and in 2014 at Hays. Yield loss reached 5% at 2.3 to 25 weeks after sorghum emergence in narrow row spacing and 3.3 to 6.3 weeks after sorghum emergence in wide row spacing, depending on location, demonstrating that removing grass weed competition during these time frames will prevent more than 5% loss in grain sorghum yields.

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Chapter 1 - Literature Review

Grain Sorghum Production in the Semi-Arid Great Plains

Grain sorghum (*Sorghum bicolor* (L.) Moench) is among the most versatile and oldest cultivated crops (Stahlman and Wicks 2000). Cultivars of sorghum have been grown for food grain, feed grain, biofuel, forage and molasses. Sorghum was first grown in the United States in New York in 1853 (Bennett et al. 1990). Grain sorghum has ranked fourth in terms of production among U.S. cereal crops in recent years with 3.1 million hectares being harvested in 2015 (NASS, 2015). Kansas sorghum production ranks number one in the United States with an estimated 1.3 million hectares being harvested in 2015. Grain sorghum tolerates drought better than corn (*Zea mays* L.) and therefore, is better adapted to the semi-arid climate of the central and southern Great Plains (Stahlman and Wicks 2000). Inadequate weed management, however, can greatly reduce yields and net returns. This presents an opportunity to look deeper into the effects of cultural control options on weed suppression, yield, and the economics of using fewer herbicides. The goal of this literature review is to understand weed control, weed competition, interaction of row spacing and seeding rate, and the critical duration of weed control in grain sorghum.

Introduction to Weed Control in Grain Sorghum Production

Weeds have been an issue in crop production that has affected mankind from the beginning of civilization (Timmons 1970). At first weeds where pulled by hand or tools were used to stir the soil for seed preparation. Mechanization of preparing soil for seed planting has progressed through the invention of the hoe and continues through today with the use of tractor-operated plows and disks. Chemical control of weeds started after chemical control of insects and diseases were discovered. This control extends from the Romans using salt to control weeds and Europeans using lime and salt for weed control in the mid-1800's (Timmons 1970). In the modern era, chemical weed control started with the independent discovery of phenoxy herbicides in Britain and in the U.S. in the early 1940's (Burnside 1996). Chemical acceptance and widespread use launched the practice of weed management with herbicides.

Grain sorghum is an important crop in the central and southern Great Plains in the United States. Weeds impact grain sorghum production in many ways by both competing for needed light, nutrients and water (Burnside et al. 1969). With more than 250,000 known plant species that grow in the world today only around 200 are sufficiently troublesome to be classified as weeds (Holm et al. 1977). Eighty of those are primary weeds. Of those primary weeds, 44% are perennials and 56% are annuals, and of the primary weeds, 35% are grasses, 56% are broadleaf species and the others are sedges and ferns. Seventy percent of these weeds can be found in the United States. Most of these species have been introduced from some other part of the world and thrived in their new environment (Holm et al. 1977).

The most significant weeds occurring in grain sorghum are summer annuals, which emerge in spring or early summer and complete their life cycles before the start of winter. Winter annual species emerge in the fall, over winter in a semi-dormant vegetative state and then resume growth and complete their life cycles in late spring or early summer. Winter annuals are controlled mostly with nonselective herbicides or tillage before planting grain sorghum. This results in fewer winter annual weeds presenting a problem in the growing season. Perennial plants live for more than two growing seasons. Most of the time perennials flower and set seeds each year but live for extended periods without flowering if conditions are unfavorable. Perennials are among the world’s worst weeds. The most serious perennial weeds in grain sorghum are field bindweed (*Convolvulus arvensis* L.) and Johnsongrass (*Sorghum halepense* (L.) Pers.). Research has shown that barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.), large crabgrass (*Digitaria sanguinalis* (L.) Scop.), green foxtail (*Setaria viridis* (L.) P. Beauv.), and longspine sandbur (*Cenchrus longispinus* (Hack.) Fernald) are troublesome weeds in grain sorghum-producing areas and can cause significant yield reductions (Hennigh and Al-Khatib 2010)

In grain sorghum production a shift in weed species has occurred over the past 66 years. Before 1950 broadleaf weeds were more plentiful than grass weeds. With changes in tillage and extensive use of herbicides such as atrazine and 2,4-D, shifts occurred in annual weed populations (Derksen et al. 1993; Froud-Williams 1988). In general the abundance and diversity of broadleaf species decreased, and grass species increased over time. An aerial survey done by flying a plane 150 m above the ground in 1981 indicated that 45% of 852 grain sorghum fields in the northern panhandle of Texas were infested with shattercane, Johnsongrass, barnyardgrass and other small-seeded annual grasses. Seventeen percent of the fields were infested with broadleaf weeds including pigweed (*Amaranthus* spp.), kochia (*Kochia scoparia* L.), and Russian thistle (*Salsola kali* L.), and 15% of the fields were infested with a mixture of grass and broadleaf weeds, with only 24% of fields weed free (Wiese et al. 1983). Emergence, growth and competitiveness vary among weed species that infest grain sorghum. In the Texas high plains over a four year period kochia emerged in early March followed by poison suckleya (*Suckleya suckleyana* (Tort.) Rydb.), common sunflower (*Helianthus annuus* L.) and common cocklebur (*Xanthium strumarium* L.) in early April. Buffalobur (*Solanum rostratum* Dunal), puncturevine (*Tribulus terrestris* L.), lanceleaf sage (*Salvia reflexa* Hornem.), and barnyardgrass emerged in late April. These weeds increased in size in May but very little dry matter accumulation occurred until June when grain sorghum was planted across most of Texas (Nussman et al. 1985).

Weed Competition with Grain Sorghum

Grain sorghum seedlings grow slowly compared to most summer annual weed species when growing together for the first 20 to 25 days (Vanderlip 1979). Grain sorghum does not compete well with most weeds in the early stages of crop growth, especially in cool and adverse conditions because optimum growing conditions for sorghum are warm and semi-arid. Plant competitiveness and density are influenced by the time of weed emergence relative to the crop, duration of interference, soil conditions, environmental conditions and cultural practices such as soil fertility level and fertilizer placement, crop row spacing and crop population (Stahlman and Wicks 2000). Research has indicated that the percentage of grain sorghum yield lost from weed competition exceeds that of most other grain crops. The losses from weeds usually range from 30 to 50%, but can be 100% (Stahlman and Wicks 2000). In 1991 state research and extension workers estimated that in the absence of herbicides, the average grain sorghum yield loss from weed interference in seven central and southern Great Plains states was 27% compared to 35% for all grain sorghum producing states (Bridges 1992). Grain sorghum yield losses due to weeds in Kansas using best management practices (BMP) was estimated to be 5%, and using BMPs without herbicides could possibly cause 20% yield loss (Bridges 1992). Near Hays, KS it was found that one redroot pigweed (*Amaranthus retroflexous* L.) within 0.6 m of cultivated grain sorghum row spaced 51 cm apart reduced yield nearly 40% and one pigweed per 0.3 m of row reduced yield by more the 50% (Phillips 1960). In a similar condition in eastern KS tall waterhemp (*Amaranthus tuberculatus* (Moq.) Sauer) was more competitive than yellow foxtail (*Setaria pumila* (Poir.) Roam. & Schult). Feltner et al. (1969a) found that broadleaf weeds have greater competitiveness because of their ability to produce more biomass and grow later into season. Grain sorghum yield was reduced by 44 and 76% when there was season-long interference by tall waterhemp and yellow foxtail (Feltner et al. 1969a, 1969b). Grain loss from annual weed interference in dryland grain sorghum in central and northwest Texas averaged 18 and 30%, respectively, in the late 1950's and early 1960's (Wiese et al. 1964). The yield losses in fields in the northern Texas panhandle in the early 1980's averaged 38% with mixtures of annual grass and broadleaf species, 31% yield loss with infestations of annual grasses and 34% with infestations of annual broadleaf weeds (Wiese et al. 1983).

The yield of grain sorghum is the sum of the number and weight of seeds per head, number of heads per plant, and number of plants per area. If there is reduction in any one of these a decrease in yield will be seen. With fewer competing weeds present, there will be more heads per plant and more and larger seeds will be produced in each sorghum head (Blum 1970). The yield components most reduced by weed competition have been number of heads per plant (Burnside and Wicks 1967), and the number of seeds per head (Knezevic et al. 1997).

Growth of Grain Sorghum and Weeds Affected by Light, Water and Nutrients

Competition for resources is a significant interaction of plants growing in close proximity in the same area. Competition does not happen unless demand for the resources grows greater than their supply. Intraspecific competition is between sorghum plants and intraspecific competition is between different plant species, all for water, nutrients, light, space and carbon dioxide. Plant growth for each individual is dependent on resource availability and timing of emergence relative to other plants. More competitive plants will be able to deplete the resources such as light, water and nutrients for surrounding plants. There is a wide variance in specific plant's ability to capture and convert resources into dry matter. Many weed species use just as much or more water and resources as grain sorghum. Most ecosystems where sorghum is grown have multiple factors influencing growth and production. Moisture is the most widely researched limited resource resulting in competition, but when moisture and nutrients are not limited light becomes the major factor limiting plant growth (Stahlman and Wicks 2000).

Water consumption by weeds will reduce the amount of available soil water to support crop growth. The water use efficiency (WUE) is the quantity of water needed to produce dry matter. Weeds with the highest WUE will be the most aggressive weeds in competition with grain sorghum. A study done in a controlled greenhouse environment found that weed response to moisture availability was species dependent (Wiese and Vandiver 1970). Within the study barnyardgrass, common cocklebur, large crabgrass, corn and grain sorghum grew best under high moisture conditions. Buffalobur, kochia, Russian thistle and tumble windmillgrass (*Chloris verticillata* Nutt.) were not competitive and produced little growth under wet conditions, but were productive in dry soil (Wiese and Vandiver 1970).

The rapid growth of weeds and enhancing competition for water and light promotes successful early capture of nutrients (Shipley and Wiese 1969). Data shows that on an area basis broad-leaf weeds consume a great deal more nutrients than grain sorghum, thus explaining why many broad leaf weeds cause greater yield losses in grain sorghum than annual grasses. Common cocklebur, kochia, puncturevine, and Russian thistle used 1.5 to 2.2 times more nitrogen, and 1.7 to 4.0 times more potassium per kg of dry matter produced than grain sorghum. Barnyardgrass and large crabgrass contain about half as much nitrogen as compared to grain sorghum (Shipley and Wiese 1969).

Another major factor impacting crop yield in mixed crop-weed populations is light availability. Plant morphology and weed density directly influence the distribution of light in the canopy and the absorption of photosynthetic active radiation (PAR) by the crop. Grain sorghum is classified as a C4 plant and therefore does not tolerate shade. A study done by Vesecky et al. (1973) in Kansas on shattercane and forage sorghum competition with grain sorghum showed that shattercane spaced 46 cm apart or less reduced the amount of solar radiation reaching the crop canopy by 75% or more, increased the effects of shading relative to other resources. As the grain sorghum approached anthesis and maturity, light quantity became increasingly important in determining final yield (Vesecky et al. 1973). Knezevic et al. (1997) found that sorghum in competition with increasing redroot pigweed densities from 0.5 to 12 plants m^{-1} of row had reduced sorghum yield from 3 to 46%. Redroot pigweed that emerged later than the 5.5-leaf stage of sorghum caused no significant yield losses, but pigweed that emerged before 5.5-leaf stage caused sorghum yield loss up to 46% because of reduced solar radiation for the grain sorghum (Knezevic et al. 1997).

Grain Sorghum Row Spacing and Seeding Rate

Grain sorghum seeded in closely spaced rows generally yield 10 to 15% more than sorghum in wider-spaced rows (Allen et al. 1970; Staggenborg et al. 1999). The yield increase in narrow row spacing is the result of more efficient use of soil nutrients, water and solar radiation. Research reveals that by narrowing the crop row spacing from 76 to 18 cm, light penetration was reduced to the soil surface by 15%, therefore limiting weed competitiveness and growth

(Northam and Stahlman 1993). In Alabama it was reported that grain sorghum grown in 45 cm row spacing had fewer weeds and produced higher yields than sorghum grown in 60 and 90 cm rows in both conventional-tillage and no-till production systems (Bishnoi et al. 1990). Staggenborg et al. (1999) reported that in eastern Kansas, grain sorghum in 25 cm row spacing had 24 and 45% less weed growth than sorghum with 50 and 76 cm row spacing, respectively.

Optimum grain sorghum seeding rates vary depending on available soil moisture (Stahlman and Wicks 2000). Staggenborg et al. (1999) concluded that producers should not alter seeding rates when converting to narrow rows because grain sorghum has the ability to adjust head number and seed number per head. Conley et al. (2005) reported that even though grain sorghum yield was lower at densities of 75,000 seeds ha^{-1}, the sorghum plants were able to compensate by developing >1 additional head per plant. Hickman et al. (1992) stated that plant densities of 200,000 to 250,000 plants ha^{-1} are recommended for irrigated sorghum, while 75,000 to 100,000 plants ha^{-1} are more appropriate for dryland conditions. Conley et al. (2005) in northern Missouri reported that grain yield was lowest at 75,000 seeds ha^{-1} when compared to all other plant densities in 2002 and when compared to 150,000, 225,000, and 300,000 seeds ha^{-1} in 2003. These data show that yield differences due to plant densities can be quite variable on a year-to-year basis. High-density grain sorghum is more prone to stress under limited soil moisture conditions (Stahlman and Wicks 2000). Moisture-stressed plants may lose leaves, and have restricted growth, delayed panicle emergence, shrunken kernels, and higher incidence of lodging. However, high sorghum plant density reduced competitiveness of weeds (Stahlman and Wicks 2000). It was reported by Burnside (1977) that weed growth was greater in low seeding rate (120,000 seeds ha^{-1}) grain sorghum with no post-emergence herbicide than for either high or low sorghum seeding rate sprayed post-emergence with atrazine and crop oil concentrate. The high seeding rate had 11% less weed biomass. Late-emerging tillers often delay grain harvest, and low seeding rates are less competitive with weeds (Stahlman and Wicks 2000). Hewitt (2015) found that grain sorghum grown in a low weed pressure site near Beloit KS showed a yield advantage to a seeding rate of 125,000 seeds ha^{-1} among seeding rates of 75, 100, 125, and 150 thousand seeds ha^{-1}. A high weed pressure situation would warrant an average seeding rate for the area of 99,000 to 125,000 seeds ha^{-1} (Hewitt 2015).

Critical Period of Weed Control in Grain Sorghum

The critical period of weed control (CPWC) is a period in the crop growth cycle in which weeds must be controlled to prevent yield losses (Knezevic et al. 2002, Zimdahl 1993). Duration of weed interference is one part of the CPWC, defined as how long weeds and crops can compete from the time of crop emergence before permanent yield loss is observed. The other part includes critical weed-free period, which is how long weeds need to be kept out of the crop to minimize the impact of late emerging weeds. Both vary with weed species, weed density and environmental conditions (Knezevic et al. 2002). Studies completed in Nebraska showed that removing weeds within three weeks after sorghum planting prevented a decrease in the number of heads per plant, but after the three week point the number of heads decreased as the duration of weed competition increased (Burnside and Wicks 1967). Four weeks after sorghum emergence, weed interference reduced sorghum yield and sorghum yield continued to decrease to week eight (Burnside and Wicks 1967).

Duration of weed interference and critical weed-free period experiments are used to develop CPWC. For critical weed-free period experiments, the crop is maintained weed-free, usually by hand removal for different periods of time, and then weeds are allowed to reinfest the area and interfere with crop the remainder of the growing season. In duration of weed interference experiments, the weeds are allowed to interfere with the crop for various lengths of time before removal, and then the area is maintained weed-free for the remainder of the season. There was no reported loss of grain sorghum yields by Burnside and Wicks (1967) when weeds were removed within three weeks after planting, if the control of the weeds was maintained from then on. Weeds in grain sorghum should be controlled within three weeks after planting to avoid yields decreasing progressively when weeds were not removed for four, five, six, or eight weeks after planting and each week after (Burnside and Wicks 1967). Yield losses increased from 2 to 55% as weed removal was delayed weekly, and if the weed-free period was extended from 2 to 8 weeks after grain sorghum emergence, yield losses decreased from 62 to 2% (Burnside and Wicks 1967).

Weeds did not cause grain yield loss if they emerged 30 days after planting grain sorghum. It was concluded that 20 weed-free days after planting were needed to prevent grain sorghum yield loss (Everaarts 1993). The critical period of longspine sandbur control in dryland sorghum in KS was four weeks across two years, even though there was a tenfold difference in sandbur density between years (Fabrizius 1998). It was observed that removing 100 longspine sandbur plants m^{-2} within four weeks after planting prevented yield loss. If longspine sandbur was allowed to compete with grain sorghum for 4, 5 and 6 weeks after crop emergence yields were reduced by 27, and 31 and 42%, respectively, compared to weed-free sorghum yield. Yields were reduced 13% when longspine sandbur was allowed to have a second flush and interfere after a two week weed free period (Fabrizius 1998).

