Evaluation of herbicide programs in acetolactate synthase-resistant grain sorghum

by

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Abstract

The acetolactate synthase inhibitor herbicide-resistant grain sorghum technology introduced will allow for the application of nicosulfuron for postemergence (POST) grass control, however it is essential to determine a program-based approach to ensure broad spectrum weed control. Field experiments were conducted at three locations across Kansas in 2015 and 2016 to assess a range of possible herbicide programs for grass and broadleaf weed control and crop tolerance using Inzen™ Sorghum. The experiments consisted of 1 early pre-plant (EPP), 2 preemergence (PRE), and 3 POST, and 5 PRE followed by POST herbicide treatments. Weed control and crop response were evaluated visually at 1, 2, and 4 weeks after POST treatment (WAPT). Treatments containing nicosulfuron and/or bromoxynil & pyrasulfotole caused 10 to 20% crop injury at 1 WAPT in both 2015 and 2016 at the three locations. Treatments containing nicosulfuron + dicamba caused up to 30% injury with more injury in 2015 than in 2016. In 2015 at Manhattan the nicosulfuron-only treatment provided 64% control of Palmer amaranth and, when tank mixed with dicamba or bromoxynil & pyrasulfotole, control ranged from 71 to 76%. When nicosulfuron POST followed PRE of *S*-metolachlor & atrazine, Palmer amaranth control was 96 to 100%. At both locations, nicosulfuron provided 35, 55, and 61% control of large crabgrass, yellow foxtail, and stinkgrass, respectively. Annual grass control ranged from 85 to 100% when nicosulfuron followed a PRE *S*-metolachlor & atrazine. Greenhouse experiments were set up to determine the efficacy of nicosulfuron on four annual grass species at six different rates, two different rates, and the addition of atrazine. The four grass species evaluated were large crabgrass, yellow foxtail, barnyardgrass, and wheat. Nicosulfuron was applied at 0.125, 0.25, 0.5, 1, 2 times its labeled rate of 35 g ha^{-1}. A full factorial of rate by height by atrazine was

applied for a total of 24 treatments replicated 4 times on each species. Each nicosulfuron rate was applied with and without atrazine at 840 g ha^{-1} on 5 to 10 cm tall plants and on 15 to 20 cm tall plants. Visual ratings were taken 1, 2, and 4 weeks after treatment (WAT). Aboveground biomass was harvested 4 WAT, dried and weighed. Treatments containing nicosulfuron from 4.4 to 70 g ha^{-1} all caused similar reduction in biomass compared to the nontreated check. Averaged over the inclusion of atrazine, nicosulfuron applied at 35 and 70 g ha^{-1} provided 17% less control when treating 15 to 20 cm large crabgrass compared to the 5 to 10 cm large crabgrass, respectively. Overall barnyardgrass, yellow foxtail, and wheat can be effectively controlled with nicosulfuron when applied at proper heights, rate, and atrazine.

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Chapter 1 - Literature Review

Grain sorghum (*Sorghum bicolor* (L.) Moench ssp. *bicolor*) is considered the fifth most important cereal crop worldwide (Peterson et al. 2011). Grain sorghum is more adapted than corn (*Zea mays* L.) to a semi-arid climate such as the Great Plains because grain sorghum can tolerate drought better by certain traits introduced by breeding (Stahlman and Wicks, 2000). Kansas currently ranks first in the United States with 1,052,182 hectares harvested in 2017 (USDA-NASS, 2017). The number of hectares planted decreased in the late 1990's and the area planted has remained fairly steady since then. Grain sorghum is known as a drought-tolerant crop that also provides high-energy protein to the end user. This crop is also known for its ease of adaptation and versatility. Due to the ability for this crop to be grown in a wide range of environments it is essential to continue to improve and maintain grain sorghum production worldwide (National Sorghum Producers, 2017).

Weed management, especially grass weeds, can be a challenging task in grain sorghum. Currently there are not many effective POST grass weed control options in grain sorghum. In 2017, DuPont Crop Protection is expecting to launch their new herbicide-tolerant technology branded Inzen™ Sorghum. This herbicide tolerant traits allows for the POST application of nicosulfuron to be applied, which is aimed to provide annual grass control in Inzen™ Sorghum. With the expected launch of this new technology there is an opportunity to explore different options for grass weed management in grain sorghum production. Work has been done with the herbicide nicosulfuron and its efficacy on annual grass control in corn as well as grain sorghum (Tapia et al. 1997; Hennigh, 2009; Currie and Geier, 2015). Challenges will be brought forward by this technology such as: managing weeds that are already resistant to nicosulfuron, hybridization with weedy relatives of grain sorghum, and the importance of crop rotation to make this technology last.

Weed Management in Grain Sorghum

Weed control in grain sorghum can have its challenges. Producers mainly rely on herbicides to control weeds, but control can be achieved in a number of different ways. It is important to integrate multiple practices such as herbicides and crop rotations to gain weed control early in grain sorghum (Stahlman and Wicks, 2000). There are also biological factors that can be used to help achieve adequate control of weeds (Stahlman and Wicks, 2000). These authors point out that the species of weeds have shifted from broadleaf weeds to grass weeds. They also highlight shattercane (*Sorghum bicolor* (L.) Moench ssp. *verticilliflorum* (Steud.) de Wet ex Wiersema & J. Dahlb) as a serious weed in grain sorghum from western Texas to South Dakota. With the current total number of resistant weeds species being 16 in Kansas (Heap, 2017), the need for additional tools other than relying on herbicides to control weeds is very much a serious issue. Understanding the timing of weed emergence and weed to crop competition will allow for the ability to better manage weeds in grain sorghum (Burnside and Wicks, 1967).

Weeds compete with grain sorghum for light, nutrients, and soil water, which can greatly reduce yields and lead to more input costs that will ultimately decrease profitability. Cool and adverse conditions early in the growing season can lead to slow growth rates of grain sorghum, which can make it difficult for grain sorghum to compete with weeds (Ross and Webster, 1970). Grain sorghum yield loss from weed competition normally ranges from 30 to 50% but can increase under situations. Yellow foxtail and pigweed species caused 44 and 45%, respectively. (Bridges 1992; Burnside and Wicks, 1967; 1972). According to Bridges (1992), in the absence of herbicides, the average grain yield loss was 27% because of weed interference in seven central and southern Great Plains states compared to 35% yield loss across all grain sorghum producing states. Data from Shipley and Wiese (1969) suggests that broadleaf weeds consumed about 2.7 times more potassium than the grain sorghum whereas annual grasses consumed about half as much potassium as grain sorghum. These data indicate one reason why broadleaf weeds can potentially cause greater yield losses than annual grasses. Burnside and Wicks (1967) reported that no yield loss occurred when weeds were removed within three weeks after planting as long as the crop remained weed-free for the remainder of the growing season. They did note that weeds removed after the 3-week window, that is, at 4, 5, 6, and 8 weeks, caused significant yield losses.

Tillage is a method that has long been used to control weeds. Tillage can be used in preparation before planting or within the grain sorghum crop as an in-row cultivation. With the increase of conservation practices there is a shift from tillage to no-tillage production. Also, in recent years producers are beginning to adopt a more integrated approach that uses cultural, mechanical, and chemical methods to control weeds (Price et al. 2011). These new practices have opened the door for more of a reduced tillage plan rather than a strict no-till plan. The reason for the recent increase in mechanical weed control has mainly been the increase of herbicide-resistant weeds, where producers weren't able to control weeds using only herbicides (Price et al. 2011).

Currently, Norsworthy et al. (2012) developed a list of best management practices (BMPs) to control weeds and reduce occurrence of herbicide resistance. There are certain BMPs that are related closely to my research on weed control in grain sorghum. With the number of herbicide-resistant weeds present, it is important to use multiple effective sites of action to control weeds. As herbicides are the most widely-used tool to control weeds, this BMP should be the one most discussed. Many weeds are now resistant to herbicides such as glyphosate; therefore if the population is resistant to glyphosate, this herbicide would not be considered an effective site of action in that program. The greatest risk element for herbicide resistance is the repeated use of the same site of action year after year on the same location (Beckie, 2006). Using multiple effective sites of action is important, but also very important is to control these weeds using the appropriate herbicide rate within label sizes. Labels are developed to make sure that labeled rates are safe to the public and still be able to control weeds effectively. A greenhouse study showed that rigid ryegrass became resistant to diclofop after repeated use of below-labeled herbicide rates (Manalil et al. 2011). When herbicide labels are not followed, efficacy can be reduced as well as encouraging the development of resistance. When battling resistance it is also important to manage field edges. The borders of fields can harbor weeds with herbicide-resistant genes, such as glyphosate resistance, which can move back into the field in subsequent years (Boutin and Jobin, 1998). It is also very important to prevent weed seed movement. Machinery can move seeds further than they normally would by natural movement (Verkaar et al. 1983). Natural seed dispersal from the host plant is usually not greater than 5 m for most weed species (Verkaar et al. 1983). Thill and Mallory-Smith (1997) stated that planting weed-free crop seed is the front line in preventing the introduction of new weeds into fields and also an important step in preventing the spread of herbicide resistance. It is also important that scouting frequently will insure that the previous practices that were implemented continue to work through the growing season. Developing a field scouting strategy that covers the entire field is essential to properly document new or existing weed populations (Clay and Johnson, 2002).

Nicosulfuron control of annual grass weeds

Nicosulfuron is an herbicide that is in the sulfonylurea class of herbicides. E.I DuPont de Numours & Co discovered the first sulfonylurea herbicides in the 1970's (Hay 1990). According to a fact sheet by Environmental Protection Agency (EPA, 1990), nicosulfuron became registered for use in 1990. Sulfonylurea herbicides are environmentally desirable due to low use rates (e.g., nicosulfuron 35 g ha^{-1}) and low mammalian toxicity that ranges from greater than 2000 mg kg^{-1} for dermal toxicity to greater than 5000 mg kg^{-1} for oral toxicity (EPA 1990). Sulfonylurea herbicides were the first class of herbicides discovered that inhibit acetolactate synthase (ALS), an enzyme in the first step in the synthesis of the branched chain amino acids valine, leucine, and isoleucine (Harms et al. 1990).

Nicosulfuron is known to control grass weeds such as shattercane, giant foxtail (*Setaria faberi* Herrm.) and woolly cupgrass (*Eriochloa villosa* (Thunb.) Kunth) (Tapia et al. 1997). Since its introduction in 1990 to control grass weeds in corn, there has been speculation on the efficacy of nicosulfuron when applied POST in regards to size of grass weeds at time of application. Tapia et al. (1997) found that nicosulfuron applied POST had a lower efficacy on woolly cupgrass than the PRE herbicide, which consisted of metolachlor and atrazine. A POST application of nicosulfuron at 35 g ha^{-1} was the most effective on wild-proso millet, giant foxtail, and woolly cupgrass, with an average of 87 to 88% control when the weeds were 5 to 10 cm in height (Tapia et al. 1997). When weeds were treated at 15 to 25 cm tall, with a nicosulfuron rate of 70 g ha^{-1}, giant foxtail control remained consistent at 90% whereas wild-proso millet and woolly cupgrass control dropped significantly to 43 and 77%, respectively. Hennigh (2009) reported similar findings, overall grass control using nicosulfuron at 35 g ha^{-1} ranged from 44 to 83% at 4 weeks after treatment across four field locations, Garden City, Hays, Hesston, and Manhattan, KS. When comparing efficacy of POST nicosulfuron to a PRE application of *S*-metolachlor and atrazine across the four locations, the PRE was more effective at controlling annual grasses (Hennigh, 2009). When comparing efficacy of POST nicosulfuron to a PRE application of *S*-metolachlor and atrazine across the four locations, the PRE was more effective at controlling annual grasses (Hennigh, 2009). Control ranged from 96 to 100% with the *S*-metolachlor and atrazine treatment, also the lack of weed control with nicosulfuron applied alone caused a significant yield loss compared to the PRE of *S*-metolachlor and atrazine across all four locations. Overall most treatments containing nicosulfuron outperformed the PRE treatment of metolachlor and atrazine in field studies, when evaluating giant foxtail, woolly cupgrass, and wild-proso millet (Tapia et al. 1997).

Grain sorghum yield ranged from 0 to 3,034 kg ha^{-1} in the nicosulfuron only treatment compared to 2,384 to 5,246 kg ha^{-1} in the PRE *S*-metolachlor and atrazine treatment across the four locations (Hennigh, 2009). Corn yields were most affected by giant foxtail, as grain yield increased as giant foxtail control increased, especially when the weeds were less than 10 cm tall. Once the weeds reached 10 cm or more before being treated, grain yield was reduce significantly (Tapia et al. 1997).

There are several annual grasses that commonly cause yield losses in grain sorghum. The most common species in Kansas are large crabgrass (*Digitaria sanguinalis* (L.) Scop.), yellow foxtail (*Setaria pumila* (Poir.) Roem. & Schult), barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.), and longspine sandbur (*Cenchrus longispinus* (Hack.) Fernald). Feltner et al. (1969) showed that a natural population of yellow foxtail decreased grain sorghum yields by 33%.

Large crabgrass and barnyardgrass decreased grain yield as well. Grain sorghum yield loss with barnyardgrass and large crabgrass growing for 8 weeks after planting was 27 and 30%, respectively in Oklahoma (Smith et al. 1990).

Hennigh (2009) conducted a greenhouse study to look at the efficacy of nicosulfuron on large crabgrass, barnyardgrass, and longspine sandbur. The results indicated that control with nicosulfuron differs by species. The nicosulfuron rate to reduce barnyardgrass, longspine sandbur, and large crabgrass growth by 50% were 10.9, 21.7, and 25.5 g ha^{-1}, respectively. Less nicosulfuron was needed for longspine sandbur compared to large crabgrass in the greenhouse study. Currie and Geier (2015) conducted a field study in southwest Kansas to determine the efficacy of nicosulfuron in controlling annual grasses. This study suggests that nicosulfuron provided adequate control of green foxtail and shattercane 62 days after planting when applied at 35 g ha^{-1}. Control of green foxtail applied with nicosulfuron alone ranged from 83 to 88% as for shattercane nicosulfuron controlled all treatments 100%. Unlike Tapia et al. (1997) this study suggested that a PRE application of *S*-metolachlor and atrazine yielded both 100% control of shattercane and green foxtail. Large crabgrass was controlled similarly with the PRE herbicide and the POST only of nicosulfuron, and control ranged from 60 to 80%. When a PRE herbicide was used in conjunction with nicosulfuron large crabgrass control was 94%. It was noted in this study that nicosulfuron did not control the broadleaf weed species, Palmer amaranth, but PRE herbicide followed by a POST did provide 100% control of Palmer amaranth. This scenario highlights the importance of having multiple effective herbicide sites of action in a weed control program.

Distribution of Herbicide-Resistant Shattercane and Johnsongrass and Gene Flow

One major issue with the release of ALS-tolerant grain sorghum (Inzen^{TM}) is presence or development of ALS-resistant weeds especially shattercane and johnsongrass (*Sorghum halepense* (L.) Pers.). There are currently eight species that are resistant to nicosulfuron including these two relatives of grain sorghum (Heap 2017). The ALS-resistant gene that is in Inzen^{TM} Sorghum was originally discovered in a shattercane population found in southwest Kansas (Tuinstra and Al-Khatib, 2008). Knowing that ALS-resistant shattercane and johnsongrass populations exist prompted studies across Kansas and Nebraska in 2014 to assess the abundance of ALS-resistant shattercane and johnsongrass populations (Werle et al. 2015). A total of 190 shattercane and 59 johnsongrass populations were sampled from across northern Kansas into Nebraska and northwest Missouri. Seed were then planted into a field to screen for resistance to ALS-inhibitor herbicides. This field screen identified seven shattercane populations that showed some level of resistance to sulfonylurea herbicides, with two populations showing full resistance and five showing intermediate resistance. The johnsongrass populations in this study yielded 2 resistant and 1 intermediate population. These resistant populations were further screened via a dose response study in the greenhouse. These populations were exposed to 7 different rates of herbicide ranging 0.5X to 32X the normal use rate of nicosulfuron. The dose response confirmed nicosulfuron resistance of 4 and 3 populations of shattercane and johnsongrass, respectively. There were two shattercane populations that showed resistance greater than 1000 fold when compared to a susceptible GR_{50} value. The importance of this study was to show the distribution of this resistance and prove that the resistant gene was still abundant in this region. Werle et al. (2015) stated that the first case of nicosulfuron resistance came from

Thayer County Nebraska in 1999 (Lee et al. 1999). There was a population collected from Thayer County, NE in this study that was still resistant to nicosulfuron many years later. Nicosulfuron was used on a regular basis in corn production before glyphosate-resistant crops meaning that this resistance has been around in these populations for a number of years. Knowing that ALS-resistant johnsongrass and shattercane are present in this geography further solidifies the point to manage gene escape from ALS-resistant grain sorghum. Modeling work has been conducted to show the importance of rotating crops to avoid the possibility the resistant allele being present in further generations by outcrossing into weedy species of sorghum (Werle et al. 2015).

Another potential issue with the Inzen™ Sorghum is that grain sorghum has the ability to interbreed closely with shattercane. This sets up the potential for the ALS resistance gene to be transferred from grain sorghum to its wild relative shattercane. The potential rate of hybridization of shattercane with grain sorghum was studied with a centralized area of grain sorghum and shattercane was planted in concentric arcs spaced 1, 3, 5, 10, 20, 40, 60, 100, and 200 m from the edge of the grain sorghum source (Schmidt et al. 2013). This study indicated that at 200 m outcrossing occurred in 12% of the panicles in 2008 and 41% of the panicles in 2009 showed outcrossing. When looking at closer distances to the grain sorghum results showed that 60 m or less showed 65% and 78% outcrossing of observed panicles in 2008 and 2009, respectively. This study did conclude that wind speed and wind direction play a significant impact on the outcrossing rate (Schmidt et al. 2013).

This literature review highlighted the potential for gene escape of the ALS-resistant sorghum into shattercane. It will be vital to use the BMPs as outlined by Norsworthy et al.

(2012) to minimize gene escape from this crop. It is also important to know if ALS-resistant shattercane or johnsongrass are present in the grain sorghum field before spraying nicosulfuron.

The overall goal of this research project is to evaluate herbicide programs for grass and broadleaf weed control in Inzen™ Sorghum. The specific objectives are to 1) evaluate PRE and/or POST herbicide programs for grass and broadleaf weed control and crop tolerance in ALS-resistant grain sorghum at Manhattan, Hutchinson, and Tribune, KS in 2015 and 2016, and 2) determine the dose response of nicosulfuron applied with and without atrazine of four annual grass species large crabgrass, barnyardgrass, yellow foxtail, and wheat and at two different weed heights of 5 to 10 and 15 to 20 cm.

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Chapter 2 - Evaluation of Herbicide Programs in Acetolactate Synthase (ALS) Inhibitor-Resistant Grain Sorghum

Abstract

New sorghum technology branded Inzen^{TM} Sorghum is being developed. This technology allows applications of sulfonylurea herbicides to be applied both preemergence (PRE) and postemergence (POST) for control of annual grass weeds. The objective was to evaluate a range of possible herbicide programs for grass and broadleaf weed control and crop tolerance using Inzen^{TM} Sorghum. Field experiments were conducted at three locations across Kansas in both 2015 and 2016. Each experiment was a randomized complete block design with four replications that had 11 treatments in 2015 and 12 in 2016. The treatments consisted of early pre-plant (EPP), PRE, and POST herbicide applications. Weed control and crop response were evaluated visually at 1, 2, and 4 weeks after POST treatment (WAPT). Treatments containing nicosulfuron and/or bromoxynil & pyrasulfotole caused 10 to 20% crop injury at 1 WAPT in both 2015 and 2016 at the three locations. Treatments containing nicosulfuron + dicamba caused up to 30% injury. When nicosulfuron POST followed PRE of *S*-metolachlor & atrazine, Palmer amaranth control was 96 to 100%. In 2016 at Hutchinson, Palmer amaranth control was not adequate with *S*-metolachlor & atrazine applied PRE due to inadequate rainfall for activation. At both locations, nicosulfuron provided 35, 55, and 61% control of large crabgrass, yellow foxtail, and stinkgrass, respectively. Annual grass control ranged from 85 to 100% when nicosulfuron followed a PRE *S*-metolachlor & atrazine. Herbicide programs for Inzen™ Sorghum can provide adequate grass control, however an essential component of the total program includes the use of an effective grass and broadleaf herbicide applied PRE followed by a POST application of nicosulfuron tank mixed with an herbicide that controls broadleaf weeds.

Introduction

Grain sorghum (*Sorghum bicolor* (L.) Moench ssp. *bicolor*) is considered the fifth most important cereal crop worldwide (Peterson et al. 2011). Grain sorghum is more adapted than corn (*Zea mays* L.) to a semi-arid climate such as the Great Plains, because grain sorghum can tolerate drought better by certain traits introduced by breeding (Stahlman and Wicks, 2000). Kansas currently ranks first in the United States with 1,052,182 hectares of grain sorghum harvested in 2017 (USDA-NASS 2017).

Weed management of grass weeds can be especially difficult in grain sorghum. Weeds adversely affect grain sorghum production in many areas by competing for light, nutrients, and water (Burnside and Wicks, 1969). Broadleaf weed species have historically been the most problematic weed in grain sorghum, however with the POST options such as 2,4-D, dicamba, and bromoxynil, the weed community is shifting to more grass species (Stahlman and Wicks, 2000). Currently, there are not many POST options to control grass weeds in grain sorghum, therefore producers have to rely on PRE herbicides in the chloroacetamide family to provide season-long grass control. When activating rainfall is not received in a timely manner after PRE application, producers are faced with the burden of not having a POST option to control the escaped annual grasses (Tapia et al. 1997). Sorghum yield loss has been documented to be 30 to 50% under weed competition, but can be greater under higher infestations (Bridges, 1992; Burnside and Wicks, 1967; 1972). Burnside and Wicks (1967) reported that no yield loss occurred when weeds were removed within three weeks after planting and the crop remained weed free for the remainder of the season. Yield loss did occur when weeds were removed after that three-week period (Burnside and Wicks, 1967).