Critical period of weed control has been researched in soybeans and corn. In soybeans, a period of control lasting up to the forth node growth stage or approximately four weeks after emergence, was adequate to prevent a yield loss of more than 2.5% in southern Ontario (Van Acker et al. 1993). The critical period in soybeans can vary with location, but could be from second node growth stage (V2, Fehr and Caviness 1977) to the beginning pod growth stage (R3), around 9 to 38 days after soybean emergence, at 2.5% yield loss. Soybean yield loss due to weed interference occurred from beginning bloom stage (R1) to beginning seed formation stage (R5) (Van Acker et al. 1993). Knezevic et al. (2003) observed that increasing row spacing from 19 to 76 cm reduced early season soybean tolerance to weeds. Wider rows reduced soybean tolerance to weed interference because additional space was available and gave an advantage to weeds for early season growth relative to the weeds in narrow rows. This observation shows that weeds may be better competitors earlier in wide than in narrow rows, resulting in an early CPWC (Knezevic et al. 2003).

When considering CPWC for corn a study was completed with the weed-free and weedy intervals being based on crop leaf stages as opposed to days after planting in order to more clearly define the occurrence of the critical period among different locations and years. It was found that the beginning of the critical weed free period varied from three to 14-leaf stages of corn and the end of the period was the 14-leaf stage (Hall et al. 1992). Another study in South Carolina examined the effect narrow and wide row corn spacing had on the CPWC and found the CPWC began five to nine days after corn emergence (V1-V2) and ended 45 to 53 days after corn emergence (V8-V10) (Norsworthy et al. 2004). Light interception was found to be more of a determinate factor than canopy formation. Light interception was found to be similar between row widths throughout growing season, resulting with similar late season weed biomass. Therefore strategies, such as increasing the population of narrow row corn will be needed to provide an advantage over wider row corn (Norsworthy et al. 2004).

Acetolactate Synthase (ALS)-Resistant Grain Sorghum

Currently there are no good post-emergent (POST) herbicide control tactics for grass weeds in conventional grain sorghum. The development of herbicide resistant crops has been a great benefit for producers as it gives more options for chemical weed control (Franz et al. 1997). Acetolactate synthase resistant grain sorghum was developed at Kansas State University (Stahlman and Wicks 2000) with a goal of providing broad spectrum POST grass control. Pre-emergence (PRE) herbicides, such as S-metolachlor, mesotrione, acetochlor and dimethenamid-P are the only options for broad-spectrum annual grass control in grain sorghum (Thompson et al. 2016). Grain sorghum in general is grown in dry areas. The efficacy of the PRE herbicides can be reduced in areas lacking soil moisture that is needed for herbicide activation (Tapia et al. 1997). Therefore, the ability to use broad-spectrum POST herbicides to control annual grasses in grain sorghum could be a benefit for producers.

Research has indicated that nicosulfuron provided greater than 80% control of giant foxtail, green foxtail, johnsongrass and velvetleaf (*Abutilon theophrasti* Medik.) (Camacho et al. 1991; Dobbels and Kapusta 1993; Schuster et al. 2008). Rimsulfuron provided more than 80% control of barnyardgrass, large crabgrass and redroot pigweed (Boydston 2007; Renner and Powell 1998; Schuster et al. 2008). When nicosulfuron and rimsulfuron are applied together, this combination provided 80% control or greater of several annual grasses, including yellow foxtail, witchgrass (*Panicum capillare* L.) and proso millet (*Panicum miliaceum* L.) (Swanton et al. 1996). Hennigh and Al-Khatib (2010) found that barnyardgrass was the most sensitive to nicosulfuron, rimsulfuron, or nicosulfuron + rimsulfuron, followed by green foxtail and longspine sandbur. The most tolerant weed to these herbicides was large crabgrass. The absorption and translocation of nicosulfuron, rimsulfuron, or nicosulfuron + rimsulfuron were greater in barnyardgrass than in large crabgrass. It was found that these differences in absorption and translocation between the two species could result in differences in the sensitivity of weeds to herbicides (Hennigh and Al-Khatib 2010).

There is an opportunity to control grass weeds POST with the ALS-inhibiting herbicide nicosulfuron (Zest^{TM}). More information on impact of grass weeds on sorghum yield is needed to optimize the application. My objectives of this research were to evaluate the impact of time of grass weed removal on grain sorghum yield when grown under different row spacing and seeding rates and to determine the critical duration of grass weed competition. My goals would be to disprove my null hypothesis, that is, the removal of grass weeds at different times after grain sorghum emergence does not impact grain sorghum yield. I would like to prove that my alternative hypothesis is true, that is, the removal of grass weeds within three to four weeks after grain sorghum emergence would prevent 2 to 5% yield loss.

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Chapter 2 - Critical Duration of Grass Weed Interference In Grain Sorghum

Abstract

The availability of ALS-inhibitor herbicide-resistant grain sorghum hybrids will provide an opportunity to control grass weeds post-emergence with the ALS-inhibiting herbicide nicosulfuron (Zest^{TM}). More information on impact of grass weeds on sorghum yield are needed to optimize the application of nicosulfuron. The research objectives were to evaluate the impact of time of grass weed removal on grain sorghum yield when grown in different crop row spacing and seeding rates and to determine the critical duration of grass weed competition. Field studies were conducted in 2014 and 2015 at the KSU Agricultural Research Center at Hays, KS and the KSU Department of Agronomy Research Farm near Manhattan, KS. Four main treatments were grain sorghum row spacing of 25 and 76 cm at Hays or 20 and 76 cm at Manhattan, and two seeding rates of 125,000 and 150,000 seed ha^{-1}. Within each main plot, seven treatments were established including: weed-free all season using pre-emergence herbicides, weed-free all season by hand, weedy for 2, 3, 4, and 5 weeks after crop emergence in 2014 or weedy for 2, 4, 6, and 8 weeks after crop emergence in 2015, and weedy all season. The main grass weeds were giant, green, and yellow foxtail species, large crabgrass, and barnyardgrass. Grass weed biomass increased through the season at both locations in 2014 and in Manhattan in 2015. Hays 2014 grain sorghum aboveground stem and leaf biomass across row spacing and seeding rates decreased as weed removal time was delayed through the growing season. Grain sorghum yield decreased with increasing duration of grass weed competition in both years in Manhattan and in 2014 at Hays. Yield loss reached 5% at 2.3 to 25 weeks after sorghum emergence in narrow row spacing and 3.3 to 6.3 weeks after sorghum emergence in wide row spacing, depending on location, demonstrating that removing grass weed competition during these timeframes will prevent more than 5% loss in grain sorghum yields.

Introduction

Grain sorghum (*Sorghum bicolor* (L.) Moench) is among the most versatile and oldest cultivated crops (Stahlman and Wicks 2000). Cultivars of sorghum have been grown for food grain, feed grain, biofuel, forage, and molasses (Bennett et al. 1990). Grain sorghum has ranked fourth in terms of production among U.S. cereal crops in recent years with 2.6 million hectares being harvested in 2014 (NASS 2015). Grain sorghum tolerates drought better than corn (*Zea mays* L.), and therefore is better adapted to the semi-arid climate of central and southern Great Plains (Stahlman and Wicks 2000). Kansas sorghum production ranks number one in the United States with an estimated 1.3 million hectares being harvested in 2015 (NASS 2015). Inadequate weed management, however, can greatly reduce yields and net returns. This presents an opportunity to look deeper into the effects of cultural control options on weed suppression, yield, and the economics of using fewer herbicides.

Weeds affect grain sorghum production in many areas due to competition for light, nutrients and water (Burnside et al. 1969). Most important weeds in grain sorghum production are summer annuals, which emerge in spring or early summer together with crop and complete their life cycles before the start of winter. There has been a shift in weed species occurring in grain sorghum production over the last 66 years (Derksen et al. 1993; Froud-Williams 1988). Before 1950 broadleaf weeds were more plentiful than grass weeds. With changes in tillage and extensive use of herbicides, like atrazine and 2,4-D, shifts in annual weed populations have occurred (Derksen et al. 1993; Froud-Williams 1988). In general the abundance and diversity of broadleaf species decreased, and the abundance and diversity of grass species have increased over time.

Grain sorghum seeded in closely spaced rows generally yields 10 to 15% more than sorghum in wider spaced rows (Allen et al. 1970, Staggenborg et al. 1999). The yield increase seen in narrow row spacing is the result of more efficient uses of soil nutrients, water, solar radiation and weed control. It was reported that reducing crop row spacing from 76 to 18 cm reduced light penetration to the soil surface by 15%, which competitiveness and growth (Northam and Stahlman 1993). Staggenborg et al. (1999) reported that in eastern Kansas, grain sorghum in 25-cm row spacing had 24 and 45% less weed growth than sorghum in 50- and 76-cm row spacing, respectively. Sorghum populations grown in rainfed environments were most productive at 75,000 to 100,000 seeds ha^{-1} (Hickman et al. 1992), but high sorghum populations reduce weed competitiveness. Hewitt (2015) found that grain sorghum grown in a low weed pressure site near Beloit KS showed a yield advantage with a seeding rate of 125,000 seeds ha^{-1} among seeding rates of 75, 100, 125, and 150 thousand seeds ha^{-1}. A high weed pressure situation would warrant an average seeding rate for the area of 125,000 seeds ha^{-1} (Hewitt 2015).

Having narrower rows in a grain sorghum crop may reduce weed competition. Wider row widths result in a crop canopy that forms slowly and provides little shading of weeds between rows until mid-season and by then weeds are well established (Burnside and Wicks 1967). Studies done in Nebraska showed removing weeds within three weeks after sorghum planting prevented a decrease in the number of heads per plant, but after this point the number decreased as the duration of weed competition increased (Burnside and Wicks 1967). Four weeks of weed interference reduced sorghum yield, but the seed weight of the sorghum at six weeks of interference was reduced (Burnside and Wicks 1967).

There are two critical, independent components within the sorghum growing season that can be defined to guide when weed control must occur to minimize yield loss occur. These two time periods are the duration of weed interference and weed-free period (Knezevic et al. 2002). Duration of weed interference is the maximum length of time that weeds emerging with a crop can interfere before reducing yields. The weed-free period, occurs early in crop growing season and is the minimum time from crop emergence that weed control must be maintained to prevent crop yield loss. If there are weeds emerging after this time they will have no effect on yield. The first four weeks after planting, when the plant is young and growing slowly, is the most critical period for weed control in grain sorghum (Stahlman and Wicks 2000).

In duration of weed interference experiments, the weeds are allowed to interfere with the crop for periods of time before removal, and then the area is maintained weed free for the rest of the season (Knezevic et al. 2002). There was no reported loss of grain sorghum yields when weeds were removed within three weeks after planting and when the control of the weeds was kept up from then on (Burnside and Wicks 1967). The study also revealed that grain sorghum yields decreased progressively when weeds were not removed for 4, 5, 6, or 8 weeks after crop emergence. The data presented by Burnside and Wicks (1967) suggested that weeds in grain sorghum should be controlled within three weeks after planting. Yield losses increased from 2 to 55% as weed control was delayed after planting. If the weeds were removed at planting and weekly for the first 2, 4, 6, or 8 weeks after grain sorghum planting and weeds were then allowed to grow, which caused sorghum yields to be reduced from 62 to 2% (Burnside and Wicks 1967).

Objectives were to evaluate the impact of time of grass weed removal on grain sorghum yield when grown in different crop row spacing and seeding rates at two locations in KS and to determine the critical duration of grass weed competition. The null hypothesis, is that the removal of grass weeds at different times after grain sorghum emergence does not impact grain sorghum yield. The alternative hypothesis is the removal of grass weeds within three to four weeks after grain sorghum emergence would prevent 2 to 5% yield loss.

Materials and Methods

Field studies were conducted in 2014 and 2015 at two locations in Kansas. The first location was at the KSU Agricultural Research Center at Hays, KS (38.51063 N 99.19217 W) on Roxbury silt loam in 2014, and planted on Crete silty clay loam and Harney silt loam in 2015 (NRCS 2015). The second location was at the KSU Department of Agronomy Ashland Bottoms Research Farm near Manhattan, KS (39.07228 N 96.38061 W) on Wymore silty clay loam soil and studies for each year were adjacent to each other (NRCS 2015). The previous crop at Hays was winter wheat (*Triticum aestivum* L.), while at Manhattan it was soybean (*Glycine max* (L.) Merr.). At Hays UAN fertilizer was applied on April 8, 2014 at 88 kg N ha^{-1} and on April 15, 2015 at 89 kg N ha^{-1}. Fertilizer was applied at Manhattan at 135 kg N ha^{-1} in 2014, and in 2015 90 kg N ha^{-1}, 28 kg P ha^{-1} and 16 kg Zn ha^{-1} were applied. A burndown application of glyphosate at 1260 g ae $ha^{-1}$and 2,4-D at 350 g ae ha^{-1}, and ammonium sulfate at 2% w/v was applied on May 29, 2014 and 1541 g ae $ha^{-1}$of glyphosate and ammonium sulfate at 2% w/v was applied on May 21, 2015 in Hays. At Manhattan, the field was disked and field cultivated on June 8, 2014 and June 10, 2015 prior to planting for weed control.

Grain sorghum hybrid DKS 4945 was planted on June 3, 2014 and June 2, 2015 at Hays and on June 18, 2014 and June 10, 2015 at Manhattan. Experiments were set up in split-plot design with four replications. The four main treatments were combinations of grain sorghum row spacing of 25- and 76-cm at Hays, or 20- and 76-cm at Manhattan and two seeding rates of 125,000 and 150,000 seed ha^{-1}. Equipment available at each location determined how these row spacing and seeding rates were established. At Manhattan, the 20-cm spacing plots were sown with a Tye grass drill while the 76-cm spacing plots were planted with a White Model 6700 6-row planter. At Hays, both row spacings of grain sorghum were sown with a Great Plains double disc drill. Row units were closed off in order to achieve the different row spacing. Hand-thinning was delayed until all sorghum had emerged and took place on June 30, 2014 and June 23, 2015 at Hays and on July 12, 2014 and June 30, 2015 at Manhattan. The grain sorghum on average was at growth stage 1 at this time (Vanderlip 1979).

The germination rate of the grass weed seed was tested in greenhouse prior to planting and it was observed to have a 95% germination rate or higher on all grass species. The species that were spread included giant foxtail (*Setaria faberi* Herm.), yellow foxtail (*Setaria pumila* (Poir.) Roam. & Schult.), barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.), and large crabgrass (*Digitaria sanguinalis* (L.) Scop.). During the same day of crop planting, grass seed was spread at both locations by hand using a seed shaker. Each grass species was spread at a rate of 375 seeds per plot. At Hays (2015) more grass weed competition was attempted by spreading green foxtail (*Setaria viridis* (L.) P. Beauv.), with a grass seeder at 5.6 kg ha^{-1}. Seven sub-plots were established within each main plot and included weed-free all season using pre-emergence (PRE) herbicides, weed-free all season by hand, weedy throughout the growing season, and weedy for two, three, four, and five weeks after crop emergence in 2014 and time lengthened to be weedy for two, four, six and eight weeks after crop emergence in 2015. Each sub-plot in Manhattan was 3.0-m wide and 9.1-m long and in Hays each sub-plot was 4.6-m wide and 9.1-m long. In Hays on May 29, 2014, the PRE herbicide subplots (Degree Xltra®) 1514 g ha^{-1} acetochlor, and 752 g ha^{-1} atrazine and on June 3, 2015 the PRE herbicide subplots (Bicep Lite II Magnum®) 1,401 g ha^{-1} S-metolachlor, and 1,123 g ha^{-1} atrazine. In Manhattan the PRE herbicide subplots (Lexar Ez®) 1806 g ha^{-1} S-metolachlor, 1806 g ha^{-1} atrazine, and 228 g ha^{-1} mesotrione on June 11, 2014 and (Lumax Ez®) 1886 g ha^{-1} S-metolachlor, 708 g ha^{-1} atrazine and 188 g ha^{-1} mesotrione applied on June 10, 2015. Broadleaf weeds were removed by hand from the plots regularly to maintain grass competition and through broadcast spray of (POST) selective herbicide application. In Hays, POST (Starane® NXT) 272 g ha^{-1} fluroxypr on June 23, 2014 and July 2, 2014 (Huskie®) 41 g. a.i. L. pyrasulfotole and 230 g. a.i. L. bromoxynil, NIS at 0.25% v/v, and ammonium sulfate at 2% w/v. No POST herbicide was used in Manhattan 2014. In 2015, all treatments in Manhattan were sprayed on June 26, (Huskie®) 38 g. a.i. L. pyrasulfotole and 214 g. a.i. L. bromoxynil, NIS at 0.25% v/v, and ammonium sulfate at 2% w/v.

Plant Sampling and Grain Yield

Sorghum growth stages and heights were recorded from week one after sorghum emergence (GS0) through physiological maturity (GS9) according to Vanderlip (1979). At both locations in 2014 two representative plants were used for the data collection in each sub-plot. In 2015 at both locations a representative meter of row in each sub-plot was used to record data on growth stages and heights. Sorghum plants were measured from ground level to upper most fully developed collar or collar of flag leaf at each week after sorghum emergence until GS6 (flowering).

Aboveground grass weed samples were harvested from randomly placed 0.25 m^2 quadrats at designated times from subplots at both locations: two, three, four, and five weeks after sorghum emergence in 2014, and one through eight and 15 weeks after sorghum emergence in 2015. Samples were dried at 66 C for four days and then weighed. Remaining weeds in appropriate treatment were manually removed by hand using a hoe and kept clean until harvest. When the grain sorghum was at flowering (GS6) two representative sorghum plants were harvested from each subplot from each location on August 13, 2014 in Hays and on August 11, 2014 and August 6, 2015 at Manhattan. On August 5, 2015 at Hays two representative plants were harvested by hand from only the weed-free and weedy plots in each replication because of low weed pressure across treatments. The plants were clipped at ground level, removing the whole plant. Each plant was dissected into three parts: the head, stem and leaves. The leaf area was measured using a leaf area meter (Model 3100 LI-Cor™). All samples were bagged separately, dried at 66 C for seven days and then weighed.

End-of-season sorghum biomass was harvested from a 1-m^2 area in each sub-plot for each year and location. Whole plants were clipped at ground level but in 2014 no sorghum heads were included in the samples but they were included in 2015. At Hays, grain harvest from each sub-plot was completed on October 25, 2014 by clipping sorghum heads by hand and on October 6, 2015 by using a plot combine (Kincaid 8-XP). The area of harvest in each treatment was 1.5 by 9 m. At Manhattan grain sorghum was harvested by clipping heads from a 1.5 by 9 m area on November 12, 2014 and November 4, 2015. Sorghum heads were threshed mechanically and grain samples were collected to determine moisture and test weight. Grain sorghum yields were adjusted to 14% moisture.

Statistical Analyses

All data were analyzed in SAS (SAS University Edition 2016, SAS® Institute Inc.) to evaluate differences among treatment main effects and to test for interactions. The degrees of freedom method used was Satterthwaite. Main effects and interactions were considered significant when $P \leq 0.05$. Since there were differences in weed populations and densities among locations and years, data were not combined and presented separately. An analysis of variance (ANOVA) was used to evaluate effects of row spacing and seeding rate, and time of removal on sorghum yield, sorghum biomass at harvest and weed biomass throughout the growing season.

To describe the response of grain sorghum yield to duration of grass weed interference, a logistic 3-parameter model was fit using SigmaPlot v. 12.3 (Systat Software, Inc., San Jose, CA):

$Y= a/1+(x/x_o)^b$ (Equation 1)

where Y is grain sorghum yield (kg ha^{-1}), parameter a is estimated weed-free grain sorghum yield (kg ha^{-1}), x is weeks after sorghum emergence, parameter b is slope at point of inflection, and x_0 is weeks to reach inflection point. A linear model was fit if equation 1 did not fit:

$Y= a+bx$ (Equation 2)

where Y is grain sorghum yield (kg ha^{-1}), a is weed-free grain sorghum yield, parameter b is slope describing decrease in yield over time, and x is weeks after sorghum emergence.

A 5% grain sorghum yield loss was deemed an acceptable threshold for determining the critical period of weed removal. All treatment data except from herbicide PRE subplots were converted to % of weed-free yield relative to the all-season grain sorghum weed-free yields and each row spacing by seeding rate treatment for each location and year.

Percent of Weed-Free Yield = 100 - [{(weed-free yield – Y)/weed-free yield}*100]

(Equation 3)

To determine the number of weeks after grain sorghum emergence when weeds must be removed in order to not have more than 5% yield loss, Equations 1 or 2 were fit to the Percent of Weed-free Yield data and parameter “a” was set to 100% for each row spacing and seeding rate treatment, location, and year. The economic cost caused by that 5% yield loss level was determined as amount of grain lost (kg ha^{-1}) multiplied by the value of grain sorghum at $0.16 kg^{-1} based on 2014 average commodity priced in Kansas (ERS, 2016). The cost of additional grain sorghum seed for the higher seeding rate was included in the economic cost as well and was based on $0.27 per thousand seed (Ibendahl et al. 2015) or an additional $6.75 ha^{-1}.

Results and Discussion

Annual precipitation across Kansas can range from <500 mm in the west to >1000 mm in the east (NOAA 2016). The growing season to be considered is from planting to harvesting of grain sorghum at a given location. Hays received 500 mm of total precipitation in 2014 with 436 mm during the growing season, while in 2015 it received a total of 446 mm with 143 mm during the growing season. Hays has a 30-yr (1980-2010) average of 596 mm of annual precipitation (Table 2-1). Manhattan received 610 mm of total precipitation in 2014 with 228 mm during the growing season, and Manhattan received 954 mm in 2015 with 392 mm fell during the growing season. Manhattan has a 30 yr (1980-2010) average of annual precipitation of 904 mm (Table 2-2) (Kansas Mesonet 2016; NOAA 2016).

Grain Sorghum Yield

Grain sorghum yield was affected differently at each location and year. In 2014 at Hays grain sorghum yield was significantly impacted by the interactions of row spacing, seeding rate and timing of grass weed removal (Appendix A-1). The ANOVA table showed that there was significant difference at the Hays location in 2014 in the interaction of row spacing seeding rate and removal times for sorghum yield (Appendix A-1). Sorghum weed-free yields were greatest in 76-cm row spacing and 150,000 seeds ha^{-1} treatments followed by 25-cm row spacing and 125,000 seeds ha^{-1} and 76-cm row spacing and 125,000 seeds ha^{-1} (Figure 2-1). The lowest weed-free yield was observed in the 76-cm row spacing and 125,000 seeds ha^{-1} in 2014 at Hays (Figure 2-1). A logistic 3-parameter regression curve was fit to yield data over time for 25-cm row spacing by 150,000 seeds ha^{-1} and 76-cm row spacing by 125,000 seeds ha^{-1} while a linear modal fit yield data over time from 25-cm row spacing and 125,000 seeds ha^{-1} and 76-cm row spacing and 150,000 seeds ha^{-1} treatments (Table 2-5). With weeds competing all season at Hays 2014, the 25-cm row spacing and 125,000 seeds ha^{-1} had the greatest yield with a total yield loss of 16% from weed-free followed by 25-cm row spacing and 150,000 seeds ha^{-1} with a yield loss of 18% and 76-cm row spacing and 150,000 seeds ha^{-1} with a yield loss of 19%. The 76-cm row spacing and 125,000 seeds ha^{-1} had the lowest yields across all times of weed removal with a 24% yield loss with weedy all season as compared to weed-free (Figure 2-1).

At Manhattan in 2014, a significant interaction was observed between row spacing and grass weed removal times throughout the growing season (Appendix A-1). Greater weed-free yields were observed in 20-cm row spacing as compared to 76-cm row spacing, but with weed competition all season, wider rows had a greater yield than narrow (Appendix A-3, A-4). The yield loss from weed-free to weedy all season was 8% in the 20-cm row spacing and was 2% in the 76-cm row spacing. No interactions was observed among row spacing, seeding rates, or time of weed removal for 2015 yields at Manhattan, but there was a significant time of weed removal main effect on grain sorghum yield (Appendix A-1).

The average grain sorghum yields expected in Hays and Manhattan, KS were found for each county and year (NASS 2015). The average yield in Ellis County KS in 2014 was 5,100 kg ha^{-1} and weed-free grain sorghum yield at Hays in 2014 >1,000 kg ha^{-1} compared to the average yield. In 2015 Ellis County, KS had an average grain sorghum yield of 4,500 kg ha^{-1} and weed-free at Hays was <1,000 kg ha^{-1} compared to the average. In Riley County, KS the average grain sorghum yield in 2014 was 6,300 kg ha^{-1} and weed-free grain sorghum yields in Manhattan 2014 were equal to or greater than the county average while in 2015 the Riley County average was 6,450 kg ha^{-1} and weed-free yields in Manhattan were >2,000 kg ha^{-1} compared to the average (NASS 2015).

Weed emergence and biomass

Grass weeds emerged with the crop in 2014 at both locations, with foxtails emerging first in Hays and large crabgrass in Manhattan. In Manhattan 2015 initial grass weeds that emerged at week two or before, were large crabgrass with giant and yellow foxtail observed later. There were very little to no grass weeds through the growing season in Hays 2015, likely due to the lack of moisture (Table 2-1).

At Manhattan 2014 there was no interaction of row spacing, seeding rate or removal times on grass weed biomass (Appendix A-2), so on average, grass weed biomass was 13 g m^{-2} at week three and increased to 19 g m^{-2} at week four after sorghum emergence in 76-cm row spacing and 125,000 seeds ha^{-1}. In Manhattan in 2015, grass weed biomass increased from weeks six through eight (Figure 2-3). After eight weeks the weed biomass plateaus with slight decrease towards sorghum harvest. The grass weed biomass at week eight had the greatest differences among row spacing and seeding rate treatments (Figures 2-3 & 2-4), with greatest grass weed biomass in wide row spacing and low seeding rate treatment (Figure 2-4).

Above ground stem and leaf biomass of grain sorghum measured at harvest in 2014 decreased in response to time of weed removal from week two after sorghum emergence until harvest across both locations, and there was a significant main effect of row spacing (Figure 2-5,

Appendix A-1). Both locations were fit to linear regression (Table 2-8). Hays 2014 sorghum aboveground stem and leaf biomass decreased 23% between weed-free all season and weedy all season plots, while Manhattan in 2014 differences between weed free and weedy all season treatments were a 22% decrease in biomass. The significant main effect of row spacing on grain sorghum aboveground stem and leaf biomass in 2014 showed that greater sorghum biomass in narrow rows contributed to greater weed suppression and greater grain yields in Hays and Manhattan 2014. In 2015, there were significant main effects of row spacing and seeding rate on sorghum above ground biomass at Hays, and only row spacing effects at Manhattan (Appendix A-1).

It was observed in both years at Hays and in Manhattan 2014 that there was significant sorghum yield loss due to increasing duration of grass weed interference (Figure 2-2, Appendix A-4). The following critical times of weed removal are based on 5% yield loss being deemed acceptable and using the mean weed-free yields at each location and year. The time of grass weed removal to prevent 5% yield loss in Hays 2014 in 25-cm row spacing and 125,000 seeds ha^{-1} was never reached (Table 2-9). In 25-cm row spacing and 150,000 seeds ha^{-1} the sorghum yield loss reach 5% at week five (Table 2-9). In 76-cm row spacing and 125,000 seeds ha^{-1} had yield loss that reached 5% at week 3.3 (Table 2-9). Within 76-cm row spacing and 150,000 seeds ha^{-1} reached a loss of 5% at week 6.3 (Table 2-9). In Hays 2014, the critical duration of weed interference that allowed 5% loss would extend from week 3.3 to 25 after sorghum emergence depending upon row spacing, seeding rate and weed pressure (Table 2-9, Figure 2-2 & 2-3). In Manhattan 2014 the 20-cm row spacing and 125,000 seeds ha^{-1} had a yield loss of 5% at week 2.5 (Appendix A-5). For 20-cm row spacing and 150,000 seeds ha^{-1} 5% loss occurred at week 2.3 (Appendix A-5). In 76-cm row spacing and 125,000 seeds ha^{-1} 5% loss occurred at week 3.6 (Appendix A-5). The 76-cm row spacing and 150,000 seeds ha^{-1} 5% loss occurred at week 5 (Appendix A-5). The critical duration of weed interference that could be allowed with 5% loss would extend from week 2.3 to week 5 at Manhattan depending upon row spacing and seeding rate (Table 2-9, Appendix A-3, A-4, A-5).

The economic value of 5% yield loss at each location in 2014 ranged from \$52.64 to \$68.35 ha^{-1} depending upon the treatment (Table 2-9). This implies that there will be different sorghum yield loss at different row spacing and seeding rates depending upon your crop weed competition, there may be benefits to narrow rows compared to wide rows. A higher seeding rate must be factored in when considering loss from weed interference. When planting 125,000 seeds ha^{-1} vs. 150,000 seeds ha^{-1} there is a \$6.75 ha^{-1} investment in seed based on average grain sorghum seed costs of \$0.27 per thousand seeds (Ibendahl et al. 2015).

Conclusions and Recommendations

Grain sorghum response to seeding rate was variable and dependent upon grass weeds and environment. When grain sorghum was grown in a low weed pressure site, such as Hays 2015, indicated that 125,000 seeds ha^{-1} had no significant yield advantage over 150,000 seeds ha^{-1}. In Hays 2014 narrow rows had the greatest yield under grass weed pressure and weed free all season treatments. However, the seeding rates utilized in this study were within recommended seeding rates to be used at Manhattan but higher than recommended rates for Hays (Staggenborg et al. 1999). There was not a wide gap in seeding rates for this study so minimal differences were observed in yields with grain sorghum sown at different seeding rates in grass weed situations.

Yield responses to row spacing at Hays and Manhattan were variable and dependent upon grass weed pressure, similar to that reported by Conley et al. (2005). Grain sorghum grown in a moderate to high weed pressure situation such as Hays 2014 yielded better with narrow row spacing. These yield responses were likely caused by grain sorghum's ability to tolerate weed pressure, rather than suppress the weeds. Past research has indicated that narrower rows should suppress weeds, such as up to 72% reduction in weed biomass in narrow-row corn (Marin and Weiner 2014).

Weed biomass levels did differ among row spacing and seeding rate treatments with increased weed biomass in wide row spacing compared to narrow in Hays 2014, suggesting that grain sorghum grown in narrow rows may out compete grass weeds more than wide rows. The data from this experiment would suggest that grain sorghum can be produced across wide and narrow row spacings. To determine the optimal row spacing and seeding rate, the weed pressure and biomass of the environment in question should be considered by the producer. Low grass weed pressure situations would permit wide row spacings for higher yield and an average or seeding rate for the area. A high weed pressure situation would permit narrow row spacings and an average seeding rate for the area.

To help increase crop competitiveness equipment choice is a main factor when deciding what row spacing will be used. Most producers have an option of grain drills, air drills, planters and twin row planters. Seed placement is very important and cannot be precisely controlled in drills, but can be in planters and air seeders. When common grain drills are used for grain sorghum seeding there are limitations on seeding rate because of the seed size and drill designs.

Narrow rows planted with a drill had pour seed placement. This suggests that for optimum seed placement, planters or twin row planters could possibly be the most profitable for the producer.

When growing ALS-inhibitor herbicide-resistant grain sorghum hybrids a quality PRE program of herbicides is important. Such a program includes PRE herbicides such as a mixture of s-metolachlor + atrazine + mesotrione that can greatly ad in broad leaf and grass weed control. This will set the producer ahead of the weed pressure for the first growth stages of grain sorghum. If grass weeds are at a density that will have negative effects on the sorghum crop then it could possibly be controlled through a POST application of nicosulfuron herbicide for grass weed control. More research needs to be completed to find out optimum application amounts and timings of POST grass herbicides in ALS-inhibitor herbicide-resistant grain sorghum hybrids.

This study recommends narrow row widths in environments with a possibility of moderate to high grass pressure, which can potentially increase yield and decrease grass weed biomass. Under low grass pressure and no broadleaf weeds there are no differences among treatments. Grain sorghum grown in weed-free situations will achieve optimal yield and highest profits, but may not always be economical due to added costs associated with achieving a weed-free environment. An integrated weed management system should be highly prioritized to achieve maximum weed control/suppression in order to achieve high yields. Future research focusing on POST grass weeds should look at a wider range of seeding rates and ensuring the establishment of a consistent density and species of grass weeds across all experimental units. This research showed that the critical duration of grass weed interference was between weeks two and six after sorghum emergence depending upon the environment. Duration of weed interference in grain sorghum is very important to consider when planting ALS-inhibitor herbicide-resistant grain sorghum hybrids in a crop rotation system. The economic loss due to the grass weeds must be evaluated by the producer. If the producers net gain from treating the crop for grass weeds has a net gain exceeding \$0.00 kg ha^{-1} then it would be justified.