DuPont Crop Protection has launched the new technology in the grain sorghum market branded Inzen™ Sorghum. This gene was found in ALS-resistant shattercane in southwest Kansas by researchers at Kansas State University (Tuinstra and Al-Khatib, 2008). This gene was transferred to grain sorghum through traditional breeding methods, therefore this technology is not considered a genetically modified organism. This new technology allows for the PRE application of rimsulfuron and the POST application of nicosulfuron.

Rimsulfuron and nicosulfuron are herbicides in the sulfonylurea family. EI DuPont de Nemours & Co discovered the first sulfonylurea herbicides in the 1970's, products which inhibit acetolactate synthase pathway (Hay, 1990). Nicosulfuron was registered for use by the Environmental Protection Agency in 1990 (EPA, 1990). Nicosulfuron and rimsulfuron were used extensively to control grass weeds in corn before Roundup Ready corn was introduced (Hennigh, 2009). Previous research showed excellent control of many annual grass weeds (Currie and Geier, 2015; Hennigh, 2009; Tapia et al. 1997). Tapia et al. (1997) reported that 5 to 10 cm tall grass weeds such as wild-proso millet (*Panicum miliaceum* L.), giant foxtail (*Setaria faberi* Herrm.), and woolly cupgrass (*Eriochloa villosa* (Thumb.) Kunth) were controlled on average 88% when nicosulfuron was applied POST at 35 g ha^{-1}. When weeds reached 15 to 25 cm tall, control of woolly cupgrass and wild-proso millet dropped significantly to 77 and 43%, respectively, when nicosulfuron was applied at 70 g ha^{-1}. Currie and Geier (2015) found that green foxtail (*Setaria viridis* (L.) P. Beauv) control ranged from 83 to 88% when treated with 35 g ha^{-1} nicosulfuron. Large crabgrass was found to have significantly lower control ranging from 60 to 80% with nicosulfuron. When a PRE was applied in conjunction with the POST application of nicosulfuron, control of large crabgrass (*Digitaria sanguinalis* (L.) Scop.) and green foxtail were greater than 94%. Hennigh (2009) reported that annual grass control was 40 to 80% with

POST nicosulfuron applied at 35 g ha^{-1} across four different field locations across Kansas Garden City, Hays, Hesston, and Manhattan. Annual grass control of 96 to 100% was more consistent when PRE *S*-metolachlor & atrazine were applied in these experiments. The effectiveness of nicosulfuron makes this herbicide a viable option for POST control of annual grasses in Inzen™ Sorghum. The objective of this research was to evaluate POST herbicide tank mixes that contain nicosulfuron applied alone or following PRE applied herbicides for grass and broadleaf weed control and crop tolerance of Inzen™ Sorghum at three locations in Kansas in 2015 and 2016.

Material and Methods

Field studies were conducted in 2015 and 2016 at three Kansas State University Experiment Stations. One location was in eastern Kansas at the Department of Agronomy Ashland Bottoms Experiment Field near Manhattan. The second location was in the central part of Kansas at the Department of Agronomy South Central Kansas Experiment Field near Hutchinson. The third location was in the western part of Kansas at the Southwest Research Center near Tribune. These locations represent major sorghum producing areas in KS. The locations allowed for the evaluation of weed control programs in three different environments on three different soil types.

Field studies at each location were established as a randomized complete block design with four replications of each treatment. Experiments consisted of 11 herbicide treatments in 2015 (Table 2.1) and 12 in 2016 (Table 2.2). Herbicides were selected based on a national protocol from DuPont Crop Protection to evaluate annual grass and broadleaf weed control. All POST herbicides were applied with atrazine at 840 g ha^{-1} and an adjuvant system that included crop oil concentrate (COC) at 1% v/v and ammonium sulfate (AMS) at 2240 g ha^{-1}. At planting in 2015, the entire experimental area at each location was sprayed with glyphosate at 1140 g ae ha^{-1} and AMS at 2% w/v. In 2016 each location was clean tilled using a field cultivator prior to planting except at Tribune which was maintained as no-till. All fields were fertilized to Kansas State University nutrient recommendations. Pioneer sorghum hybrid YSA4520 was planted in 2015 and Advanta hybrid XG31017ALS was planted in 2016, both ALS-resistant hybrids. It must be noted that the 2016 Advanta hybrid was male sterile. In all experiments single rows of conventional sorghum and wheat were planted perpendicular across all plots to evaluate control of conventional sorghum and wheat with each herbicide program. Plots were 3 m wide by 9 m long with 4 crop rows spaced 76 cm apart. Herbicide treatments were applied with a CO_2 backpack sprayer and a 1.93 m handheld boom equipped with 4 nozzles to deliver 140 L ha^{-1} at a pressure of 317 kPa in 2015 and 234 kPa in 2016 traveling at 4.82 km h^{-1}. A full description of spray information and target weed species and heights at time of application for all locations for each year can be found in Tables 2.3 and 2.4.

At Manhattan, the soil type is a Reading silt loam, a fine silty, mixed, superactive, mesic Pachic Argiudolls (NCSS, 2017). The organic matter content was 2.1% and the pH was 6.0. In 2015, an early preplant (EPP) treatment was applied two weeks before planting on June 2. Grain sorghum was planted at a depth of 3.8 cm and a seeding rate of 148,000 seeds ha^{-1} on June 19, 2015 and June 2, 2016, and PRE herbicides were applied the same day following planting. POST treatments were applied on July 14, 2015 and June 27, 2016 when the target weed species reached 5 to 10 cm in height

At Hutchinson, the soil type was a Darlow silt loam, a fine-loamy, mixed, superactive, mesic Vertic Natrustalfs (NCSS, 2017). The organic matter content was 2.5% and the pH was 5.6. The 2015 EPP treatment was applied June 5. Grain sorghum was planted at a depth of 2.5

cm and a seeding rate of 111,000 seeds ha^{-1} on June 23, 2015 and June 8, 2016. Preemergence herbicides were applied immediately following planting. The POST treatments were applied on July 14, 2015 and June 28, 2016.

At Tribune, the soil type was a Ulysses silt loam, a fine silty, superactive, mesic Torriorthentic Haplustolls (NCSS, 2017). The organic matter content was 1.5% and the pH was 8.1. The EPP treatment was applied on June 3, 2015. Grain sorghum was planted at a depth of 3.8 cm and at a seeding rate of 98,000 seeds ha^{-1} on June 17, 2015 and May 25 2016. All PRE treatments were applied the same day as planting and POST treatments were applied on July 15, 2015 and June 28, 2016.

Visual ratings for crop injury and weed control for each individual species were taken 1, 2, and 4 weeks after POST treatment (WAPT) in all plots at all locations. Visual ratings were based on 0 = no control and 100 = complete mortality relative to running nontreated checks. Grain sorghum plants were harvested at the boot stage by clipping all plants from 1 m of crop row at all locations. The biomass harvest dates varied from 2015 to 2016, on average samples were collected 52 in 2015 and 70 days after planting in 2016. Total fresh weight of all plants was measured in the field as well as a subsample of two plants. Leaves were removed from main stems only to measure leaf area using an area meter (LI-3100C Area Meter, LICOR, Lincoln, NE). Leaves, stem, and reproductive parts from the main stems were bagged separately and placed in a drier at 60 C for seven days, and weighed. This weight was then combined with the main plants and tillers to total up 1 m of row. Grain was harvested from the middle two rows of each plot, an area of 2 m wide by 8 m long, , and subsamples were taken to the lab for moisture and test weight analysis (DICKEY-john model 2100 Agri, Auburn, IL), and yield determined to 14.5% moisture. Grain sorghum seed samples from Manhattan 2015 were analyzed further by counting out two subsets of 100 seeds (Seedburo 801 Count-A-Pak, Des Plaines, IL) and averaging the two weights.

The response data that were analyzed in this study were visual crop injury, visual weed control at 1, 2, and 4 WAPT, grain sorghum leaf area and biomass, and grain yields in response to herbicide treatments at three locations over two years where such data were measured. Data were analyzed using JMP PRO 12 from SAS (SAS Institute Inc, Cary, NC) using the Mixed procedure. Means were separated using LSD $\alpha = 0.05$. Location and year were considered fixed effects in the analysis of interaction with treatment. When non-significant interactions were observed, location and year were included as random effects where location was nested within year. Location was always a fixed effect and replications were always a random effect.

Results and Discussion

There was sufficient rainfall received to activate the PRE treatments across the three locations over two years, however the timing of receiving the activation rainfall ranged from two to 26 days after application (DAA). The efficacy of the PRE treatments at each location was affected by differences in timely rainfall for herbicide activation. At Manhattan, 0.76 cm of activating rainfall was received 6 DAA in 2015 and 2.54 cm received 26 DAA in 2016. At Hutchinson, 1.32 cm of activating rainfall was received in 2015 and 4.26 cm was received in 2016, both at 9 DAA. At Tribune, 2.54 cm of activating rainfall was received 14 DAA in 2015 and 6.35 cm was received 2 DAA in 2016. The long term average annual precipitation was 90, 77, and 45 cm and mean temperature was 13, 13, and 11 C in Manhattan, Hutchinson, and Tribune, respectively (U.S. Climate Data, 2017).

Crop Injury. There was a significant interaction for visual crop injury among year, location, and treatment; therefore, data will be presented for each year and location by treatment. There was crop injury observed 1 WAPT across all locations and years but depended on the treatment (Tables 2.5 and 2.6). For example, less than 5% injury was observed with all PRE treatments alone at 1 WAPT. Nicosulfuron by itself or after a PRE herbicide caused 5 to 13% injury at 1 WAPT. Nicosulfuron injury symptoms included prominent chlorosis of the leaves. Treatments that contained nicosulfuron + bromoxynil & pyrasulfotole caused crop injury that ranged from 2.5 to 19% in 2015 and from 16 to 27% in 2016 at 1 WAPT (Tables 2.5 and 2.6). These symptoms showed nicosulfuron injury along with added phytotoxicity from the bromoxynil & pyrasulfotole. The treatment that caused the most injury among locations in all years were those that contained nicosulfuron + dicamba POST. Injury from this treatment ranged from 18 to 30% across all locations and years 1 WAPT (Tables 2.5 and 2.6) These treatments showed symptoms that were consistent with nicosulfuron injury and also showed epinasty, lodging, and stunting from the dicamba application. It must be noted the treatment containing dicamba is off label due to the addition of ammonium sulfate plus crop oil concentrate. Bromoxynil & pyrasulfotole with nicosulfuron is also not a labeled treatment.

Visual crop injury from nicosulfuron declined greatly by 2 WAPT and was completely gone by 4 WAPT, however treatments that contained dicamba or bromoxynil & pyrasulfotole continued to show slight visual injury out to 4 WAPT (Tables 2.5 and 2.6). Visual crop injury was reported so that producers will know what to expect when applying POST treatments to Inzen™ Sorghum. Previous research had similar results such that when Inzen™ Sorghum was treated with nicosulfuron POST, primarily chlorosis was observed 1 WAPT and by 3 WAPT no visual crop injury was observed (Hennigh 2009).

Visual Weed Control. There was a significant interaction of year and location; therefore visual ratings for weed control will be presented by weed species for each year and location at the 4 WAPT evaluation. At Tribune in both 2015 and 2016, low weed pressure occurred and therefore no weed control data were collected. The POST applications at Tribune were made due to the crop reaching maximum size based on label treatments.