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Figures and Tables

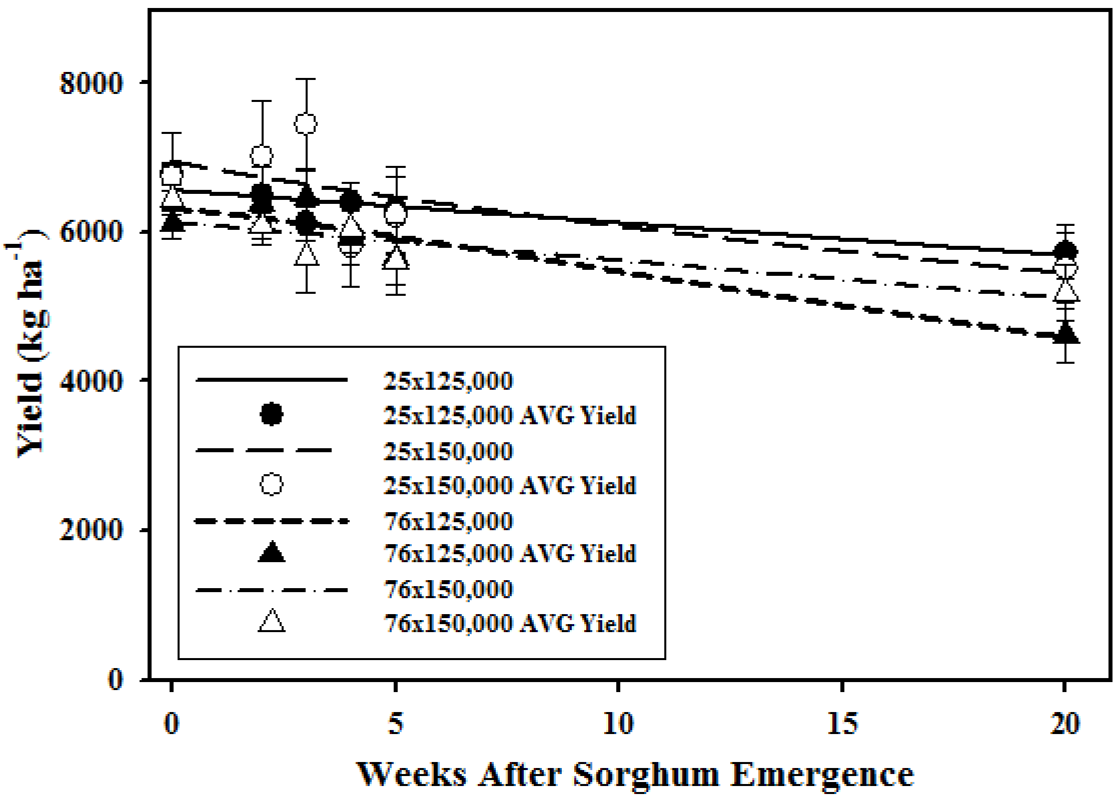


Figure 2-1 Grain sorghum yield at each time of weed removal for each row spacing and seeding rate treatment at Hays 2014. Points represent average yield with standard error and lines represent the predicted yield across weeks after sorghum emergence (Using eq # 1 and 2). Parameter estimates for fitted models in Table 2.5.

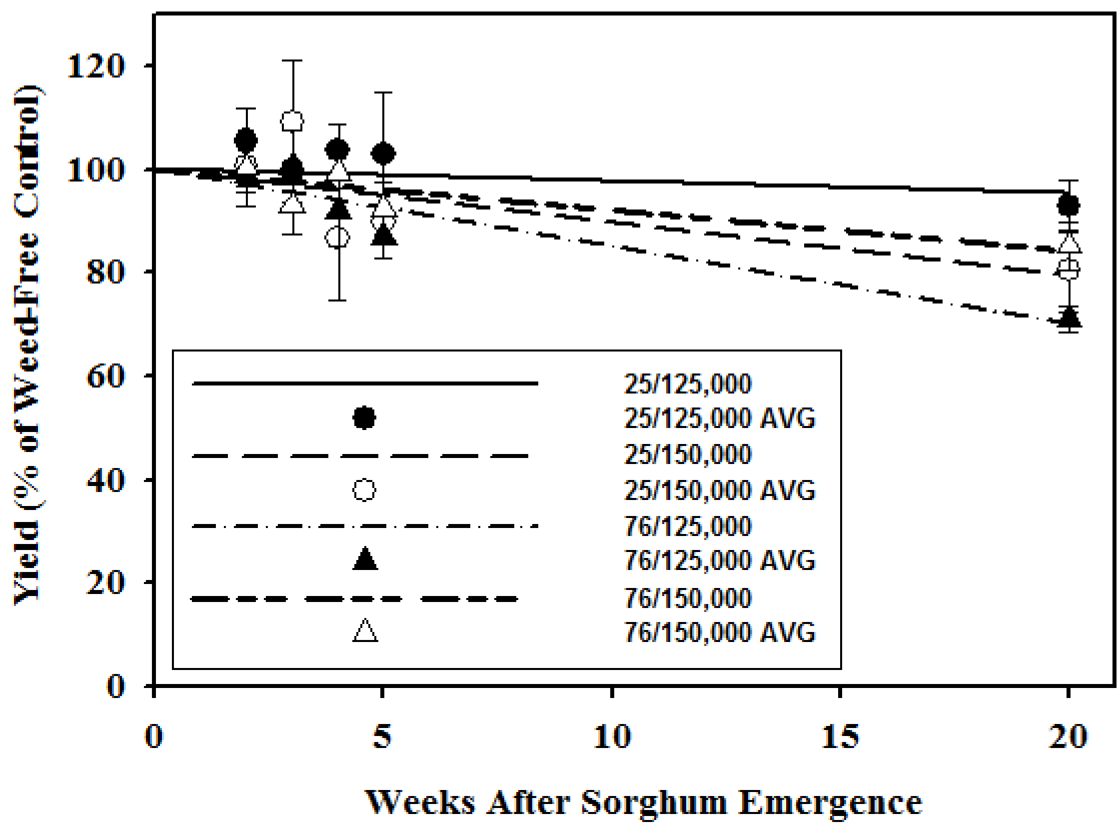


Figure 2-2 Grain sorghum yield as a percent of weed-free Hays in 2014 calculated from sorghum grain harvest data (eq. #2). Parameter estimates for fitted models in Table 2.6.

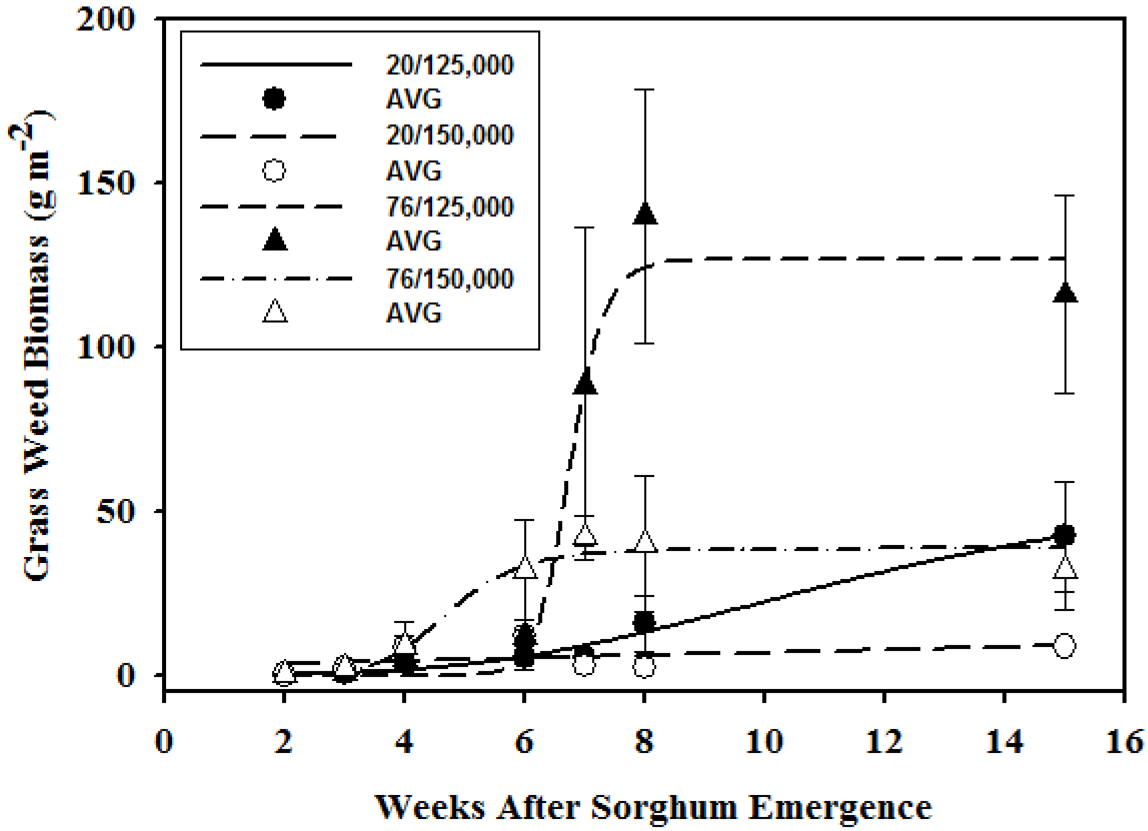


Figure 2-3 Grass weed biomass (g m^{-2}) measured each week after sorghum emergence for each row spacing and seeding rate treatment in Manhattan 2015. Points represent observed average biomass and lines predicted grass biomass over time using equations #1 and 2. Parameter estimates for fitted models in Table 2.7.

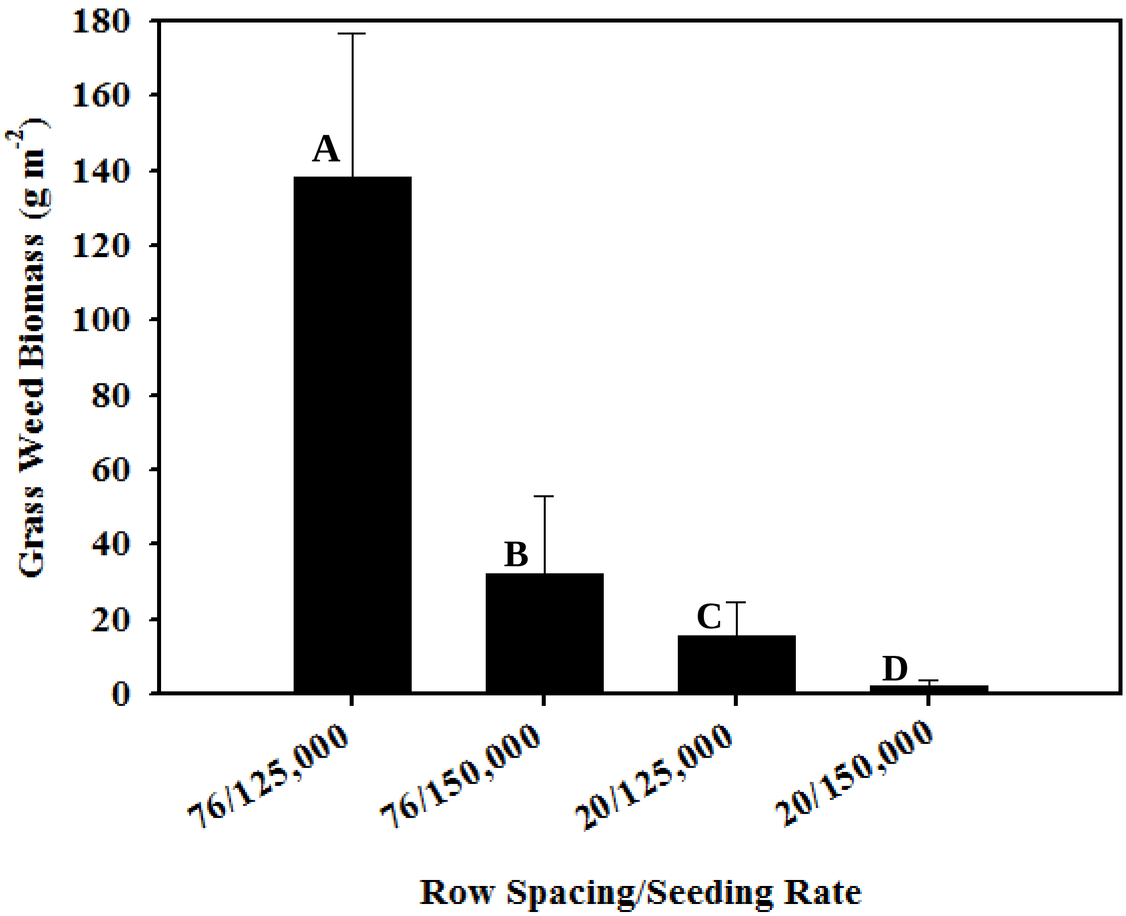


Figure 2-4 Grass weed biomass (g m^{-2}) at 8 weeks after grain sorghum emergence for each row spacing (cm) and seeding rate (seeds ha^{-1}) combination at Manhattan 2015 followed by different letter were different at LSD (α = 0.05).

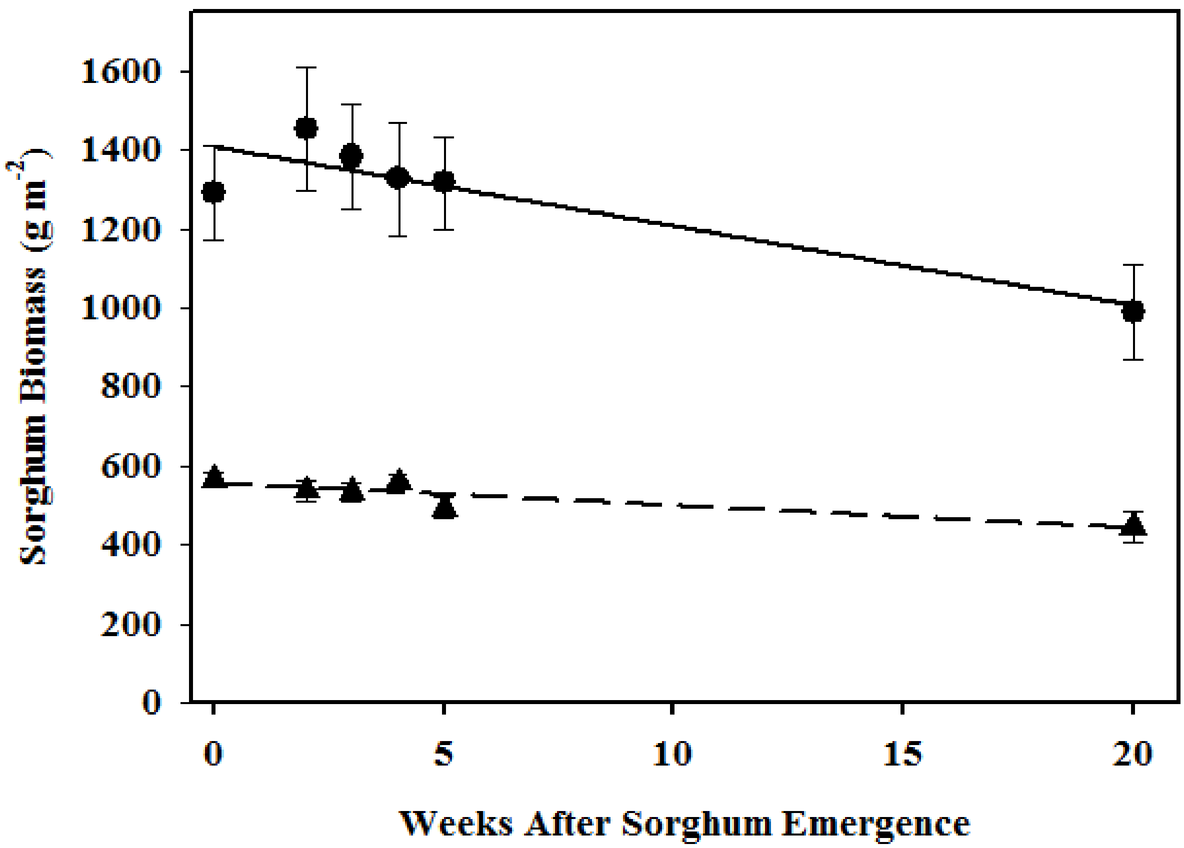


Figure 2-5 Grain sorghum above ground stem and leaf biomass (g m^{-2}) averaged across row spacing and seeding rates for each grass weed removal time at Hays (●) and Manhattan (▲) in 2014 (eq. #2). Parameter estimates in Table 2.8.

Table 2-1 Total monthly and yearly precipitation, maximum and minimum monthly temperatures and 30-yr average (1980-2010) precipitation for Hays, KS in 2014 and 2015.

	2014			2015			30 yr average
Month	Precipitation	Temperature		Precipitation	Temperature		Precipitation
	mm	Max ºC	Min ºC	mm	Max ºC	Min ºC	mm
January	0	7	-9	17	8	-7	13
February	0	4	-9	4	7	-8	18
March	0	13	-4	1	18	-1	46
April	23	20	4	21	21	5	54
May	15	17	9	153	22	10	83
June	200	31	17	16	32	17	72
July	43	32	18	103	33	19	100
August	41	34	18	10	33	17	77
September	117	28	13	10	31	17	52
October	44	22	6	43	22	8	40
November	1	12	-5	38	14	0	23
December	16	6	-4	30	8	-4	18
Total	500			446			596

Table 2-2 Total monthly and yearly precipitation, maximum and minimum monthly temperatures and 30-yr average (1980-2010) precipitation for Manhattan, KS in 2014 and 2015.

	2014			2015			30 yr average
Month	Precipitation	Temperature		Precipitation	Temperature		Precipitation
	mm	Max ºC	Min ºC	mm	Max ºC	Min ºC	mm
January	1	4	-9	22	7	-8	16
February	23	3	-9	10	4	-9	27
March	0	11	-5	4	15	-1	63
April	89	21	9	68	21	7	81
May	50	26	12	219	23	12	129
June	177	29	18	108	31	19	145
July	21	32	18	128	32	21	112
August	91	33	20	81	30	17	105
September	29	27	14	105	30	17	87
October	74	22	8	16	22	8	68
November	1	10	-4	111	16	3	44
December	54	6	-2	82	9	-2	27
Total	610			954			904

Table 2-3 Average grain sorghum yields (kg ha^{-1}) and standard errors (SE) for each row width and seeding rate across all time of grass weed removal excluding PRE herbicide treatment at Hays and Manhattan 2015.

Row Width	Seeding Rate	Hays	Manhattan
	Seeds ha^{-1}	kg ha^{-1} (SE)	
Narrow	125,000	3659 (152)	9021 (265)
	150,000	3348 (152)	9007 (217)
Wide	125,000	3062 (172)	9061 (101)
	150,000	3232 (219)	8730 (139)

Table 2-4 Grain sorghum yields for each grass weed removal time averaged across all row spacing and seeding rates excluding PRE herbicide treatments in weeks after sorghum emergence at Hays and Manhattan 2015. Values followed by the same letter were not different at LSD ($\alpha = 0.05$).

Time	Hays	Manhattan
Weeks	kg ha^{-1}	
0	3258 a	9143 ab
2	3101 a	9475 a
4	3522 a	8814 b
6	3337 a	8765 b
8	3202 a	8763 b
20	3553 a	8719 b
LSD	453	587

Table 2-5 Parameter estimates (SE) for Hays 2014 grain sorghum yield for each row spacing, seeding rate treatment in response to grass weed removal times as seen in Figure 2-1. Equations #1 and 2.

Parameter Estimates				
Row Spacing/ Seeding Rate	**a**	**b**	**X_0**	**R^2**
25/125,000	**6553.6 (204.1)**	**-43.7 (23.5)**	**-**	**0.08**
25/150,000	**6941.5 (536.8)**	**0.9 (0.89)**	**78.8 (104.5)**	**0.09**
76/125,000	**6307.0 (339.9)**	**1.3 (0.86)**	**42.6 (21.6)**	**0.35**
76/150,000	**6125.8 (173.7)**	**-51.1 (20)**	**-**	**0.19**

a=maximum weed free yield, b=slope, X_0= weeks to reach 50% yield, R^2 = regression and "-"=not estimated

Table 2-6 Parameter estimates (SE) for Hays 2014 in percent of weed-free grain sorghum yield for each row spacing and seeding rate in response to grass weed removal times as seen in Figure 2-2(equation #2).

Parameter Estimates			
Row Spacing/ Seeding Rate	**a**	**b**	**R^2**
25/125,000	**100 (0)**	**-0.2 (0.3)**	**0.03**
25/150,000	**100 (0)**	**-1.0 (0.4)**	**0.17**
76/125,000	**100 (0)**	**-1.5 (0.2)**	**0.53**
76/150,000	**100 (0)**	**-0.8 (0.2)**	**0.27**

a=weed free yield set to 100%, b=slope, R^2=regression coefficient.

Table 2-7 Parameter estimates (SE) of grass weed biomass for each row spacing and seeding rate treatment in response to time of grass weed removal for Manhattan in 2015 as seen in Figure 2-3. Equations #1 and 2.

Parameter Estimates				
Row Spacing/ Seeding Rate	**a**	**b**	**X_0**	**R^2**
20/125,000	**15.1 (24.8)**	**-3.4 (4.7)**	**11.6 (14.8)**	**0.62**
20/150,000	**0.63 (0.3)**	**0.11 (0.1)**	**-**	**0.004**
76/125,000	**31.7 (4.6)**	**-23.3 (22.7)**	**6.7 (0.3)**	**0.56**
76/150,000	**9.6 (2.0)**	**-7.7 (7.4)**	**4.7 (1.0)**	**0.37**

a=maximum weed biomass, b=slope, X_0= weeks to reach 50% biomass, R^2=regression coefficient and “-“=not estimated

Table 2-8 Parameter estimates (SE) for grain sorghum above ground stem and leaf biomass (g m^{-2}) across row spacing and seeding rates in response to grass weed removal times at Hays and Manhattan in 2014 as seen in Figure 2-5 (equation #2).

Parameter Estimates			
Location	**a**	**b**	**R^2**
Hays	**1407 (70.0)**	**-20 (8.0)**	**0.06**
Manhattan	**555 (14.0)**	**-5 (1.6)**	**0.12**

a=weed free biomass, b=slope, R^2=regression

Table 2-9 Critical time of grass weed removal, 5% loss from weed-free yield, and economic loss including added seed cost for each row spacing and seeding rate at Hays and Manhattan in 2014. Commodity price in Kansas (2014) of \$0.16 kg^{-1} (\$4.30 bu^{-1}) was used and \$0.27 thousand seed-1 for added seed cost.

Location	Row Spacing/ Seeding Rate	Critical Time of Removal	5% Yield Loss	Economic Loss
		weeks	kg ha^{-1}	\$ ha^{-1}
Hays	25/125,000	25.0	341	54.56
	25/150,000	5.0	338	60.83
	76/125,000	3.3	306	48.96
	76/150,000	6.3	322	58.27
Manhattan	20/125,000	2.5	329	52.64
	20/150,000	2.3	385	68.35
	76/125,000	3.6	334	53.44
	76/150,000	5.0	341	61.31

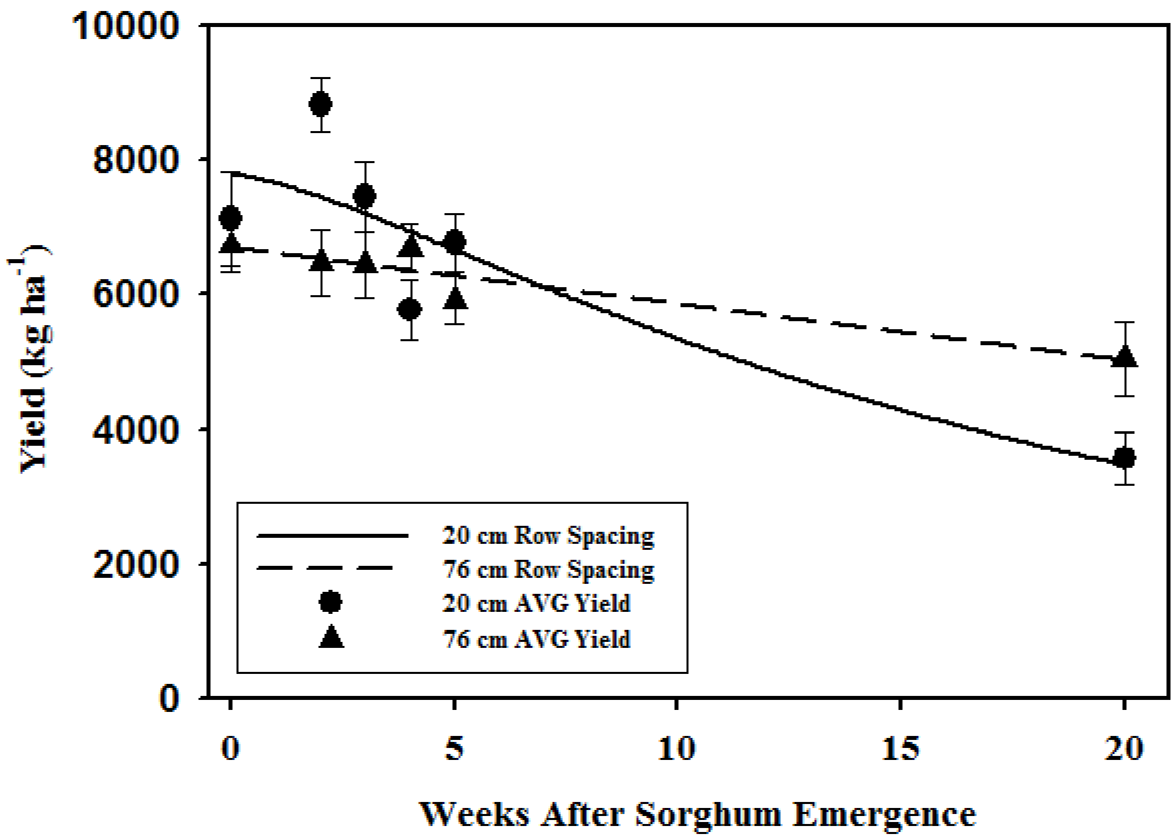
Appendix

Appendix A- 1 ANOVA: Significance (P<0.05) of main effects and interactions for grain sorghum yield and above ground biomass at harvest in 2014 and 2015 for Hays and Manhattan.

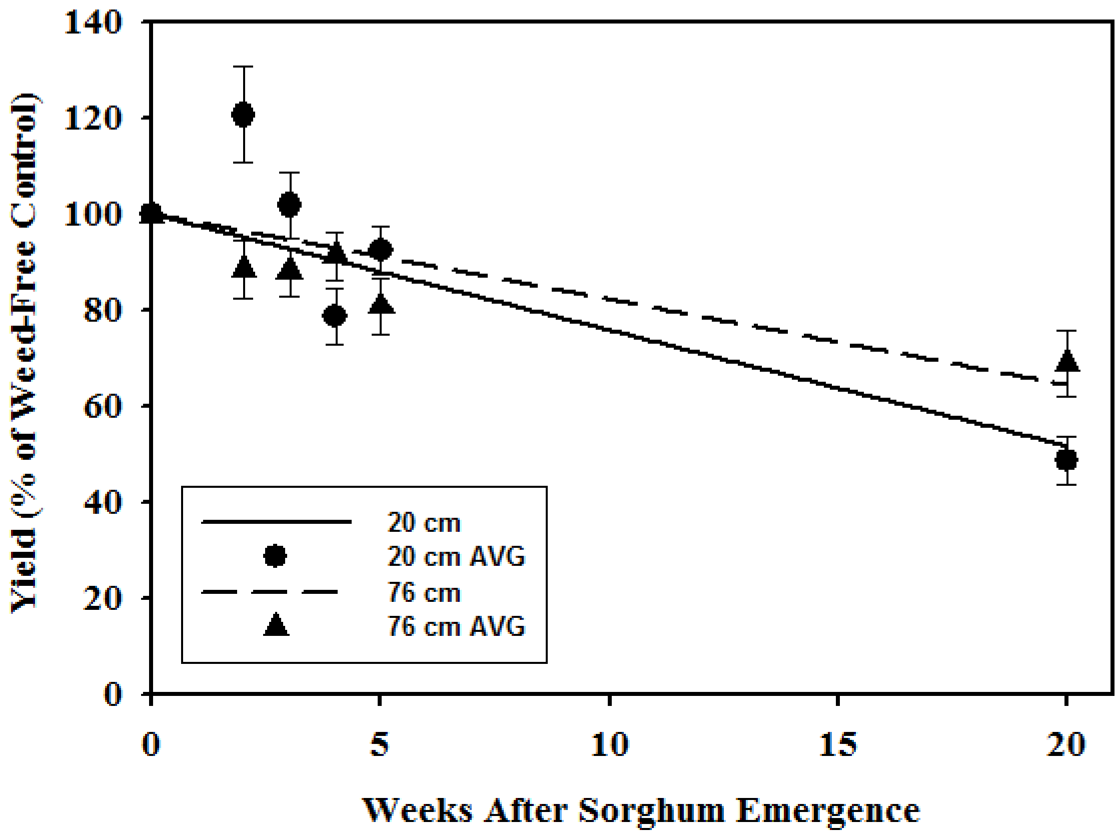
	Sorghum Grain Yield				Sorghum Above Ground Plant Biomass			
	2014		2015		2014		2015	
	Hays	Manhattan	Hays	Manhattan	Hays	Manhattan	Hays	Manhattan
rep	NS	NS	0.0043	NS	0.0027	0.0027	0.0027	NS
row	NS	NS	NS	NS	<0.0001	<0.0001	<0.0001	<0.0001
seed	NS	NS	NS	NS	NS	NS	0.0003	NS
row*seed	NS	NS	NS	NS	NS	NS	NS	NS
remove	<0.0001	<0.0001	NS	0.044	0.0004	0.0004	NS	NS
row*remove	NS	0.0002	NS	NS	NS	NS	NS	NS
seed*remove	NS	NS	NS	NS	NS	NS	NS	NS
row*seed*remove	0.013	NS	NS	NS	NS	NS	NS	NS

Appendix A- 2 ANOVA: Significance (P<0.05) of main effects and interactions for grass weed biomass for each time of grass removal treatment from weeks 2 through 5 in 2014 and weeks 1 through 8 and 20 in 2015 for Hays and Manhattan.

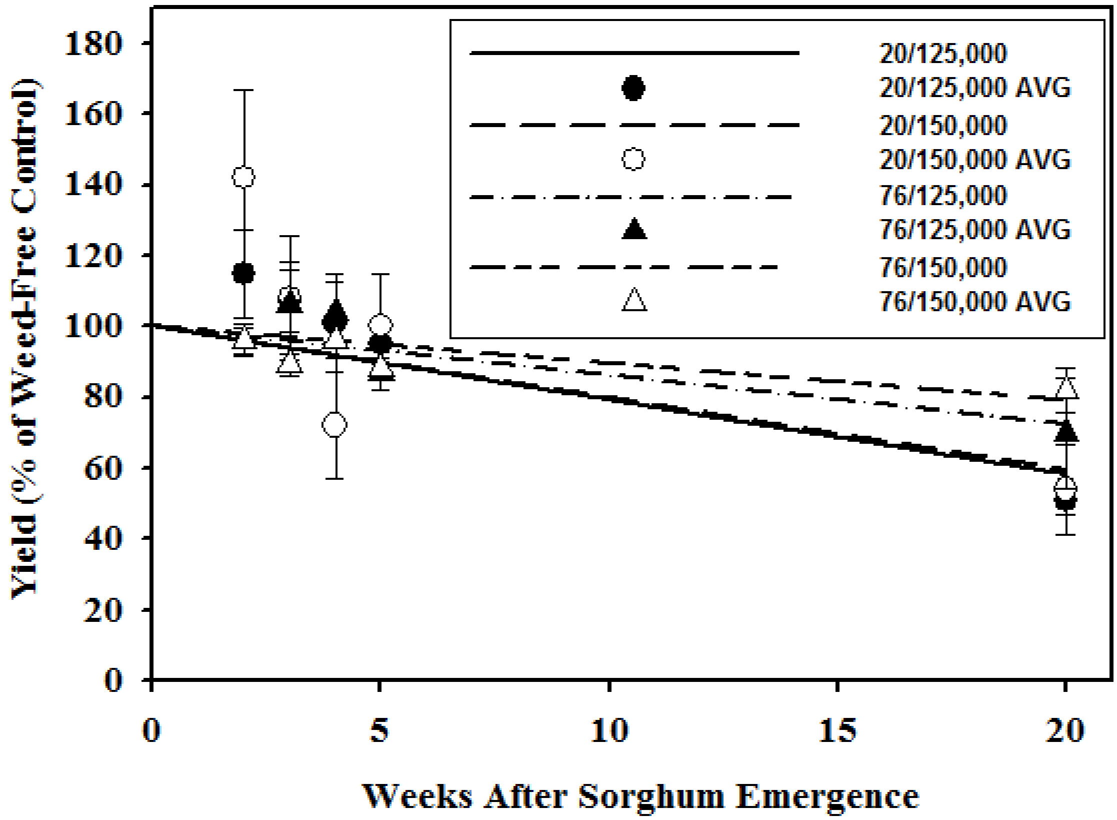
	Hays 2014			Manhattan 2014			Hays 2015			Manhattan 2015		
	row	seed	row*seed	row	seed	row*seed	row	seed	row*seed	row	seed	row*seed
week 1	--	--	--	--	--	--	NS	NS	NS	NS	NS	NS
week 2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
week 3	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
week 4	0.0429	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
week 5	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
week 6	--	--	--	--	--	--	NS	NS	NS	NS	NS	NS
week 7	--	--	--	--	--	--	NS	NS	NS	NS	NS	NS
week 8	--	--	--	--	--	--	NS	NS	NS	0.0283	0.045	NS
week 20	--	--	--	--	--	--	NS	NS	NS	NS	NS	NS



Appendix A- 3 Grain sorghum yield at each time of weed removal for each row spacing treatment at Manhattan 2014. Points represent average yield with standard error and lines represent the predicted yield across weeks after sorghum emergence (eq. #1 and 2). Parameter estimates for fitted models in Appendix A-6.



Appendix A- 4 Grain sorghum yield as a percent of weed-free in Manhattan 2014 averaged across row spacings, calculated from sorghum grain harvest data (eq. 2). Parameter estimates for fitted models in Appendix A-7.



Appendix A- 5 Grain sorghum yield as a percent of weed-free in Manhattan 2014 calculated from sorghum grain harvest data (eq. #1 and 2). Interaction of row spacing, seeding rate and time or removal were not significant. Row spacing and time of removal were significant (Appendix A-3, A-4). Parameter estimates for fitted models in Table Appendix A-8.