Large crabgrass. At Manhattan, large crabgrass control in 2015 was 99% when a PRE application contained *S*-metolachlor & atrazine, while treatments that contained nicosulfuron POST only without a PRE treatment controlled large crabgrass 45 to 57% (Table 2.7). This study indicated there was no benefit by adding rimsulfuron + thifensulfuron to a PRE or EPP treatment alone to control large crabgrass (Table 2.11). At Hutchinson in 2015 the EPP treatment of rimsulfuron + thifensulfuron provided minimal control of large crabgrass by the time of POST application (Tables 2.11). The PRE-only treatments of *S*-metolachlor & atrazine and rimsulfuron + thifensulfuron + *S*-metolachlor & atrazine provided 57 to 65% control of large crabgrass. This was partially due to weed emergence that occurred in the nine days before the PRE herbicides were activated. Large crabgrass control with POST-only treatments of nicosulfuron provided 43 to 55% control, which was not different than the PRE-only treatments. Large crabgrass was controlled best with a PRE treatment of *S*-metolachlor & atrazine fb POST treatments containing nicosulfuron. These treatments controlled large crabgrass 75 to 89% (Table 2.7).

Stinkgrass. At Manhattan in 2015, stinkgrass was 99% controlled with all treatments that contained *S*-metolachlor & atrazine (Table 2.7). The EPP treatment of rimsulfuron + thifensulfuron fb nicosulfuron provided 57% control of stinkgrass, which was less than the PRE treatments containing *S*-metolachlor & atrazine. The treatments that contained POST-only nicosulfuron did not provide adequate control of stinkgrass, only ranging from 32 to 38%, which was significantly less than the PRE and EPP treatments containing *S*-metolachlor & atrazine (Table 2.7).

Yellow foxtail. Yellow foxtail at Hutchinson in 2015 were controlled 57 to 65% with the PRE-only treatments and 58 to 65% with the POST-only treatments (Table 2.7). Yellow foxtail control ranged from 91 to 97% and was greatest with a PRE fb POST program was implemented, specifically *S*-metolachlor & atrazine fb nicosulfuron. Only the two-pass herbicide program provided adequate control of yellow foxtail.

Volunteer wheat. Volunteer wheat was present in Manhattan in 2016, and control was excellent at > 96% with all treatments containing POST-applied nicosulfuron (Table 2.8). Treatments that only contained a PRE with *S*-metolachlor & atrazine + rimsulfuron + thifensulfuron and rimsulfuron + thifensulfuron provided minimal control of volunteer wheat at 1 to 6% prior to an application of nicosulfuron (Table 2.11).

Palmer amaranth. Palmer amaranth occurred both at Manhattan in 2015 and at Hutchinson in 2016. Palmer amaranth control was greatest (>98%) with treatments that contained PRE *S*-metolachlor & atrazine at Manhattan in 2015 (Table 2.11). The POST-only treatments had less Palmer amaranth control of 71 and 76% with nicosulfuron+ dicamba and nicosulfuron+ bromoxynil & pyrasulfotole, respectively (Table 2.7). At Hutchinson in 2016, Palmer amaranth control with PRE treatments of *S*-metolachlor & atrazine ranged from 11 to 17%, and it was poor because weed emergence occurred before the PRE herbicides were activated. POST treatments that contained nicosulfuron provided 43 to 66% Palmer amaranth control, which was more than the PRE-only treatments. Palmer amaranth control increased to 75 and 86% when bromoxynil + pyrasulfotole or dicamba were added to POST nicosulfuron (Table 2.8). It must be noted that the Palmer amaranth population at Hutchinson was documented to be ALS-susceptible. There is widespread occurrence of ALS-resistant Palmer amaranth in Kansas (Horak and Peterson 1995) and is a common problem for many farmers; therefore one must be sure to know if they are targeting ALS-susceptible or -resistant Palmer amaranth populations. Horak and Peterson (1995) documented that ALS-resistant Palmer amaranth was not effectively controlled at 8 times the labeled rate of thifensulfuron. Nicosulfuron would also be ineffective at controlling these ALS-resistant populations, therefore one would be relying on tank mix partners such as dicamba.

The PRE treatments provided 10% or less control of conventional sorghum in all experiments (Table 2.8). In Hutchinson in 2016, treatments that contained nicosulfuron POST controlled 20-cm tall conventional sorghum 96% or greater (Table 2.8). In 2016 at Manhattan conventional sorghum control ranged from 63 to 67% in treatments that contained nicosulfuron. This lower level of control was due to 30 cm tall conventional sorghum at time of application (Table 2.8).

Grain sorghum biomass and leaf area. The three-way interaction of year by location by treatment was significant, but the two-way interaction of location by treatment for grain sorghum whole plant biomass harvested at boot stage, was not significant (P-value=0.1838), thus data were combined across all three locations in both 2015 and 2016 (Table 2.9 and 2.10). The difference in year is attributed to the different timing of biomass harvest, samples were taken 52 and 70 days after planting in 2015 and 2016, respectively. In 2015, the greatest accumulation of biomass occurred in PRE treatments that contained *S*-metolachlor & atrazine alone or with rimsulfuron + thifensulfuron. These treatments had a range of biomass from 230 to 280 g m^{-2}. Treatments containing dicamba POST significantly reduced biomass to 220 to 230 g m^{-2}, which was similar to the biomass of the nontreated weedy check (Table 2.9). In 2016, the greatest accumulation was 970 g m^{-2}, which occurred in the PRE-only treatment *S*-metolachlor & atrazine

(Table 2.10). However, when PRE *S*-metolachlor & atrazine was followed by POST nicosulfuron + dicamba or nicosulfuron + bromoxynil & pyrasulfotole, biomass was reduced to 840 and 860 g m^{-2}, respectively.

The interaction of year by location by treatment was significant for grain sorghum leaf area when measured at boot stage but the interaction of location by treatment was not significant (P-value=0.4535), therefore locations were combined in 2015 (Table 2.9). In 2016, the interaction of location by treatment was significant therefore locations were analyzed individually (Table 2.10). In 2015 grain sorghum leaf area from two main culms in the PRE treatment of *S*-metolachlor & atrazine + rimsulfuron + thifensulfuron had a leaf area of 8,720 cm^2 (Table 2.9). All POST-only treatments and treatments that had PRE S-metolachlor & atrazine fb nicosulfuron tank mixed conjunction with dicamba or bromoxynil + pyrasulfotole had less leaf area than the PRE treatment of *S*-metolachlor & atrazine + rimsulfuron + thifensulfuron (Table 2.9). This result indicates that POST treatments did have a negative impact on leaf area. In 2016, leaf area was different for each location. At Manhattan there were no differences in leaf area among any herbicide treatments or the nontreated check. At Hutchinson, leaf area was very dependent on level of weed control. All herbicide applications, except for *S*-metolachlor & atrazine + rimsulfuron + thifensulfuron, had more leaf area than the nontreated check. The grain sorghum leaf area in the plots treated with *S*-metolachlor & atrazine + rimsulfuron + thifensulfuron were similar to the nontreated check because of more weed pressure from poor activation of the herbicide. At Tribune there were no differences in leaf area as there was no weed pressure and little crop injury from any of the herbicide treatments. The leaf area for *S*-metolachlor & atrazine fb nicosulfuron was 4,540 cm^2 (Table 2.10). The POST treatment of nicosulfuron+ bromoxynil & pyrasulfotole had reduced leaf area, however this was not different among all treatments containing bromoxynil & pyrasulfotole.

Grain sorghum yield. Yield data were only available for Hutchinson and Manhattan in 2015 and, even though the Advanta hybrid was male sterile, yield was measured at Tribune in 2016 as there was conventional sorghum planted around this study, which allowed for pollination of the male-sterile hybrid. At Hutchinson in 2015, grain sorghum yield was the greatest when the two-pass herbicide program of rimsulfuron + thifensulfuron applied EPP fb POST nicosulfuron (Table 2.9). Yields from all other treatments were not different from the nontreated check. Level of weed control or crop injury did not have any effect on grain sorghum yields. At Manhattan in 2015, grain sorghum yields did not present a statistical difference in all treatments that contained PRE of *S*-metolachlor & atrazine fb any POST and ranged from 6,460 to 7,300 kg ha^{-1}. Grain sorghum yield was 5,220 kg ha^{-1} in the EPP fb nicosulfuron and was less than all treatments that contained a PRE of *S*-metolachlor & atrazine alone or fb any POST. Sorghum yield when competing with weeds in the nontreated check was 2,800 kg ha^{-1}, however this low yield provided the heaviest 100-kernel weights among treatments in 2015 (Table 2.11). There was a 4,510 kg ha^{-1} yield advantage when proper weed control measures were implemented, such as a PRE fb a POST herbicide, to control weeds at Manhattan in 2015 (Table 2.9). There was major yield loss due to weed competition, however biomass was not affected, indicating that damage may have occurred during head initiation at growth stage V3. At Tribune in 2016, the treatments that contained dicamba or bromoxynil & pyrasulfotole produced 5,150 to 5,360 kg ha^{-1} which was less yield than PRE-only treatments (Table 2.10). The highest yields were 6,360 and 6,380 kg ha^{-1}, associated with the treatments of *S*-metolachlor & atrazine and rimsulfuron + thifensulfuron + *S*-metolachlor & atrazine, respectively. There was strong indication that reduced yield was due to the POST treatments that contained dicamba, bromoxynil & pyrasulfotole, and nicosulfuron (Table 2.10). When comparing yield from treatment of *S*-metolachlor & atrazine applied alone (6,360 kg ha^{-1}) to yield from *S*-metolachlor & atrazine fb nicosulfuron (5,730 kg ha^{-1}), yields were significantly lower in the treatment containing nicosulfuron.

This study illustrated the importance of having a multiple step plan in place to control weeds as well as to avoid crop injury. This study indicated that crop injury was more prominent in POST treatments compared with PRE-only treatments. The application and timely activation of a PRE herbicide may minimize the need for a POST herbicide that is known to greatly increase the risk of crop injury, however timely scouting must be used to determine when to apply a POST. The yield data in this study set aside crop injury and showed the importance of controlling weeds. Up to 4,510 kg ha^{-1} yield increase was observed when comparing to the nontreated check at Manhattan in 2015.

This study showed that annual grass control was most effective when the PRE herbicide of *S*-metolachlor & atrazine was activated within a few days after application but when the herbicide was not activated, a POST treatment was necessary. At Hutchinson, annual grass control was more effective in a two-pass herbicide program of *S*-metolachlor & atrazine fb nicosulfuron. This two-pass herbicide program provides an effective tool to control annual grasses in grain sorghum. The two-pass herbicide program can also benefit Palmer amaranth control, which was effectively controlled by an activated PRE herbicide treatment. The POST-only treatment of nicosulfuron did not provide adequate control of annual grasses such as large crabgrass, stinkgrass, and yellow foxtail in any year or location. Nicosulfuron did provide acceptable control of wheat. Nicosulfuron is not a stand-alone herbicide program to be used in

Inzen^{TM} Sorghum, but can provide adequate control of annual grasses when used in conjunction with a PRE herbicide.

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Table 2.1 List of herbicide treatments, application timings, and rates among all locations in 2015.