Appendix A- 6 Parameter estimates (SE) for Manhattan 2014 grain sorghum yield averaged across seeding rates for each row spacing in response to grass weed removal times as seen in Appendix A-3. Equations #1 and 2.

Parameter Estimates				
Row Spacing (cm)	**a**	**b**	**X_0**	**R^2**
20	**7781.8 (559.2)**	**1.40 (0.51)**	**17 (4.0)**	**0.56**
76	**6694.3 (225.7)**	**-83.65 (25.9)**	**--**	**0.29**

a=weed free yield, b=slope, X_0= weeks to reach 50% yield, R^2=regression coefficient and "--"=not estimated

Appendix A- 7 Parameter estimates (SE) for percent of weed-free grain sorghum yield averaged across seeding rates for each row spacing in response to grass weed removal times for Manhattan 2014 as seen in Appendix A-4. Lines fit using equation 2.

Parameter Estimates			
Row Spacing	**a**	**b**	**R^2**
20	**100 (0)**	**-2.4 (0.3)**	**0.44**
76	**100 (0)**	**-1.7 (0.2)**	**0.18**

a=weed free yield, b=slope and R^2=regression coefficient

Appendix A- 8 Parameter estimates (SE) for percent of weed-free grain sorghum yield averaged across seeding rates for each row spacing in response to grass weed removal times for Manhattan 2014 as seen in Appendix A-5. Lines fit using equation 2.

Parameter Estimates			
Row Spacing/ Seeding Rate	**a**	**b**	**R^2**
20/125,000	**100 (0)**	**-2.0 (0.4)**	**0.47**
20/150,000	**100 (0)**	**-2.2 (0.8)**	**0.19**
76/125,000	**100 (0)**	**-1.4 (0.4)**	**0.27**
76/150,000	**100 (0)**	**-1.0 (2.2)**	**0.16**

a=weed free yield, b=slope and R^2=regression coefficient

Appendix A- 9 Critical time of grass weed removal, 5% loss from weed-free yield, and economic loss including added seed cost for each row spacing and seeding rate at Manhattan in 2014. Commodity price in Kansas (2014) of $0.16 kg^{-1} ($4.30 bu^{-1}) was used and $0.27 thousand seed-1 for added seed cost.

Location	Row Spacing	Critical Time of Removal	5% Yield Loss	Economic Loss
	cm	weeks	kg ha^{-1}	$ ha^{-1}
Manhattan	20	2.0	357	57.12
	76	2.8	337	47.19

Appendix A- 10 Grain sorghum above ground stem, leaf and head biomass (g m^{-2}) across row spacing and seeding rates for each grass weed removal time at Hays and Manhattan 2015.

Location	Treatment	Row Spacing/Seeding Rate			
	Weeks	25/125,000	25/150,000	76/125,000	76/150,000
		g m^{-2}			
Hays	0	1229	1670	2015	2352
	2	1244	1317	1685	2143
	4	1183	1420	1740	1659
	6	1166	1567	1669	2471
	8	1164	1504	1792	1664
	20	966	1585	1957	2329
		20/125,000	20/150,000	76/125,000	76/150,000
Manhattan	0	1514	1533	2744	2831
	2	2021	1793	3128	3126
	4	1538	1733	2913	3125
	6	1641	1645	3082	3067
	8	1677	1991	2940	2851
	20	1600	1824	3134	2668

Appendix A- 11 Grain sorghum yields (SE) from PRE herbicide treatment averaged across time of weed removal treatments for each row spacing and seeding rates in Hays and Manhattan 2014 and 2015.

Location & Year	Row Spacing	Seeding Rate	Yield (SE)
	cm	seeds ha^{-1}	kg ha^{-1}
Hays 2014	25	125,000	6182 (259)
	76	150,000	6969 (700)
	25	125,000	6533 (555)
	76	150,000	6075 (210)
Hays 2015	25	125,000	3316 (380)
	76	150,000	3703 (552)
	25	125,000	2541 (285)
	76	150,000	3295 (411)
Manhattan 2014	20	125,000	5982 (529)
	76	150,000	7914 (1316)
	20	125,000	6633 (537)
	76	150,000	6911 (1112)
Manhattan 2015	20	125,000	8477 (261)
	76	150,000	8064 (173)
	20	125,000	9305 (180)
	76	150,000	8918 (187)

Appendix A- 12 Grass weed biomass for each row spacing (narrow=20- and 25-cm, wide=76-cm) and seeding rate each week for each treatment in Hays and Manhattan in 2014 and 2015 (g m^{-2}). Treatments 2 to 5 (2014), 2 to 8 (2015) and 20 are weeks after sorghum emergence. "-"=no data.

			Hays		Manhattan	
Row Spacing	**Seeding Density**	**Trt**	**2014**	**2015**	**2014**	**2015**
	Seeds ha^{-1}		**g**	**g**	**g**	**g**
narrow	125,000	2	9.5	-	3.9	-
narrow	125,000	3	25.7	-	11.4	0.1
narrow	125,000	4	3.5	-	17.9	1.1
narrow	125,000	5	24.7	-	13.7	-
narrow	125,000	6	-	-	-	1.3
narrow	125,000	7	-	-	-	1.3
narrow	125,000	8	-	-	-	3.9
narrow	125,000	20	-	-	-	10.6
narrow	150,000	2	26.0	-	4.0	-
narrow	150,000	3	31.0	-	7.6	0.5
narrow	150,000	4	7.0	-	14.4	2.1
narrow	150,000	5	19.0	-	24.0	-
narrow	150,000	6	-	-	-	2.9
narrow	150,000	7	-	0.1	-	0.7
narrow	150,000	8	-	0.1	-	0.6
narrow	150,000	20	-	-	-	2.2
wide	125,000	2	13.5	0.1	4.8	0.2
wide	125,000	3	55.5	-	13.0	0.2
wide	125,000	4	43.4	-	19.0	1.2
wide	125,000	6	33.4	0.2	15.9	2.9
wide	125,000	7	-	0.3	-	21.8
wide	125,000	8	-	0.8	-	34.5

wide	125,000	20	-	-	-	28.7
wide	150,000	2	7.8	-	6.9	-
wide	150,000	3	45.0	-	13.6	0.5
wide	150,000	4	9.8	0.1	13.9	2.2
wide	150,000	5	7.5	-	19.4	-
wide	150,000	6	-	0.1	-	7.6
wide	150,000	7	-	0.3	-	10.5
wide	150,000	8	-	0.7	-	10.3
wide	150,000	20	-	-	-	8.3

Appendix A- 13 Grain sorghum leaf area, stem, leaf, and head including all grain and stalk dry weights (average of 2 plants per subplot) for each row spacing, seeding rate, and time of weed removal in Hays, KS in 2014. Treatments 0=weed-free by hand, 0.5=PRE herbicide, 2 to 5 and 20 are weeks after sorghum emergence.

Row Spacing	Seeding Rate	Treatment	Leaf Area	Stem	Leaf	Head
cm	seeds ha^{-1}		cm^2 plant^{-1}	g plant^{-1}	g plant^{-1}	g plant^{-1}
25.4	125,000	0	2700	30	18	14
25.4	125,000	0	1728	24	11	12
25.4	125,000	0	3365	36	19	22
25.4	125,000	0	2886	32	19	38
25.4	150,000	0	2251	29	14	12
25.4	150,000	0	3164	41	20	18
25.4	150,000	0	2592	24	16	11
25.4	150,000	0	2488	29	15	31
76.2	125,000	0	3840	50	27	24
76.2	125,000	0	3303	42	21	28
76.2	125,000	0	3691	48	27	46
76.2	125,000	0	2833	26	16	25
76.2	150,000	0	3543	47	26	33
76.2	150,000	0	2728	42	23	20
76.2	150,000	0	2818	43	22	29
76.2	150,000	0	2549	25	16	28
25.4	125,000	0.5	3434	50	25	31
25.4	125,000	0.5	3071	37	20	27
25.4	125,000	0.5	2632	33	16	12
25.4	125,000	0.5	2201	25	13	27
25.4	150,000	0.5	2985	39	20	18
25.4	150,000	0.5	2384	33	15	22
25.4	150,000	0.5	2370	33	17	24

25.4	150,000	0.5	2647	27	15	21
76.2	125,000	0.5	2281	35	18	12
76.2	125,000	0.5	2767	39	20	47
76.2	125,000	0.5	2774	37	19	31
76.2	125,000	0.5	3622	47	26	33
76.2	150,000	0.5	3072	45	21	19
76.2	150,000	0.5	3610	50	24	25
76.2	150,000	0.5	3255	45	25	24
76.2	150,000	0.5	3389	43	24	26
25.4	125,000	2	3470	50	25	20
25.4	125,000	2	2836	38	20	25
25.4	125,000	2	2538	34	17	15
25.4	125,000	2	3132	36	19	24
25.4	150,000	2	3108	46	23	19
25.4	150,000	2	3330	43	21	17
25.4	150,000	2	2593	29	17	19
25.4	150,000	2	3443	41	22	24
76.2	125,000	2	3958	57	30	27
76.2	125,000	2	3808	59	27	23
76.2	125,000	2	2742	32	18	16
76.2	125,000	2	2923	41	19	23
76.2	150,000	2	3630	47	24	40
76.2	150,000	2	3337	43	23	35
76.2	150,000	2	3307	43	24	20
76.2	150,000	2	3538	52	25	37
25.4	125,000	3	2155	29	14	15
25.4	125,000	3	2449	28	15	12
25.4	125,000	3	3096	43	22	19
25.4	125,000	3	2443	24	14	11
25.4	150,000	3	2859	32	18	14

25.4	150,000	3	2215	24	14	12
25.4	150,000	3	2984	49	22	28
25.4	150,000	3	3209	37	20	14
76.2	125,000	3	3799	51	25	17
76.2	125,000	3	3080	39	21	18
76.2	125,000	3	2564	32	16	18
76.2	125,000	3	3219	39	20	18
76.2	150,000	3	3220	52	25	28
76.2	150,000	3	3316	31	17	29
76.2	150,000	3	2562	37	18	19
76.2	150,000	3	2862	34	18	30
25.4	125,000	4	2881	37	19	19
25.4	125,000	4	2217	24	14	22
25.4	125,000	4	2362	27	16	13
25.4	125,000	4	2883	29	16	28
25.4	150,000	4	3000	35	20	18
25.4	150,000	4	2189	23	13	11
25.4	150,000	4	2236	22	15	18
25.4	150,000	4	2609	30	16	20
76.2	125,000	4	3163	45	21	20
76.2	125,000	4	3415	45	22	21
76.2	125,000	4	3800	53	28	28
76.2	125,000	4	3751	48	25	27
76.2	150,000	4	2986	40	20	17
76.2	150,000	4	2982	36	18	24
76.2	150,000	4	2422	31	16	24
76.2	150,000	4	3766	46	25	28
25.4	125,000	5	2879	38	20	16
25.4	125,000	5	2403	24	15	15
25.4	125,000	5	2983	40	22	19

25.4	125,000	5	2149	24	12	10
25.4	150,000	5	2854	45	20	19
25.4	150,000	5	2855	34	18	18
25.4	150,000	5	2082	26	14	11
25.4	150,000	5	3130	30	19	22
76.2	125,000	5	2879	45	20	34
76.2	125,000	5	3616	49	26	29
76.2	125,000	5	3266	48	24	35
76.2	125,000	5	3509	47	24	23
76.2	150,000	5	3546	54	25	32
76.2	150,000	5	2923	33	19	26
76.2	150,000	5	2745	45	24	29
76.2	150,000	5	3524	40	24	31
25.4	125,000	20	3211	37	23	27
25.4	125,000	20	2162	24	13	12
25.4	125,000	20	2231	27	16	22
25.4	125,000	20	2761	30	17	11
25.4	150,000	20	2328	37	19	21
25.4	150,000	20	2067	37	20	17
25.4	150,000	20	2388	32	16	13
25.4	150,000	20	3302	33	20	22
76.2	125,000	20	2285	26	15	10
76.2	125,000	20	3448	46	24	20
76.2	125,000	20	2803	29	18	37
76.2	125,000	20	3458	49	24	22
76.2	150,000	20	2949	25	14	10
76.2	150,000	20	3262	39	22	22
76.2	150,000	20	2883	37	20	19
76.2	150,000	20	3389	45	24	23

Appendix A- 14 Grain sorghum average leaf area, stem, leaf, and head weights for wide row spacing, each seeding rate, and time of weed removal (average 2 plants per subplot) in Manhattan 2014. Treatments 0=weed-free by hand, 0.5=PRE herbicide, 2 to 5 and 20 are weeks after sorghum emergence. 76.2 cm row widths only because of poor stands in narrow row sorghum.

Row Spacing	Seeding Rate	Treatment	Leaf Area	Stem	Leaf	Head
cm	seeds ha^{-1}		cm^2 plant^{-1}	g plant^{-1}	g plant^{-1}	g plant^{-1}
76.2	125,000	0	2914	31	18	11
76.2	125,000	0	2364	24	15	9
76.2	125,000	0	2979	28	20	11
76.2	125,000	0	2513	27	15	6
76.2	150,000	0	2497	23	14	10
76.2	150,000	0	2674	29	16	10
76.2	150,000	0	2588	34	16	8
76.2	150,000	0	2408	23	15	7
76.2	125,000	0.5	2709	30	17	10
76.2	125,000	0.5	2479	22	14	16
76.2	125,000	0.5	4063	22	16	9
76.2	125,000	0.5	2838	32	17	6
76.2	150,000	0.5	2717	26	16	8
76.2	150,000	0.5	2328	19	13	15
76.2	150,000	0.5	2774	32	17	13
76.2	150,000	0.5	2192	17	13	13
76.2	125,000	2	2764	29	16	7
76.2	125,000	2	1994	18	12	14
76.2	125,000	2	2209	30	19	4
76.2	125,000	2	2540	29	16	4
76.2	150,000	2	3035	34	18	10
76.2	150,000	2	2756	27	16	13

76.2	150,000	2	2271	22	15	7
76.2	150,000	2	2200	19	14	8
76.2	125,000	3	2707	28	17	8
76.2	125,000	3	2660	30	17	11
76.2	125,000	3	2145	24	13	9
76.2	125,000	3	2120	20	13	18
76.2	150,000	3	2589	26	15	8
76.2	150,000	3	2674	26	16	9
76.2	150,000	3	1633	21	14	11
76.2	150,000	3	1805	16	11	6
76.2	125,000	4	2451	23	14	12
76.2	125,000	4	2418	27	15	5
76.2	125,000	4	4063	24	14	13
76.2	125,000	4	1895	19	11	10
76.2	150,000	4	2837	34	17	10
76.2	150,000	4	1980	16	11	9
76.2	150,000	4	2701	33	17	8
76.2	150,000	4	2538	25	16	7
76.2	125,000	5	2519	29	15	5
76.2	125,000	5	2442	28	15	11
76.2	125,000	5	2728	32	15	15
76.2	125,000	5	2745	30	17	7
76.2	150,000	5	2811	31	17	9
76.2	150,000	5	3079	35	17	7
76.2	150,000	5	2280	24	11	8
76.2	150,000	5	1742	13	11	7
76.2	125,000	20	2793	30	17	9
76.2	125,000	20	2437	24	14	9
76.2	125,000	20	2447	24	15	13
76.2	125,000	20	1993	18	12	9

76.2	150,000	20	2501	22	14	13
76.2	150,000	20	2292	23	14	11
76.2	150,000	20	2810	28	17	11
76.2	150,000	20	2368	20	15	14

Appendix A- 15 Grain sorghum leaf area, stem, leaf, and head weights (average 2 plants per subplot) for each row spacing and seeding rate in the weed-free by hand plots in Hays, KS 2015. Treatment 0=weed-free by hand.

Row Spacing	Seeding Rate	Treatment	Leaf Area	Stem	Leaf	Head
cm	seeds ha^{-1}		cm^2 plant^{-1}	g plant^{-1}	g plant^{-1}	g plant^{-1}
25.4	125,000	0	2719	8	25	7
25.4	125,000	0	3287	13	72	12
25.4	125,000	0	3026	11	42	7
25.4	125,000	0	2870	11	32	6
25.4	150,000	0	3238	13	57	10
25.4	150,000	0	2907	10	47	13
25.4	150,000	0	2706	8	22	7
25.4	150,000	0	3473	14	69	9
76.2	125,000	0	3333	15	70	15
76.2	125,000	0	3235	12	38	13
76.2	125,000	0	3294	13	87	13
76.2	125,000	0	3882	17	81	14
76.2	150,000	0	3510	17	87	18
76.2	150,000	0	3403	14	56	11
76.2	150,000	0	3258	12	59	14
76.2	150,000	0	3275	13	59	10

Appendix A- 16 Grain sorghum leaf area, stem, leaf, and head weights (average 2 plants per subplot) for each row spacing, seeding rate and time of weed removal in Manhattan 2015. Treatments 0=weed-free by hand, 0.5=PRE herbicide, 2, 4, 6, 8 and 20 are weeks after sorghum emergence. "-"=no data.

Row Spacing	Seeding Rate	Treatment	Leaf Area	Stem	Leaf	Head
cm	seeds ha^{-1}		cm^2 plant^{-1}	g plant^{-1}	g plant^{-1}	g plant^{-1}
25.4	125,000	0	3613	14	36	10
25.4	125,000	0	3362	13	73	10
25.4	125,000	0	3520	18	63	6
25.4	150,000	0	2575	9	26	-
25.4	150,000	0	2534	5	37	5
25.4	150,000	0	2638	6	30	7
76.2	125,000	0	3476	14	60	9
76.2	125,000	0	3332	10	63	10
76.2	125,000	0	3537	11	66	8
76.2	125,000	0	3425	19	94	7
76.2	150,000	0	3242	10	38	7
76.2	150,000	0	2476	7	50	10
76.2	150,000	0	3149	10	62	9
76.2	150,000	0	3057	15	74	6
25.4	125,000	0.5	1645	0	1	-
25.4	125,000	0.5	3443	13	66	6
25.4	125,000	0.5	1380	4	5	-
25.4	150,000	0.5	4395	20	82	0
25.4	150,000	0.5	2740	8	38	4
25.4	150,000	0.5	1691	1	8	-
76.2	125,000	0.5	3674	14	46	-
76.2	125,000	0.5	3318	11	49	-
76.2	125,000	0.5	4390	18	83	-
76.2	125,000	0.5	3796	18	75	-

76.2	150,000	0.5	3127	13	63	6
76.2	150,000	0.5	2494	7	64	-
76.2	150,000	0.5	2979	9	50	8
76.2	150,000	0.5	3040	19	95	1
25.4	125,000	2	3471	10	43	6
25.4	125,000	2	3212	13	51	-
25.4	125,000	2	3200	15	56	10
25.4	150,000	2	3072	9	35	-
25.4	150,000	2	2838	8	54	6
25.4	150,000	2	2683	7	25	8
76.2	125,000	2	3344	13	47	8
76.2	125,000	2	3326	12	78	11
76.2	125,000	2	3381	12	73	13
76.2	125,000	2	3205	17	92	8
76.2	150,000	2	2992	10	39	5
76.2	150,000	2	3172	12	76	11
76.2	150,000	2	3328	11	69	13
76.2	150,000	2	3000	16	70	6
25.4	125,000	4	2973	8	34	6
25.4	125,000	4	3152	11	54	5
25.4	125,000	4	3331	16	57	7
25.4	150,000	4	3927	13	43	-
25.4	150,000	4	2458	6	32	3
25.4	150,000	4	3556	12	51	6
76.2	125,000	4	3670	14	69	8
76.2	125,000	4	3334	12	68	10
76.2	125,000	4	3423	12	79	12
76.2	125,000	4	2949	16	85	6
76.2	150,000	4	3176	9	36	7
76.2	150,000	4	2780	9	52	10

76.2	150,000	4	2982	8	45	7
76.2	150,000	4	3147	16	77	8
25.4	125,000	6	3337	12	33	5
25.4	125,000	6	3142	11	43	2
25.4	125,000	6	3578	14	76	8
25.4	150,000	6	3550	13	52	-
25.4	150,000	6	2823	8	65	5
25.4	150,000	6	2994	7	55	4
76.2	125,000	6	3607	14	74	-
76.2	125,000	6	3091	10	51	5
76.2	125,000	6	3203	10	72	13
76.2	125,000	6	2712	14	80	6
76.2	150,000	6	3196	10	43	6
76.2	150,000	6	2590	7	67	7
76.2	150,000	6	2806	6	52	7
76.2	150,000	6	2635	13	77	9
25.4	125,000	8	3313	12	47	7
25.4	125,000	8	3317	14	63	3
25.4	125,000	8	3055	13	44	3
25.4	150,000	8	2681	7	22	-
25.4	150,000	8	1422	3	19	-
25.4	150,000	8	3282	10	61	5
76.2	125,000	8	3038	10	44	8
76.2	125,000	8	3697	13	65	9
76.2	125,000	8	2913	7	39	8
76.2	125,000	8	3640	19	85	4
76.2	150,000	8	3287	9	46	5
76.2	150,000	8	2512	9	48	9
76.2	150,000	8	3404	12	59	6
76.2	150,000	8	2622	14	68	7

25.4	125,000	20	2887	8	29	5
25.4	125,000	20	2680	8	35	4
25.4	125,000	20	3785	18	64	5
25.4	150,000	20	3438	12	50	-
25.4	150,000	20	2595	7	46	2
25.4	150,000	20	2664	7	31	2
76.2	125,000	20	3112	10	44	4
76.2	125,000	20	3153	10	65	7
76.2	125,000	20	3407	12	60	13
76.2	125,000	20	3142	15	90	5
76.2	150,000	20	3692	13	50	5
76.2	150,000	20	2934	11	65	12
76.2	150,000	20	3208	9	61	9
76.2	150,000	20	3140	17	92	7

Appendix A- 17 Grain sorghum growth stage GS0 to GS9 according to Vanderlip 1979 and sorghum height for each row spacing (narrow=20- and 25-cm, wide=76-cm) and seeding rate each week for each treatment in Hays and Manhattan in 2014 (average of 2 plants per subplot). Treatments 0=weed-free by hand, 0.5=PRE herbicide, 2 to 5 (2014), 2 to 8 (2015) and 20 are weeks after sorghum emergence. "-"=no data.

				Hays				Manhattan			
				2014		2015		2014		2015	
Row Spacing	**Seeding density**	**Wk**	**Trt**	**GS**	**Height**	**GS**	**Height**	**GS**	**Height**	**GS**	**Height**
	Seed ha^{-1}				**cm**		**cm**		**cm**		**cm**
narrow	125,000	1	0	-	-	1	4	-	-	-	-
narrow	150,000	1	0	-	-	1	4	-	-	-	-
wide	125,000	1	0	-	-	1	4	-	-	-	-
wide	150,000	1	0	-	-	1	4	-	-	-	-
narrow	125,000	1	0.5	-	-	1	4	-	-	1	4
narrow	150,000	1	0.5	-	-	1	4	-	-	1	3
wide	125,000	1	0.5	-	-	1	4	-	-	1	4
wide	150,000	1	0.5	-	-	1	4	-	-	1	4
narrow	125,000	1	2	-	-	1	4	-	-	1	4
narrow	150,000	1	2	-	-	1	4	-	-	1	3
wide	125,000	1	2	-	-	1	4	-	-	1	4
wide	150,000	1	2	-	-	1	4	-	-	1	4
narrow	125,000	1	3	-	-	1	4	-	-	1	4
narrow	150,000	1	3	-	-	1	4	-	-	1	4
wide	125,000	1	3	-	-	1	3	-	-	1	4
wide	150,000	1	3	-	-	1	4	-	-	1	3
narrow	125,000	1	4	-	-	1	4	-	-	1	4
narrow	150,000	1	4	-	-	1	4	-	-	1	3
wide	125,000	1	4	-	-	1	4	-	-	1	4
wide	150,000	1	4	-	-	1	4	-	-	1	4

narrow	125,000	1	5	-	-	1	4	-	-	1	4
narrow	150,000	1	5	-	-	1	4	-	-	1	4
wide	125,000	1	5	-	-	1	4	-	-	1	4
wide	150,000	1	5	-	-	1	3	-	-	1	4
narrow	125,000	1	20	-	-	1	4	-	-	1	3
narrow	150,000	1	20	-	-	1	4	-	-	1	4
wide	125,000	1	20	-	-	1	4	-	-	1	4
wide	150,000	1	20	-	-	1	4	-	-	1	4
narrow	125,000	2	0	-	-	2	7	1	5	-	-
narrow	150,000	2	0	-	-	2	6	1	4	-	-
wide	125,000	2	0	-	-	2	7	1	5	-	-
wide	150,000	2	0	-	-	1	7	1	4	-	-
narrow	125,000	2	0.5	-	-	2	7	1	4	1	6
narrow	150,000	2	0.5	-	-	2	7	1	4	1	5
wide	125,000	2	0.5	-	-	1	7	1	5	1	6
wide	150,000	2	0.5	-	-	1	6	1	5	1	6
narrow	125,000	2	2	-	-	2	7	1	4	1	6
narrow	150,000	2	2	-	-	2	7	1	4	1	5
wide	125,000	2	2	-	-	1	6	1	4	1	6
wide	150,000	2	2	-	-	1	6	1	5	1	7
narrow	125,000	2	3	-	-	2	7	1	5	1	6
narrow	150,000	2	3	-	-	2	7	1	5	1	6
wide	125,000	2	3	-	-	1	6	1	4	1	6
wide	150,000	2	3	-	-	2	7	1	5	1	7
narrow	125,000	2	4	-	-	2	7	1	4	1	6
narrow	150,000	2	4	-	-	2	7	1	5	1	6
wide	125,000	2	4	-	-	1	7	1	5	1	6
wide	150,000	2	4	-	-	1	6	1	4	1	6
narrow	125,000	2	5	-	-	2	7	1	4	1	6
narrow	150,000	2	5	-	-	2	7	1	5	1	5

wide	125,000	2	5	-	-	1	6	1	4	1	6
wide	150,000	2	5	-	-	1	6	1	4	1	7
narrow	125,000	2	20	-	-	2	7	1	4	1	6
narrow	150,000	2	20	-	-	2	7	1	4	1	5
wide	125,000	2	20	-	-	1	6	1	4	1	6
wide	150,000	2	20	-	-	1	7	1	5	1	7
narrow	125,000	3	0	2	19	2	14	2	8	-	-
narrow	150,000	3	0	2	21	2	14	2	7	-	-
wide	125,000	3	0	2	19	2	15	2	8	-	-
wide	150,000	3	0	2	17	2	15	2	8	-	-
narrow	125,000	3	0.5	2	21	2	13	1	9	1	12
narrow	150,000	3	0.5	2	22	2	13	2	9	1	11
wide	125,000	3	0.5	2	18	2	15	2	9	1	11
wide	150,000	3	0.5	2	18	2	15	2	9	2	14
narrow	125,000	3	2	2	19	2	14	2	9	1	12
narrow	150,000	3	2	2	20	2	14	2	8	1	10
wide	125,000	3	2	2	18	2	14	1	8	1	13
wide	150,000	3	2	2	19	2	15	2	7	2	15
narrow	125,000	3	3	2	19	2	15	2	8	1	12
narrow	150,000	3	3	2	21	2	14	2	8	1	11
wide	125,000	3	3	2	20	2	15	2	7	1	14
wide	150,000	3	3	2	19	2	17	2	8	2	14
narrow	125,000	3	4	2	17	2	14	2	8	1	12
narrow	150,000	3	4	2	22	2	14	2	7	1	12
wide	125,000	3	4	2	18	2	15	2	8	1	12
wide	150,000	3	4	2	18	2	14	2	8	2	15
narrow	125,000	3	5	2	19	2	15	2	8	1	11
narrow	150,000	3	5	2	20	2	17	2	8	1	10
wide	125,000	3	5	2	18	2	14	2	7	1	13
wide	150,000	3	5	2	19	2	14	2	7	2	14

narrow	125,000	3	20	2	19	2	14	2	8	1	12
narrow	150,000	3	20	2	20	2	14	2	8	1	10
wide	125,000	3	20	2	18	2	14	2	7	1	12
wide	150,000	3	20	2	18	2	15	2	8	2	13
narrow	125,000	4	0	2	26	2	27	3	12	-	-
narrow	150,000	4	0	2	27	2	25	3	12	-	-
wide	125,000	4	0	3	25	2	26	3	12	-	-
wide	150,000	4	0	3	25	2	25	3	12	-	-
narrow	125,000	4	0.5	3	30	2	25	3	13	2	24
narrow	150,000	4	0.5	3	28	2	24	3	13	1	19
wide	125,000	4	0.5	3	26	2	26	3	12	2	23
wide	150,000	4	0.5	3	24	2	27	3	13	2	26
narrow	125,000	4	2	3	28	2	25	3	12	2	22
narrow	150,000	4	2	3	28	2	26	2	12	2	22
wide	125,000	4	2	3	25	2	25	3	12	2	25
wide	150,000	4	2	3	27	2	26	3	12	2	24
narrow	125,000	4	3	3	26	2	25	3	11	2	23
narrow	150,000	4	3	3	28	2	27	2	14	2	22
wide	125,000	4	3	3	29	2	26	3	11	2	24
wide	150,000	4	3	3	25	2	26	3	12	2	27
narrow	125,000	4	4	3	25	2	27	2	12	2	24
narrow	150,000	4	4	3	30	2	26	3	12	2	22
wide	125,000	4	4	3	25	2	25	3	12	2	24
wide	150,000	4	4	3	26	2	27	3	12	2	27
narrow	125,000	4	5	3	28	2	26	3	11	2	22
narrow	150,000	4	5	3	27	2	26	3	13	2	21
wide	125,000	4	5	3	27	2	25	2	11	2	24
wide	150,000	4	5	3	27	2	26	3	12	2	25
narrow	125,000	4	20	3	26	2	25	3	14	2	22
narrow	150,000	4	20	3	28	2	25	3	12	2	21

wide	125,000	4	20	3	26	2	27	3	11	2	25
wide	150,000	4	20	3	26	2	28	3	13	2	26
narrow	125,000	5	0	4	42	3	33	4	14	-	-
narrow	150,000	5	0	3	41	3	32	4	13	-	-
wide	125,000	5	0	3	38	3	33	4	13	-	-
wide	150,000	5	0	4	44	3	34	4	14	-	-
narrow	125,000	5	0.5	3	46	3	31	4	14	-	-
narrow	150,000	5	0.5	4	45	3	29	4	15	-	-
wide	125,000	5	0.5	4	44	3	33	4	14	-	-
wide	150,000	5	0.5	4	41	3	34	4	15	-	-
narrow	125,000	5	2	4	43	3	33	3	12	-	-
narrow	150,000	5	2	4	44	3	33	4	13	-	-
wide	125,000	5	2	4	38	3	32	4	14	-	-
wide	150,000	5	2	4	47	3	34	4	13	-	-
narrow	125,000	5	3	4	41	3	33	4	12	-	-
narrow	150,000	5	3	4	43	3	32	3	14	-	-
wide	125,000	5	3	3	45	3	35	4	13	-	-
wide	150,000	5	3	3	46	3	35	4	13	-	-
narrow	125,000	5	4	3	42	3	32	4	14	-	-
narrow	150,000	5	4	3	45	3	32	4	13	-	-
wide	125,000	5	4	3	40	3	35	4	13	-	-
wide	150,000	5	4	3	43	3	34	4	14	-	-
narrow	125,000	5	5	3	43	3	33	4	14	-	-
narrow	150,000	5	5	4	43	3	33	4	14	-	-
wide	125,000	5	5	3	39	3	31	3	12	-	-
wide	150,000	5	5	4	47	3	33	4	12	-	-
narrow	125,000	5	20	3	43	3	33	4	13	-	-
narrow	150,000	5	20	4	43	3	32	3	12	-	-
wide	125,000	5	20	3	45	3	34	4	13	-	-
wide	150,000	5	20	4	44	3	33	4	14	-	-

narrow	125,000	6	0	4	48	-	-	4	13	2	45
narrow	150,000	6	0	4	44	-	-	3	11	2	35
wide	125,000	6	0	4	45	-	-	4	13	2	42
wide	150,000	6	0	4	48	-	-	4	13	2	45
narrow	125,000	6	0.5	4	53	-	-	4	13	3	54
narrow	150,000	6	0.5	4	49	-	-	4	15	3	48
wide	125,000	6	0.5	4	48	-	-	4	13	3	50
wide	150,000	6	0.5	4	46	-	-	4	15	3	61
narrow	125,000	6	2	4	46	-	-	4	12	3	54
narrow	150,000	6	2	4	49	-	-	4	12	3	49
wide	125,000	6	2	4	43	-	-	4	12	3	56
wide	150,000	6	2	4	50	-	-	4	12	3	53
narrow	125,000	6	3	4	45	-	-	4	12	3	53
narrow	150,000	6	3	4	50	-	-	4	12	3	51
wide	125,000	6	3	4	48	-	-	4	12	3	54
wide	150,000	6	3	5	48	-	-	4	12	3	60
narrow	125,000	6	4	4	45	-	-	4	13	3	53
narrow	150,000	6	4	4	47	-	-	4	12	3	52
wide	125,000	6	4	4	45	-	-	4	12	3	53
wide	150,000	6	4	4	46	-	-	4	13	3	60
narrow	125,000	6	5	4	46	-	-	4	12	3	50
narrow	150,000	6	5	4	47	-	-	4	14	3	49
wide	125,000	6	5	4	45	-	-	4	11	3	53
wide	150,000	6	5	4	53	-	-	3	11	3	62
narrow	125,000	6	20	4	46	-	-	4	12	3	53
narrow	150,000	6	20	4	49	-	-	3	12	3	48
wide	125,000	6	20	4	47	-	-	4	13	3	54
wide	150,000	6	20	4	49	-	-	4	13	3	59
narrow	125,000	7	0	5	52	5	81	-	-	4	60
narrow	150,000	7	0	5	50	5	78	-	-	4	54