Herbicide Treatment[a]	Application Timing[b]	Rate[a]
		g ha^{-1}
1. Rimsulfuron + thifensulfuron fb nicosulfuron	EPP fb POST	32 +32 fb 35
2. Rimsulfuron + thifensulfuron + *S*-metolachlor & atrazine fb nicosulfuron	PRE fb POST	32 + 32 +1388 & 1075 fb 35
3. *S*-metolachlor & atrazine fb nicosulfuron	PRE fb POST	1388 & 1075 fb 35
4. Rimsulfuron + thifensulfuron + *S*-metolachlor & atrazine	PRE	32 + 32 + 1388 & 1075
5. Nicosulfuron	POST	35
6. Nicosulfuron + bromoxynil & pyrasulfotole	POST	35 + 200 & 35
7. Nicosulfuron + dicamba	POST	35 + 280
8. *S*-metolachlor & atrazine	PRE	1388 & 1075
9. *S*-metolachlor & atrazine fb nicosulfuron + bromoxynil & pyrasulfotole	PRE fb POST	1388 & 1075 fb 35 + 200 & 35
10. *S*-metolachlor & atrazine fb nicosulfuron + dicamba	PRE fb POST	1388 & 1075 fb 35 + 280
11. Nontreated check		

[a] fb, followed by; &, commercially packaged herbicide

[b] EPP, Early Preplant 15 days before planting, PRE, preemergence at planting, POST, postemergence, all POST treatments contained atrazine at 840 g ha^{-1}, crop oil concentrate at 1% v/v and ammonium sulfate at 2240 g ha^{-1}.

Table 2.2 List of herbicide treatments, application timings, and rates among all locations in 2016.

Herbicide Treatment[a, c]	Application Timing[b]	Rate[a]
		g ha $^{-1}$
1. Rimsulfuron + thifensulfuron fb nicosulfuron	PRE fb POST	32+32 fb 35
2. Rimsulfuron + thifensulfuron + *S*-metolachlor & atrazine fb nicosulfuron	PRE fb POST	32 + 32 + 1388 & 1075 fb 35
3. *S*-metolachlor & atrazine fb nicosulfuron	PRE fb POST	1388 & 1075 fb 35
4. Rimsulfuron + thifensulfuron + *S*-metolachlor & atrazine	PRE	32 + 32+ 1388 & 1075
5. Nicosulfuron	POST	35
6. Nicosulfuron + bromoxynil & pyrasulfotole	POST	35 + 200 & 35
7. Nicosulfuron + dicamba	POST	35 + 280
8. *S*-metolachlor & atrazine + nicosulfuron	POST	1388 & 1075 + 35
9. *S*-metolachlor & atrazine	PRE	1388 & 1075
10. *S*-metolachlor & atrazine fb nicosulfuron + bromoxynil & pyrasulfotole	PRE fb POST	1388 & 1075 fb 35+200 & 35
11. *S*-metolachlor & atrazine fb nicosulfuron + dicamba	PRE fb POST	1388 & 1075 fb 35 + 280
12. Nontreated check		

[a] fb, followed by, &, commercially packaged product

[b] PRE, preemergence at planting, POST, postemergence,

[c] All POST treatments contained atrazine at 840 g ha-1, crop oil concentrate at 1% v/v and ammonium sulfate at 2240 g ha $^{-1}$.

Table 2.3 Herbicide application dates, time, sprayer type and setup information, crop height, and weed size information at the time of applications across all locations in 2015

	Manhattan			Hutchinson			Tribune		
	EPP[1]	PRE[2]	POST[3]	EPP[1]	PRE[2]	POST[3]	EPP[1]	PRE[2]	POST[3]
Application date	June 2	June 19	July 14	June 5	June 23	July 14	June 13	June 17	July 15
Appl. Start time	2:25 pm	2:00 pm	10:55 am	9:05 am	12:30 pm	7:45 am	10:45 am	10:00 am	2:10 pm
Appl. Stop time	2:30 pm	2:19 pm	11:20 pm	9:10 am	1:00 pm	8:15 am	10:50 am	10:20 am	2:40 pm
Appl. Placement	Soil	Soil	Foliar	Soil	Soil	Foliar	Soil	Soil	Foliar
Temperature ^{0}C	28	28	32	23	26	26	23	28	32
%Humidity	64	40	54	68	40	62	68	n50	32
Wind speed km/h	11	4	6	11	12	6	11	9	6
Wind Direction	SE	E	NNE	E	S	E	NE	NE	NW
Dew Yes/No	No	No	No	No	No	No	No	No	No
Soil Temperature ^{O}C	19	30	30	22	20	27	20	23	29
% cloud cover	20	10	10	15	20	30	100	40	40
Appl. Equipment	Backpack	Backpack	Backpack	Backpack	Backpack	Backpack	Backpack	Backpack	Backpack
Pressure kPa	317	317	317	317	317	317	317	317	317
Nozzle type/size	AIXR 110015	AIXR 110015	AIXR 110015	AIXR 110015	AIXR 110015	AIXR 110015	AIXR 110015	AIXR 110015	AIXR 110015
Nozzle spacing cm	48	48	48	48	48	48	48	48	48
Ground speed km/h	4.82	4.82	4.82	4.82	4.82	4.82	4.82	4.82	4.82
Carrier	Water	Water	Water	Water	Water	Water	Water	Water	Water
Spray volume L ha^{-1}	140	140	140	140	140	140	140	140	140
Mix Size L	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42
Propellant	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2
Crop Height	-	-	30 cm	-	-	15-20cm	-	-	35 cm
DIGSA Height[4]	-	-	5- 15 cm	-	-	2.5-8cm	-	-	-
Conv. Sorghum	-	-	15-20 cm	-	-	10-15 cm	-	-	-
AMAPA Height[5]	-	-	2-8 cm	-	-	-	-	-	-
SETPU Height[6]	-	-	-	-	-	2.5-8cm	-	-	-

[1]EPP, early preplant application timing.

[2]PRE, Preemergence application timing.

[3]POST, Postemergence application timing.

[4] DIGSA, large crabgrass

[5]AMAPA, Palmer amaranth

[6]SETPU, yellow foxtail

Table 2.4 Herbicide application dates, time, sprayer type and setup information, crop height, and weed size information at the time of applications across all locations in 2016.

	Manhattan		Hutchinson		Tribune	
	PRE[1]	POST[2]	PRE[1]	POST[2]	PRE[1]	POST[2]
Application date	June 2	June 27	June 8	June 28	May 25	June 23
Appl. Start time	11:45 am	2:00 am	10:50 am	11:00 am	1:00 pm	11:00 am
Appl. Stop time	12:25 am	2:30 pm	11:10 am	11:30 am	2:00 pm	12:00 pm
Appl. Method	Soil	Foliar	Soil	Foliar	Soil	Foliar
Temperature ^{0}C	30	35	30	30	26	30
%Humidity	44	32	39	41	45	48
Wind speed km/h	7	6	12	10.13	3.21	14.48
Wind Direction	ESE	ENE	S	ENE	SW	SSE
Dew Yes/No	No	No	No	No	No	No
Soil Temperature ^{O}C	22.22	32.22	25.3	28	22	25
% cloud cover	15	25	0	50	10	65
Appl. Equipment	Backpack	Backpack	Backpack	Backpack	Backpack	Backpack
Pressure kPa	213	213	213	213	213	213
Nozzle type/size	TT11002	TT11002	AIXR 11002	TT11002	TT11002	TT11002
Nozzle spacing cm	48	48	48	48	48	48
Ground speed km/h	4.82	4.82	4.82	4.82	4.82	4.82
Carrier	water	water	water	water	water	water
Spray volume L ha^{-1}	140	140	140	140	140	140
Mix Size L	1.42	1.42	1.42	1.42	1.42	1.42
Propellant	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2
Crop Height	-	30 cm	-	20- 25 cm	-	20 cm
DIGSA Height[3]	-	15 cm	-	-	-	-
Conv. Sorghum	-	30 cm	-	20 cm	-	-
AMAPA Height[4]	-	-	-	2- 10 cm	-	-
Wheat Height	-	5-8 cm	-	-	-	-

[1]PRE, Preemergence
[2] POST, Postemergence
[3] DIGSA, large crabgrass
[4] AMAPA, Palmer amaranth

Table 2.5 Visual ratings of crop injury to Inzen™ Sorghum 1, 2 and 4 weeks after the postemergence application (WAT) with the following herbicide treatments across 3 locations in 2015.

Herbicide Treatment[a]	Manhattan			Hutchinson			Tribune		
	1 WAT	2 WAT	4 WAT	1 WAT	2 WAT	4 WAT	1 WAT	2 WAT	4 WAT
1. Rimsulfuron + thifensulfuron[b] fb nicosulfuron	11 b	1 c	0 c	10 cd	0 c	0 c	13 c	3 de	0
2. Rimsulfuron + thifensulfuron+ *S*-metolachlor & atrazine fb nicosulfuron	11 b	3 bc	3 bc	13 bc	3 bc	0 c	11 cd	8 cd	0
3. *S*-metolachlor & atrazine fb nicosulfuron	8 bc	1 c	0 c	10 cd	0 c	0 c	11 cd	5 cde	0
4. Rimsulfuron + thifensulfuron+ *S*-metolachlor & atrazine[d]	4 c	0 c	0 c	4 de	0 c	0 c	3 e	0 e	0
5. Nicosulfuron[c]	5 c	1 c	0 c	11 bc	0 c	0 c	8 d	8 c	0
6. Nicosulfuron + bromoxynil & pyrasulfotole[c]	8 bc	4 b	0 c	13 bc	9 ab	3 bc	3 e	10 bc	0
7. Nicosulfuron + dicamba[c]	31 a	19 a	13a	30 a	15 a	9 a	29 a	29 a	0
8. *S*-metolachlor & atrazine[d]	4 c	0 c	0 c	1 e	0 c	0 c	1 e	0 e	0
9. *S*-metolachlor & atrazine fb nicosulfuron + bromoxynil & pyrasulfotole	11 b	5 b	3 bc	12 bc	10 a	5 abc	19 b	15 b	0
10. *S*-metolachlor & atrazine fb nicosulfuron + dicamba	30 a	16 a	8 ab	18 b	11 a	8 ab	29 a	25 a	0

[a] fb, followed by; herbicides listed before fb were applied PRE, listed after fb were applied POST

[b] Early Preplant, 15 days before planting

[c] POST-only treatment

[d] PRE-only treatment

Values in a column with the same letter were not different at p=0.05

WAT= Weeks after post treatment was applied

&= indicates commercial prepackages mixture of active ingredients

All POST treatments were applied with atrazine

Table 2.6 Visual ratings of crop injury to Inzen ™ Sorghum 1, 2, and 4 weeks after the postemergence application (WAT) with the following herbicide treatments across 3 locations in 2016.