wide	125,000	7	0	5	51	5	80	-	-	4	64
wide	150,000	7	0	5	55	5	83	-	-	4	66
narrow	125,000	7	0.5	5	60	5	81	-	-	5	86
narrow	150,000	7	0.5	5	52	5	78	-	-	5	77
wide	125,000	7	0.5	5	53	5	80	-	-	5	83
wide	150,000	7	0.5	5	54	5	82	-	-	5	88
narrow	125,000	7	2	5	55	5	78	-	-	5	85
narrow	150,000	7	2	5	56	5	79	-	-	5	83
wide	125,000	7	2	5	48	5	81	-	-	5	88
wide	150,000	7	2	5	51	5	84	-	-	6	89
narrow	125,000	7	3	5	45	5	80	-	-	4	86
narrow	150,000	7	3	5	54	5	82	-	-	5	81
wide	125,000	7	3	5	59	5	83	-	-	5	88
wide	150,000	7	3	5	54	5	81	-	-	5	90
narrow	125,000	7	4	5	52	5	79	-	-	5	87
narrow	150,000	7	4	5	54	5	82	-	-	5	80
wide	125,000	7	4	5	51	5	84	-	-	5	84
wide	150,000	7	4	5	52	5	78	-	-	5	90
narrow	125,000	7	5	5	51	5	80	-	-	4	77
narrow	150,000	7	5	5	51	5	79	-	-	5	79
wide	125,000	7	5	5	54	5	80	-	-	5	86
wide	150,000	7	5	5	58	5	82	-	-	5	88
narrow	125,000	7	20	5	51	5	81	-	-	5	82
narrow	150,000	7	20	5	51	5	16	-	-	4	70
wide	125,000	7	20	5	53	5	20	-	-	5	84
wide	150,000	7	20	5	53	5	20	-	-	5	88
narrow	125,000	8	0	5	65	6	-	5	29	5	78
narrow	150,000	8	0	5	62	6	-	5	26	5	73
wide	125,000	8	0	6	67	6	-	5	29	5	56
wide	150,000	8	0	5	69	6	-	5	28	5	58

narrow	125,000	8	0.5	6	78	6	-	5	28	6	-
narrow	150,000	8	0.5	6	67	6	-	5	29	6	-
wide	125,000	8	0.5	6	69	6	-	5	30	6	-
wide	150,000	8	0.5	6	67	6	-	5	32	6	-
narrow	125,000	8	2	6	70	6	-	5	24	6	-
narrow	150,000	8	2	6	72	6	-	5	26	6	-
wide	125,000	8	2	5	57	6	-	5	33	6	-
wide	150,000	8	2	6	72	6	-	5	25	6	-
narrow	125,000	8	3	6	58	6	-	5	24	6	-
narrow	150,000	8	3	6	69	6	-	5	25	6	-
wide	125,000	8	3	6	74	6	-	5	23	6	-
wide	150,000	8	3	6	69	6	-	5	25	6	-
narrow	125,000	8	4	5	65	6	-	5	27	6	-
narrow	150,000	8	4	6	68	6	-	5	25	6	-
wide	125,000	8	4	5	65	7	-	5	24	6	-
wide	150,000	8	4	6	68	6	-	5	27	6	-
narrow	125,000	8	5	5	60	6	-	5	26	6	-
narrow	150,000	8	5	5	67	6	-	5	25	6	-
wide	125,000	8	5	6	67	6	-	5	23	6	-
wide	150,000	8	5	6	69	6	-	5	21	6	-
narrow	125,000	8	20	6	64	6	-	5	27	6	-
narrow	150,000	8	20	5	65	6	-	5	25	6	-
wide	125,000	8	20	6	67	6	-	5	27	6	-
wide	150,000	8	20	5	64	6	-	5	27	6	-
narrow	125,000	9	0	-	-	7	-	6	31	5	-
narrow	150,000	9	0	-	-	7	-	6	29	5	-
wide	125,000	9	0	-	-	7	-	6	32	5	-
wide	150,000	9	0	-	-	7	-	6	31	6	-
narrow	125,000	9	0.5	-	-	7	-	6	31	6	-
narrow	150,000	9	0.5	-	-	6	-	6	32	6	-

wide	125,000	9	0.5	-	-	7	-	6	31	6	-
wide	150,000	9	0.5	-	-	7	-	6	33	6	-
narrow	125,000	9	2	-	-	7	-	6	29	6	-
narrow	150,000	9	2	-	-	7	-	6	31	6	-
wide	125,000	9	2	-	-	7	-	6	31	6	-
wide	150,000	9	2	-	-	7	-	5	27	6	-
narrow	125,000	9	3	-	-	7	-	6	28	6	-
narrow	150,000	9	3	-	-	7	-	6	29	6	-
wide	125,000	9	3	-	-	7	-	6	26	6	-
wide	150,000	9	3	-	-	7	-	6	31	6	-
narrow	125,000	9	4	-	-	7	-	6	29	6	-
narrow	150,000	9	4	-	-	7	-	6	32	6	-
wide	125,000	9	4	-	-	7	-	6	28	6	-
wide	150,000	9	4	-	-	7	-	6	31	6	-
narrow	125,000	9	5	-	-	7	-	6	30	6	-
narrow	150,000	9	5	-	-	7	-	6	32	6	-
wide	125,000	9	5	-	-	7	-	6	27	6	-
wide	150,000	9	5	-	-	7	-	6	26	6	-
narrow	125,000	9	20	-	-	7	-	6	31	6	-
narrow	150,000	9	20	-	-	7	-	6	31	6	-
wide	125,000	9	20	-	-	7	-	6	30	6	-
wide	150,000	9	20	-	-	7	-	6	29	6	-
narrow	125,000	10	0	6	65	7	-	7	-	7	-
narrow	150,000	10	0	6	62	7	-	7	-	6	-
wide	125,000	10	0	6	67	7	-	7	-	6	-
wide	150,000	10	0	6	70	7	-	7	-	7	-
narrow	125,000	10	0.5	6	78	7	-	7	-	7	-
narrow	150,000	10	0.5	6	67	7	-	7	-	7	-
wide	125,000	10	0.5	6	69	7	-	7	-	7	-
wide	150,000	10	0.5	6	67	7	-	7	-	7	-

narrow	125,000	10	2	6	70	7	-	7	-	7	-
narrow	150,000	10	2	6	72	7	-	7	-	7	-
wide	125,000	10	2	6	57	7	-	7	-	7	-
wide	150,000	10	2	6	73	7	-	7	-	7	-
narrow	125,000	10	3	6	58	7	-	7	-	7	-
narrow	150,000	10	3	6	69	7	-	7	-	7	-
wide	125,000	10	3	6	74	7	-	7	-	7	-
wide	150,000	10	3	6	69	7	-	7	-	7	-
narrow	125,000	10	4	6	65	7	-	7	-	7	-
narrow	150,000	10	4	6	68	7	-	7	-	7	-
wide	125,000	10	4	6	65	7	-	7	-	7	-
wide	150,000	10	4	6	69	7	-	7	-	7	-
narrow	125,000	10	5	6	60	7	-	7	-	7	-
narrow	150,000	10	5	6	67	7	-	7	-	7	-
wide	125,000	10	5	6	67	7	-	7	-	7	-
wide	150,000	10	5	6	70	7	-	7	-	7	-
narrow	125,000	10	20	6	64	7	-	7	-	7	-
narrow	150,000	10	20	6	65	7	-	7	-	7	-
wide	125,000	10	20	6	67	7	-	7	-	7	-
wide	150,000	10	20	6	64	7	-	7	-	7	-
narrow	125,000	11	0	7	-	7	-	7	-	8	-
narrow	150,000	11	0	7	-	7	-	7	-	7	-
wide	125,000	11	0	7	-	7	-	7	-	7	-
wide	150,000	11	0	7	-	7	-	7	-	8	-
narrow	125,000	11	0.5	7	-	7	-	7	-	8	-
narrow	150,000	11	0.5	8	-	7	-	7	-	8	-
wide	125,000	11	0.5	7	-	7	-	7	-	8	-
wide	150,000	11	0.5	7	-	7	-	7	-	8	-
narrow	125,000	11	2	7	-	7	-	7	-	8	-
narrow	150,000	11	2	8	-	7	-	7	-	8	-

wide	125,000	11	2	7	-	7	-	7	-	8	-
wide	150,000	11	2	7	-	7	-	7	-	8	-
narrow	125,000	11	3	7	-	7	-	7	-	8	-
narrow	150,000	11	3	7	-	7	-	7	-	8	-
wide	125,000	11	3	8	-	7	-	7	-	8	-
wide	150,000	11	3	7	-	7	-	7	-	8	-
narrow	125,000	11	4	7	-	7	-	7	-	8	-
narrow	150,000	11	4	8	-	7	-	7	-	8	-
wide	125,000	11	4	7	-	7	-	7	-	8	-
wide	150,000	11	4	7	-	7	-	7	-	8	-
narrow	125,000	11	5	7	-	7	-	7	-	8	-
narrow	150,000	11	5	7	-	7	-	7	-	8	-
wide	125,000	11	5	8	-	7	-	7	-	8	-
wide	150,000	11	5	7	-	7	-	7	-	8	-
narrow	125,000	11	20	7	-	7	-	7	-	8	-
narrow	150,000	11	20	7	-	7	-	7	-	8	-
wide	125,000	11	20	7	-	7	-	7	-	8	-
wide	150,000	11	20	7	-	7	-	7	-	8	-
narrow	125,000	12	0	8	-	8	-	8	-	8	-
narrow	150,000	12	0	8	-	8	-	8	-	7	-
wide	125,000	12	0	8	-	8	-	8	-	7	-
wide	150,000	12	0	8	-	8	-	8	-	8	-
narrow	125,000	12	0.5	8	-	8	-	8	-	8	-
narrow	150,000	12	0.5	8	-	8	-	8	-	8	-
wide	125,000	12	0.5	8	-	8	-	8	-	8	-
wide	150,000	12	0.5	8	-	8	-	8	-	8	-
narrow	125,000	12	2	8	-	8	-	8	-	8	-
narrow	150,000	12	2	8	-	8	-	8	-	8	-
wide	125,000	12	2	8	-	8	-	8	-	8	-
wide	150,000	12	2	8	-	8	-	8	-	8	-

narrow	125,000	12	3	8	-	8	-	8	-	8	-
narrow	150,000	12	3	8	-	8	-	8	-	8	-
wide	125,000	12	3	8	-	8	-	8	-	8	-
wide	150,000	12	3	8	-	8	-	8	-	8	-
narrow	125,000	12	4	8	-	8	-	8	-	8	-
narrow	150,000	12	4	8	-	8	-	8	-	8	-
wide	125,000	12	4	8	-	8	-	8	-	8	-
wide	150,000	12	4	8	-	8	-	8	-	8	-
narrow	125,000	12	5	8	-	8	-	8	-	8	-
narrow	150,000	12	5	8	-	8	-	8	-	8	-
wide	125,000	12	5	8	-	8	-	8	-	8	-
wide	150,000	12	5	8	-	8	-	8	-	8	-
narrow	125,000	12	20	8	-	8	-	8	-	8	-
narrow	150,000	12	20	8	-	8	-	8	-	8	-
wide	125,000	12	20	8	-	8	-	8	-	8	-
wide	150,000	12	20	8	-	8	-	8	-	8	-
narrow	125,000	13	0	9	-	9	-	8	-	9	-
narrow	150,000	13	0	9	-	9	-	8	-	9	-
wide	125,000	13	0	9	-	9	-	8	-	9	-
wide	150,000	13	0	9	-	9	-	8	-	9	-
narrow	125,000	13	0.5	9	-	9	-	8	-	9	-
narrow	150,000	13	0.5	9	-	9	-	8	-	9	-
wide	125,000	13	0.5	9	-	9	-	8	-	9	-
wide	150,000	13	0.5	9	-	9	-	8	-	9	-
narrow	125,000	13	2	9	-	9	-	8	-	9	-
narrow	150,000	13	2	9	-	9	-	8	-	9	-
wide	125,000	13	2	9	-	9	-	8	-	9	-
wide	150,000	13	2	9	-	9	-	8	-	9	-
narrow	125,000	13	3	9	-	9	-	8	-	9	-
narrow	150,000	13	3	9	-	9	-	8	-	9	-

wide	125,000	13	3	9	-	9	-	8	-	9	-
wide	150,000	13	3	9	-	9	-	8	-	9	-
narrow	125,000	13	4	9	-	9	-	8	-	9	-
narrow	150,000	13	4	9	-	9	-	8	-	9	-
wide	125,000	13	4	9	-	9	-	8	-	9	-
wide	150,000	13	4	9	-	9	-	8	-	9	-
narrow	125,000	13	5	9	-	9	-	8	-	9	-
narrow	150,000	13	5	9	-	9	-	8	-	9	-
wide	125,000	13	5	9	-	9	-	8	-	9	-
wide	150,000	13	5	9	-	9	-	8	-	9	-
narrow	125,000	13	20	9	-	9	-	8	-	8	-
narrow	150,000	13	20	9	-	9	-	8	-	8	-
wide	125,000	13	20	9	-	9	-	8	-	8	-
wide	150,000	13	20	9	-	9	-	8	-	8	-
narrow	125,000	14	0	9	-	9	-	9	-	9	-
narrow	150,000	14	0	9	-	9	-	9	-	9	-
wide	125,000	14	0	9	-	9	-	9	-	9	-
wide	150,000	14	0	9	-	9	-	9	-	9	-
narrow	125,000	14	0.5	9	-	9	-	9	-	9	-
narrow	150,000	14	0.5	9	-	9	-	9	-	9	-
wide	125,000	14	0.5	9	-	9	-	9	-	9	-
wide	150,000	14	0.5	9	-	9	-	9	-	9	-
narrow	125,000	14	2	9	-	9	-	9	-	9	-
narrow	150,000	14	2	9	-	9	-	9	-	9	-
wide	125,000	14	2	9	-	9	-	9	-	9	-
wide	150,000	14	2	9	-	9	-	9	-	9	-
narrow	125,000	14	3	9	-	9	-	9	-	9	-
narrow	150,000	14	3	9	-	9	-	9	-	9	-
wide	125,000	14	3	9	-	9	-	9	-	9	-
wide	150,000	14	3	9	-	9	-	9	-	9	-

narrow	125,000	14	4	9	-	9	-	9	-	9	-
narrow	150,000	14	4	9	-	9	-	9	-	9	-
wide	125,000	14	4	9	-	9	-	9	-	9	-
wide	150,000	14	4	9	-	9	-	9	-	9	-
narrow	125,000	14	5	9	-	9	-	9	-	9	-
narrow	150,000	14	5	9	-	9	-	9	-	9	-
wide	125,000	14	5	9	-	9	-	9	-	9	-
wide	150,000	14	5	9	-	9	-	9	-	9	-
narrow	125,000	14	20	9	-	9	-	9	-	9	-
narrow	150,000	14	20	9	-	9	-	9	-	9	-
wide	125,000	14	20	9	-	9	-	9	-	9	-
wide	150,000	14	20	9	-	9	-	9	-	9	-
narrow	125,000	15	0	9	-	9	-	9	-	9	-
narrow	150,000	15	0	9	-	9	-	9	-	9	-
wide	125,000	15	0	9	-	9	-	9	-	9	-
wide	150,000	15	0	9	-	9	-	9	-	9	-
narrow	125,000	15	0.5	9	-	9	-	9	-	9	-
narrow	150,000	15	0.5	9	-	9	-	9	-	9	-
wide	125,000	15	0.5	9	-	9	-	9	-	9	-
wide	150,000	15	0.5	9	-	9	-	9	-	9	-
narrow	125,000	15	2	9	-	9	-	9	-	9	-
narrow	150,000	15	2	9	-	9	-	9	-	9	-
wide	125,000	15	2	9	-	9	-	9	-	9	-
wide	150,000	15	2	9	-	9	-	9	-	9	-
narrow	125,000	15	3	9	-	9	-	9	-	9	-
narrow	150,000	15	3	9	-	9	-	9	-	9	-
wide	125,000	15	3	9	-	9	-	9	-	9	-
wide	150,000	15	3	9	-	9	-	9	-	9	-
narrow	125,000	15	4	9	-	9	-	9	-	9	-
narrow	150,000	15	4	9	-	9	-	9	-	9	-

wide	125,000	15	4	9	-	9	-	9	-	9	-
wide	150,000	15	4	9	-	9	-	9	-	9	-
narrow	125,000	15	5	9	-	9	-	9	-	9	-
narrow	150,000	15	5	9	-	9	-	9	-	9	-
wide	125,000	15	5	9	-	9	-	9	-	9	-
wide	150,000	15	5	9	-	9	-	9	-	9	-
narrow	125,000	15	20	9	-	9	-	9	-	9	-
narrow	150,000	15	20	9	-	9	-	9	-	9	-
wide	125,000	15	20	9	-	9	-	9	-	9	-
wide	150,000	15	20	9	-	9	-	9	-	9	-