Herbicide Treatment[a]	Manhattan			Hutchinson			Tribune		
	1 WAT	2 WAT	4 WAT	1 WAT	2 WAT	4 WAT	1 WAT	2 WAT	4 WAT
1. Rimsulfuron + thifensulfuron fb nicosulfuron	8 b	0 b	0 c	13 bc	0 c	0 c	13 bcd	9 e	0 c
2. Rimsulfuron + thifensulfuron+ *S*-metolachlor& atrazine fb nicosulfuron	6 bc	0 b	0 c	13 bc	3 bc	0 c	7 e	3 de	0 c
3. *S*-metolachlor & atrazine fb nicosulfuron	6 bc	0 b	1 bc	13 bc	0 c	3 bc	18 ab	9 bcd	0 c
4. Rimsulfuron+ thifensulfuron+ *S*-metolachlor& atrazine[c]	1 c	0 b	0 c	5 c	0 c	0 c	1 f	3 de	0 c
5. Nicosulfuron[b]	6 bc	0 b	0 c	11 bc	0 c	0 c	10 de	6 cde	0 c
6. Nicosulfuron + bromoxynil & pyrasulfotole[b]	27 a	5 a	1 bc	17 ab	9 ab	0 c	16 bc	11 bc	1 bc
7. Nicosulfuron + dicamba[b]	23 a	6 a	3 b	20 ab	15 a	13 a	23 a	16 ab	1 bc
8. *S*-metolachlor & atrazine + nicosulfuron[b]	10 b	0 b	0 c	13 bc	0 c	0 c	12 cde	6 cde	0 c
9. *S*-metolachlor & atrazine[c]	1 c	0 b	0 c	4 c	10 a	3 bc	1 f	0 e	0 c
10. *S*-metolachlor & atrazine fb nicosulfuron + bromoxynil & pyrasulfotole	27 a	4 ab	10 c	18 ab	11 a	8 ab	18 ab	14 abc	3 ab
11. *S*-metolachlor & atrazine fb nicosulfuron + dicamba	23 a	4 ab	9 a	23 a	0 c	0 c	23 a	20 a	4 a

[a] fb, followed by; herbicides listed before fb were applied PRE, listed after fb were applied POST

[b] POST-only treatment

[c] PRE-only treatment

Values in a column with the same letter were not different at p=0.05

WAT= Weeks after POST treatment was applied

&= indicates commercial prepackages mixture of active ingredients

All POST treatments were applied with atrazine

Table 2.7 Weed control with the following herbicides treatments at 4 weeks after postemergence treatment at Manhattan and Hutchinson in 2015.

	Manhattan			Hutchinson	
Herbicide Treatment[a]	Large crabgrass	Stinkgrass	Palmer Amaranth	Large crabgrass	Yellow foxtail
	-----------------------------------% Control			-----------------------------------	
1. Rimsulfuron + thifensulfuron[b] fb nicosulfuron	57 b	55 b	61 c	61 cd	61 b
2. Rimsulfuron + thifensulfuron + *S*-metolachlor& atrazine fb nicosulfuron	99 a	99 a	98 a	89 a	95 a
3. *S*-metolachlor & atrazine fb nicosulfuron	99 a	99 a	99 a	87 ab	92 a
4. Rimsulfuron + thifensulfuron + *S*-metolachlor & atrazine[d]	99 a	99 a	96 a	57 de	57 b
5. Nicosulfuron[c]	45 b	38 c	63 bc	51 de	65 b
6. Nicosulfuron + bromoxynil & pyrasulfotole[c]	47 b	36 c	76 b	43 e	66 b
7. Nicosulfuron + dicamba[c]	46 b	32 c	71 bc	55 de	58 b
8. *S*-metolachlor & atrazine[d]	99 a	99 a	99 a	65 cd	65 b
9. *S*-metolachlor & atrazine fb nicosulfuron + bromoxynil & pyrasulfotole	99 a	99 a	99 a	75 bc	91 a
10. *S*-metolachlor & atrazine fb nicosulfuron + dicamba	99 a	99 a	99 a	85 ab	97 a

[a] fb, followed by; herbicides listed before fb were applied PRE, listed after fb were applied POST

[b] Early Preplant, 15 days before planting

[c] POST-only treatment

[d] PRE-only treatment

Values in a column with the same letter were not different at p=0.05

WAT= Weeks after post treatment was applied

&= indicates commercial prepackages mixture of active ingredients

All POST treatments were applied with atrazine

Table 2.8 Volunteer wheat, conventional sorghum, and Palmer amaranth control with the following herbicide treatments 4 weeks after the postemergence treatments at Manhattan and Hutchinson in 2016.

	Manhattan		Hutchinson	
Herbicide Treatment[a]	Wheat	Conv. sorghum	Palmer amaranth	Conv. sorghum
	-------------------------------% Control	---	---	----------------------------------
1. Rimsulfuron + thifensulfuron fb nicosulfuron	98 a	63 b	43 d	96 a
2. Rimsulfuron + thifensulfuron + *S*-metolachlor & atrazine fb nicosulfuron	98 a	65 ab	73 abc	96 a
3. *S*-metolachlor & atrazine fb nicosulfuron	96 a	63 b	66 bc	96 a
4. Rimsulfuron + thifensulfuron + *S*-metolachlor & atrazine[c]	3 b	1 c	11 e	10 b
5. Nicosulfuron[b]	98 a	66 ab	56 cd	98 a
6. Nicosulfuron + bromoxynil & pyrasulfotole[b]	96 a	67a	75 abc	96 a
7. Nicosulfuron + dicamba[b]	96 a	64 ab	85 ab	96 a
8. *S*-metolachlor & atrazine + nicosulfuron[b]	96 a	66 ab	87 ab	96 a
9. *S*-metolachlor & atrazine[c]	2 b	2 c	17 e	2 bc
10. *S*-metolachlor & atrazine fb nicosulfuron + bromoxynil & pyrasulfotole	96 a	66 ab	86 ab	96 a
11. *S*-metolachlor & atrazine fb nicosulfuron + dicamba	96 a	66 ab	92 a	96 a

[a] fb, followed by; herbicides listed before fb were applied PRE, listed after fb were applied POST

[b] POST-only treatment

[c] PRE-only treatment

Values in a column with the same letter were not different at p=0.05

WAT= Weeks after POST treatment was applied

&= indicates commercial prepackages mixture of active ingredients

All POST treatments were applied with atrazine

Table 2.9 Grain sorghum leaf area from two plants, biomass from 0.76 m^{-2}, and yield components for the locations where parameters were gathered based on the herbicide treatments listed below in 2015.

Herbicide Treatment[a]	All locations Leaf Area	All locations Biomass	Hutchinson Yield	Manhattan Yield	Manhattan Head Weight	Hutchinson[f] Head Weight	Manhattan 1000 kernel weight
	cm^2	g m^{-2}	kg ha^{-1}	kg ha^{-1}	g	g	g
1. Rimsulfuron + thifensulfuron[b] fb nicosulfuron	7900 abc	270 a	7620 a	5220 d	55 b	50	13.7 a-d
2. Rimsulfuron + thifensulfuron + *S*-metolachlor & atrazine fb nicosulfuron	7850 abc	260 ab	5780 b	7000 ab	69 a	46	11.5 e
3. *S*-metolachlor & atrazine fb nicosulfuron	7920 ab	250 ab	6830 ab	6220 bc	60 ab	49	14.1abc
4. Rimsulfuron + thifensulfuron + *S*-metolachlor & atrazine[d]	8720 a	270 a	6150 ab	6440 abc	61 ab	48	13.9abc
5. Nicosulfuron[c]	7470 bcd	270 a	6470 ab	5570 cd	61 ab	53	12.9 b-e
6. Nicosulfuron + bromoxynil & pyrasulfotole[c]	7620 bcd	260 ab	6550 ab	6580 ab	60 ab	49	12.9 b-e
7. Nicosulfuron + dicamba[c]	6900 d	220 b	6460 ab	6790 ab	60 ab	53	11.7 de
8. *S*-metolachlor & atrazine[d]	8030 ab	280 a	5950 b	6460 abc	57 b	47	14.9 ab
9. *S*-metolachlor & atrazine fb nicosulfuron + bromoxynil & pyrasulfotole	7450 bcd	260 ab	5980 b	7300 a	61 ab	48	12.7cde
10. *S*-metolachlor & atrazine fb nicosulfuron + dicamba	7330 bcd	230 b	5470 b	6970 ab	61 ab	49	13.5 a-e
11. Nontreated Check	6990 cd	220 b	5990 b	2800 e	41 c	49	15.5 a

[a] fb, followed by; herbicides listed before fb were applied PRE, listed after fb were applied POST

[b] Early Preplant, 15 days before planting

[c] POST-only treatment

[d] PRE-only treatment

Values in a column with the same letter were not different at p=0.05

&= indicates commercial prepackages mixture of active ingredients

All POST treatments were applied with atrazine

[e]All Sites, Manhattan, Hutchinson, and Tribune were not significant p= 0.1838 for biomass and p=0.4535 for leaf area, therefore sites were combined.

Values in a column with the same letter were not different at p=0.05

[f] column not significant p value=0.79

&= indicates commercial prepackages mixture of active ingredients

Table 2.10 Grain sorghum leaf area from two plants, biomass from 0.76 m^{-2} area, and grain yield for the locations where parameters were gathered based on the herbicide treatments listed below in 2016.

Herbicide Treatment[a]	Hutchinson Leaf Area[f]	Tribune Leaf Area[f]	All locations[e] Biomass	Tribune Yield
	cm^2	cm^2	g m^{-2}	kg ha^{-1}
1. Rimsulfuron + thifensulfuron fb nicosulfuron	6470 bc	3990 abc	960 a	6130 abc
2. Rimsulfuron + thifensulfuron + *S*-metolachlor & atrazine fb nicosulfuron	7810 ab	4390 ab	840 b	6130 abc
3. *S*-metolachlor & atrazine fb nicosulfuron	9090 a	4540 a	900 ab	5730 cd
4. Rimsulfuron + thifensulfuron + *S*-metolachlor & atrazine[c]	6010 cd	4020 abc	910 ab	6380 a
5. Nicosulfuron[b]	7450 bc	3830 bc	910 ab	5860 bc
6. Nicosulfuron + bromoxynil & pyrasulfotole[b]	7480 bc	3700 c	900 ab	6130 abc
7. Nicosulfuron + dicamba[b]	7180 bc	3820 bc	890 ab	5150 e
8. *S*-metolachlor & atrazine + nicosulfuron[b]	7600 ab	3900 abc	900 ab	5860 bc
9. *S*-metolachlor & atrazine[c]	6310 bc	3830 bc	970 a	6360 a
10. *S*-metolachlor & atrazine fb nicosulfuron + bromoxynil & pyrasulfotole	7560 ab	4310 abc	860 b	5360 de
11. *S*-metolachlor & atrazine fb nicosulfuron + dicamba	7300 bc	4150 abc	840 b	5170 e
12. Nontreated Check	4580 d	3830 bc	910 ab	6300 ab

[a] fb, followed by; herbicides listed before fb were applied PRE, listed after fb were applied POST

[b] POST-only treatment

[c] PRE-only treatment

Values in a column with the same letter were not different at p=0.05

&= indicates commercial prepackages mixture of active ingredients

All POST treatments were applied with atrazine

[e]All locations (Manhattan, Hutchinson, and Tribune) were not significant p=0.5369 therefore locations were combined.

Values in a column with the same letter were not different at p=0.05
&= indicates commercial prepackages mixture of active ingredients

[f] Leaf area from main culm of two plants

Table 2.11 Large crabgrass, stinkgrass, yellow foxtail, wheat, and Palmer amaranth control with the following herbicides treatments 1 week after preemergence treatment at Manhattan and Hutchinson in 2015 and 2016.

	2015					2016	
	Manhattan			Hutchinson		Manhattan	Hutchinson
Herbicide Treatment	Large crabgrass	Stinkgrass	Palmer Amaranth	Large crabgrass	Yellow foxtail	Wheat	Palmer Amaranth
	---------------------------------% control-------------------------------------						
1. Rimsulfuron + thifensulfuron[a]	11 b	11 b	21 b	8 d	10 d	--[b]	--
2. Rimsulfuron + thifensulfuron + *S*-metolachlor & atrazine	99 a	99 a	99 a	49 bc	44 c	1 a	21 ab
3. *S*-metolachlor & atrazine	99 a	99 a	99 a	61 a	66 a	3 a	29 a
4. Rimsulfuron + thifensulfuron + *S*-metolachlor & atrazine	99 a	99 a	99 a	43 c	50 bc	1 a	20 ab
5. *S*-metolachlor & atrazine	99 a	99 a	99 a	55 ab	54 b	6 a	28 a
6. *S*-metolachlor & atrazine	99 a	99 a	99 a	48 bc	45 c	6 a	28 a
7. *S*-metolachlor & atrazine	99 a	99 a	99 a	61 a	64 a	1 a	26 a
8. Rimsulfuron + thifensulfuron	--	--	--	--	--	3 a	15 b

[a] Early Preplant, 15 days before planting

[b] --, Treatment not applied

Values in a column with the same letter were not different at p=0.05

&= indicates commercial prepackages mixture of active ingredients

Chapter 3 - Efficacy of Nicosulfuron on Large Crabgrass, Barnyardgrass, Yellow Foxtail, and Wheat

Abstract

New sorghum technology branded Inzen[TM] Sorghum is becoming available. This technology allows for a POST application of the sulfonylurea herbicide, nicosulfuron. The objectives were to determine the efficacy of nicosulfuron at six different rates a) on four annual grass species, b) with or without atrazine, and c) applied to annual grasses at different heights. The four grass species evaluated were large crabgrass, barnyardgrass, yellow foxtail, and wheat. Nicosulfuron was applied at 0.125, 0.25, 0.5, 1, and 2 times its labeled rate of 35 g ha^{-1}. Each rate was also applied with and without atrazine at 840 g ha^{-1} on 5 to 10 cm tall plants and on 15 to 20 cm tall plants. A total of 24 treatments were applied on each grass species. Visual control ratings were taken 1, 2, and 4 weeks after treatment (WAT). Aboveground biomass was determined at 4 WAT. Biomass reduction for barnyardgrass was greater than 40% for all treatments. Treatments containing 4.4 to 70 g ha^{-1} nicosulfuron caused similar reduction in barnyardgrass biomass compared to the nontreated check. Averaged over the addition of atrazine, nicosulfuron applied at 35 and 70 g ha^{-1} provided 17% less control when treating 15 to 20 cm tall large crabgrass compared to treating 5 to 10 cm tall large crabgrass. Adequate control of large crabgrass was not achieved with any nicosulfuron rate used in this study. Overall, barnyardgrass, yellow foxtail, and wheat were effectively controlled with nicosulfuron when applied at 5 and 10 cm heights, across rates, and without atrazine.

Introduction

Acetolactate synthase (ALS)-resistant grain sorghum was developed by Kansas State University with the goal of being able to provide producers with an option to control annual grasses POST in grain sorghum (Hennigh 2009). This technology is branded Inzen ™ Sorghum and is being released by DuPont Crop Protection. According to the herbicides for grain sorghum table in the Chemical Weed Control Guide there are no herbicides rated better than poor for POST grass weed control (Thompson et al. 2017). In dry climates like the High Plains where grain sorghum is predominately grown, efficacy of PRE herbicides can be poor because of the lack of rainfall and limited herbicide activation (Tapia et al. 1997). Research has shown that grain sorghum yields were greatly reduced by annual grass weed competition (Feltner et al. 1969; Hewitt, 2015; Smith et al. 1990). Feltner et al. (1969) reported that a natural population of yellow foxtail (*Setaria pumila* (Poir.) Roem & Schult) reduced grain sorghum yields by as much as 33% if not controlled. Knowing the impacts that grass weeds have on yield of grain sorghum highlights the importance and need of POST herbicide options to control annual grasses in grain sorghum.

The new Inzen™ Sorghum allows for a POST application of nicosulfuron. Nicosulfuron is an ALS-inhibiting herbicide in the sulfonylurea class. This herbicide was registered for use on corn by the Environmental Protection Agency in 1990 (EPA, 1990). The nicosulfuron label has maximum height recommendations for annual grasses such as barnyardgrass *(Echinochloa crus-galli* (Thunb.) Kunth) at 10 cm, yellow foxtail at 10 cm, volunteer wheat (*Triticum aestivum* L.) at 5 cm, and large crabgrass (*Digitaria sanguinalis* (L.) Scop.) at 5 cm (Anonymous, 2017). The efficacy of nicosulfuron has been documented to vary greatly among the different species (Currie and Geier, 2015; Hennigh, 2009; Tapia et al. 1997). When applied at 35 g ha^{-1}, nicosulfuron was the most effective on wild-proso millet (*Panicum miliaceum* L.), giant foxtail (*Setaria faberi* Herrm.), and woolly cupgrass (*Eriochloa villosa* (Thunb) Kunth.) averaging 87 to 88% control when applied on 5 to 10 cm tall plants (Tapia et al. 1997). When weeds were treated at 15 to 25 cm tall with nicosulfuron at 70 g ha^{-1}, giant foxtail was controlled 90%, whereas wild-proso millet and woolly cupgrass were controlled 43 and 77%, respectively (Tapia et al. 1997). Nicosulfuron applied at 35 g ha^{-1} controlled large crabgrass 80%, green foxtail (*Setaria viridis L*.) by 88%, and shattercane (*Sorghum bicolor* (L.) Moench ssp. *verticilliflorum* (Steud.) de Wet ex Wiersema & J. Dahlb) by 100% (Currie and Geier, 2015). Hennigh (2009) conducted field and greenhouse experiments to determine efficacy of nicosulfuron on annual grasses. In the field study, annual grass control with nicosulfuron ranged from 44 to 88% across four locations. Weed size in this study ranged from 5 to 25 cm. In the greenhouse study, nicosulfuron rates that provided 50% growth reduction (GR_{50}) were 10.9, 14.4, 21.7 and 25.5 g ha^{-1} when barnyardgrass, green foxtail, longspine sandbur (*Cenchrus longispinus* (Hack.) Fernald), and large crabgrass were treated at 5 to 10 cm tall, respectively (Hennigh and Al-Khatib, 2010).

Although previous research showed that nicosulfuron provided good control of barnyardgrass and green foxtail, there are few data that show nicosulfuron efficacy on grass species common in Kansas such as yellow foxtail and volunteer wheat. There are also few data that directly studies the impacts of the addition of atrazine to nicosulfuron in a tank mix and their efficacy at different grass weed heights. Thus, the objectives were to determine the efficacy of nicosulfuron at six different rates a) on four annual grasses, b) with the addition of atrazine, and c) when applied to annual grasses at two different heights.

Material and Methods

Large crabgrass, barnyardgrass, and yellow foxtail seeds were purchased to ensure a common source of each species (Azlin Seed Service, Leland, MS). The wheat variety used in this experiment was Everest. Seeds were sown in 8 cm by 8 cm by 8 cm deep pots. These pots were filled with potting mix (Sungro Metro-Mix 360 RSi Sun Gro Horticulture, Agawam, MA). Each species was planted on two different dates, 10 days apart, to generate the two different plant heights. Plants were grown under greenhouse conditions at 30/26 ± 3ºC day/night temperatures with a 16/8 h day/night periods. The supplemental light intensity was 90 μmol m^{-2} s^{-1} photosynthetic photon flux. Plants were watered from below as needed. All plants were treated one time with imidacloprid for systemic insect control. Plants were thinned to four per pot one day before herbicide application.

Each grass species was treated when plants from the second seeding date reached 5 to 10 cm in height, and the heights of plants from the first seeding were generally 15 to 20 cm tall. Each experimental unit was treated with one of six rates of nicosulfuron, 0, 0.125, 0.25, 0.5, 1, and 2 times the labeled use rate of 35 g ha^{-1}, with or without atrazine at 840 g ha^{-1}. All treatments included crop oil concentrate (COC) at 1% v/v and ammonium sulfate (AMS) at 2,240 g ha^{-1}. To achieve correct rates a dilution method was used starting at the 2 times rate and halving the solution four times to achieve each of the nicosulfuron use rates. Treatments that contained no nicosulfuron were still treated with COC and AMS, as well as atrazine in the treatments that were designated to contain atrazine.

Treatments were applied with a research booth sprayer (DeVries Manufacturing Generation III, Hollandale, MN). The sprayer was calibrated to deliver 187 L ha^{-1} at 220 kPa and traveling at 5.6 km h^{-1}. The nozzle delivering a 40 cm band was placed 24 cm above the plant canopy.

Visual rating of herbicide control of large crabgrass, yellow foxtail, barnyardgrass, and volunteer wheat were taken 1, 2, and 4 weeks after treatment (WAT). These ratings were done on a scale of 0 to 100% with 0%= no control and 100%= complete mortality. Aboveground biomass was harvested by clipping the four plants at the soil surface at 4 WAT. These samples were then bagged, dried at 60 C drier for 7 days and then weighed.

Experiments were conducted as a randomized complete block design. Treatments were replicated four times and experiments were conducted twice. The response data were visual control and biomass reduction for each species as affected by grass weed height, addition of atrazine, and nicosulfuron rate. Visual control and biomass reduction were relative to the 0 nicosulfuron rate. Biomass percent reduction was calculated for each experimental unit by dividing the weight of the treated plants by the weight of the nontreated plants. ANOVA was conducted using the mixed procedure in JMP PRO 12 (SAS Institute Inc., Cary, NC) to test main effects for significant interactions. Grass weed height, addition of atrazine, and nicosulfuron rate were considered fixed effects, where replication was nested in run and was a random effect. No interaction of run was observed and therefore, run and replication (nested within run) were considered random effects, and runs were combined. Appropriate means were separated using LSD $\alpha = 0.05$.

Results and Discussion

The F-ratio and P-values for visual control (Table 3.1) and biomass reduction (Table 3.2) indicate significant sources of variation and thus will be discussed separately for each grass weed species**.** In general, control of all species increased as nicosulfuron rate increased, with the 70 g ha^{-1} rate applied at the 5 to 10 cm grasses providing the greatest level of control. The symptoms from nicosulfuron application were consistent with sulfonylurea herbicide injury, which consisted of chlorosis, progressing to stunting, and in some instances, necrosis.

The interaction of grass height by atrazine by nicosulfuron rate was significant for visual control of barnyardgrass 4 WAT (Table 3.1). In general, nicosulfuron applied at 17.5 g ha^{-1} or more, alone or with atrazine, controlled barnyardgrass 92% or greater with two exceptions. Nicosulfuron at 17.5 g ha^{-1} with atrazine applied to 5 to 10 cm tall barnyardgrass and nicosulfuron at 35 g ha^{-1} without atrazine applied to 15 to 20 cm barnyardgrass only provided 75% control (Table 3.3). The lowest level of control (45%) came from nicosulfuron at 4.4 g ha^{-1} without atrazine applied to 15 to 20 cm barnyardgrass. The addition of atrazine appeared to antagonize nicosulfuron at 8.8 and 17.5 g ha^{-1} applied to 5 to 10 cm barnyardgrass however, control appeared to increase when nicosulfuron was applied at 4.4 or 35 g ha^{-1} with atrazine on 15 to 20 cm tall barnyardgrass. The addition of atrazine provided mixed results with the different plant heights; a closer look is needed to determine the effect of atrazine with nicosulfuron on barnyardgrass. Previous studies have shown a 12% decrease in control of barnyardgrass when nicosulfuron + rimsulfuron was applied with atrazine (Hennigh, 2009). In general, control of barnyardgrass at both heights was similar with 70 g ha^{-1} rate of nicosulfuron, this can be attributed to high susceptibility of barnyardgrass to nicosulfuron. Biomass reduction of barnyardgrass only varied by rate of nicosulfuron (Table 3.2). Barnyardgrass biomass reduction was greater than 40% for all treatments regardless of the rate of nicosulfuron used.

The two-way interaction of grass weed height by nicosulfuron rate was significant for visual control of yellow foxtail (Table 3.1). Nicosulfuron at 17.5 to 70 g ha^{-1} provided 85 to 98% control of short (5 to 10 cm) yellow foxtail. Nicosulfuron applied at 70 g ha^{-1} provided similar control of 10 to 20 cm tall yellow foxtail as nicosulfuron at 17.5 g ha^{-1} to 5 to 10 cm yellow foxtail. Nicosulfuron rates less than 70 g ha^{-1} did not provide adequate control of the taller yellow foxtail (12 to 56%). Only nicosulfuron at 70 g ha^{-1} provided adequate control of both heights of yellow foxtail (Table 3.5).

The two-way interaction of grass weed height by atrazine and main effect of nicosulfuron rate were significant for biomass reduction of yellow foxtail relative to the nontreated control (Table 3.2). Biomass reduction increased as nicosulfuron rate increased, averaged over addition of atrazine and grass weed height, from 40% with 4.4 g ha^{-1} to 57% with 70 g ha^{-1} (Table 3.4). Biomass was reduced less when taller yellow foxtail were treated compared to shorter yellow foxtail. Atrazine reduced control of yellow foxtail when treated at both heights, however, a greater difference in efficacy was observed on short than tall yellow foxtail when atrazine was added (Table 3.6).

The three-way interaction of grass weed height by atrazine by nicosulfuron rate was significant for visual control of wheat (Table 3.1). Nicosulfuron more effectively controlled the 5 to 10 cm wheat than the 15 to 20 cm (Table 3.7). The short wheat (5 to 10 cm) was controlled 94 and 97% when nicosulfuron at 35 g ha^{-1} was applied with and without atrazine, respectively. Nicosulfuron at 35 g ha^{-1} applied to tall wheat provided 39% control, and when tank mixed with atrazine provided 71% control, which was significantly less control than when applications were made to short wheat. Atrazine enhanced control when applied with nicosulfuron at 4.4 and 8.8 g ha^{-1} to 5 to 10 cm tall wheat, by 66 and 22%, respectively. Atrazine did not enhance control of nicosulfuron at the higher rates when applied to short wheat however, when nicosulfuron was applied on tall wheat, atrazine enhanced control of the 35 and 70 g ha^{-1} rates of nicosulfuron by 32 and 27%, respectively. The addition of atrazine did not enhance the control provided by nicosulfuron rates less than 35 g ha^{-1} when applied to tall wheat. Tall wheat treated with nicosulfuron and no atrazine was not controlled. Short wheat treated with atrazine and only 4.4 g ha^{-1} rate of nicosulfuron was controlled 74% and increased to 98% control as rates increased to 70 g ha^{-1}.

Main effects of grass weed height, atrazine, or nicosulfuron rate were significant for biomass reduction of wheat (Table 3.2). As nicosulfuron rate increased, wheat biomass was reduced (Table 3.4). A fourfold increase between nicosulfuron rates was needed to reduce biomass (e.g., 0.125 vs. 0.5 times). Biomass reduction of short wheat averaged 14% more than that of tall wheat when averaged over all herbicide treatments (Table 3.8). Averaged over nicosulfuron rates and plant height at time of application, treatments with atrazine reduced biomass 18% more than treatments applied without atrazine (Table 3.8).This highlights the benefit of applying atrazine in conjunction with nicosulfuron across all rates and wheat stages.

The two-way interactions of atrazine by nicosulfuron rate and grass weed height by nicosulfuron rate were significant for visual control of large crabgrass (Table 3.1). Large crabgrass control was less than 87% regardless of nicosulfuron rate or grass weed height at time of application. This was different than what was observed with the other grass species evaluated in this experiment. Averaged over grass weed heights, the addition of atrazine enhanced control of large crabgrass with nicosulfuron applied at 17.5 g ha^{-1} by 13% (Table 3.9). Atrazine applied alone provided no control of large crabgrass. Averaged over the addition of atrazine, nicosulfuron applied at 35 g ha^{-1} and 70 g ha^{-1} provided 16 to 17% less control when applied to taller compare to shorter large crabgrass plants (Table 3.9). Nicosulfuron rates less than 35 g ha^{-1} provided inadequate control regardless of height of large crabgrass when treated. This result indicates an application with 2 times nicosulfuron rate on large crabgrass that is shorter than 5 to

10 cm may be needed to obtain adequate control. The maximum biomass reduction observed on large crabgrass was 49%. As nicosulfuron rate was reduced biomass reduction also decreased significantly. Large crabgrass showed the widest range of biomass reduction across rates compared to the other species (Table 3.4).

These results indicate that grass weed species and height, addition of atrazine, and nicosulfuron rate all affect control. Across all species, plant height at the time of application played a key role in determining the effectiveness of nicosulfuron. Treating short (5 to 10 cm) plants resulted in greater control than treating tall (15 to 20 cm) plants across all species. This was consistent with the heights that are posted on the nicosulfuron label (Table 3.10). The nicosulfuron label has maximum height for barnyardgrass listed at 10 cm, which was controlled with the normal field rate of nicosulfuron. Adequate control was achieved at the labeled heights for both yellow foxtail and wheat and the normal field rate of nicosulfuron. The labeled height for large crabgrass is 5 cm and in this study most plants were taller than 5 cm, therefore adequate control was not achieved with the recommended field dose.

Control of grasses increased as nicosulfuron rate increased, however the rate providing optimum control was dependent on the species treated. The species listed in order, starting with the most susceptible, were barnyardgrass, yellow foxtail, wheat, and large crabgrass.

In general, the presence or absence of atrazine had inconclusive results in this study. Atrazine had different effects for each species. In wheat, there was evidence that atrazine improved control with several treatments, whereas in yellow foxtail atrazine showed a decrease in control. For large crabgrass and barnyardgrass, results were inconclusive enough to not be confident whether atrazine was beneficial for control. When comparing visual control of the 35 g ha^{-1} treatment of nicosulfuron with and without atrazine across all species and heights, the addition of atrazine with nicosulfuron provided equal or greater control. It must be noted however that evidence of antagonism did occur across lower rates. Further research will be needed to confirm the effects or benefits of adding atrazine to nicosulfuron. Previous research observed improved control of large crabgrass when atrazine was applied in conjunction with nicosulfuron at 26 g ha^{-1}, however at 34 g ha^{-1} of nicosulfuron, atrazine had no added benefit or effect on control (Whaley 2005). Giant foxtail showed no antagonism when atrazine was applied in conjunction with nicosulfuron (Whaley 2005). Another study however, showed a reduction in control of giant foxtail when nicosulfuron at 24 g ha^{-1} was applied with atrazine (Dobbels and Kapusta, 1993).

In conclusion, nicosulfuron can control grass weeds POST in grain sorghum. Adequate control was achieved more consistently among the grass weed species that were 5 to 10 cm tall at time of nicosulfuron application. These results emphasize the importance of using timely applications of the labeled rate of nicosulfuron, which is 35 g ha^{-1}. Results from this experiment provide evidence of atrazine antagonism among certain species especially at lower rates of nicosulfuron. The addition of atrazine did provide a benefit to controlling wheat with low rates of nicosulfuron. The rate of nicosulfuron was a significant effect for visual control and biomass reduction for each grass species. Nicosulfuron can be effective in providing adequate control of barnyardgrass, yellow foxtail, wheat, and large crabgrass, however proper herbicide rate and application timing to recommended plant heights or less must be followed to achieve adequate control.

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Table 3.1 ANOVA table for fixed effects and interactions of visual weed control 4 WAT, including F-ratio and P-values for of atrazine (ATZ), grass weed height, and nicosulfuron rate. Random effects were 2 Runs and Replications within Runs.

Effect	Barnyardgrass		Yellow foxtail		Wheat		Large crabgrass	
	F Ratio	P value	F Ratio	P value	F Ratio	P value	F Ratio	P value
ATZ	1.28	0.26	2.63	0.104	5.15	0.023	0.862	0.353
Height	0.033	0.85	6.89	0.009	46.59	<0.0001	0.870	0.351
ATZ*Height	0.955	0.32	2.63	0.105	8.02	0.005	0.0006	0.980
Rate	105.2	<0.001	184.19	<0.0001	461.37	<0.0001	1535.9	<0.0001
ATZ*Rate	11.09	0.026	6.22	0.183	23.4	0.0001	17.84	**0.0013**
Height*Rate	12.51	0.028	13.43	**0.019**	12.45	0.029	41.43	**<0.0001**
ATZ*Height*Rate	11.74	**0.019**	4.021	0.403	93.52	**<0.0001**	0.962	0.915

Table 3.2 ANOVA table for fixed effects and interactions of biomass reduction 4 WAT including F-ratio and P-values for of atrazine (ATZ), grass weed height, and nicosulfuron rate. Random effects were 2 Runs and Replications within Runs.

Effect	Barnyardgrass		Yellow foxtail		Wheat		Large crabgrass	
	F Ratio	P value	F Ratio	P value	F Ratio	P value	F Ratio	P value
ATZ	0.647	0.42	0.130	0.72	28.22	**<0.001**	0.124	0.724
Height	0.09	0.76	35.11	<0.0001	15.22	**<0.001**	0.489	0.484
ATZ*Height	0.02	0.88	5.20	**0.022**	0.74	0.39	0.331	0.565
Rate	15.47	**0.008**	173.49	**<0.0001**	17.70	**0.003**	48.31	**<0.0001**
ATZ*Rate	0.98	0.96	7.83	0.165	0.84	0.97	0.423	0.994
Height*Rate	0.20	0.99	2.074	0.839	3.79	0.58	0.239	0.999
ATZ*Height*Rate	0.48	0.99	9.50	0.091	2.51	0.77	0.204	0.999

Table 3.3 Visual barnyardgrass control 4 WAT as affected by grass weed height at time of application, addition of atrazine and nicosulfuron rate.

	Visual control						
	Nicosulfuron rate (g ha^{-1})						
Atrazine, height	0	4.375	8.8	17.5	35	70	LSD (0.05)
	%						Atz*Rate*Height
With ATZ, Short[1,3]	6	69	74	76	99	98	18
With ATZ, Tall[1,4]	2	84	85	98	92	97	
W/O ATZ, Short[2,3]	0	71	98	98	98	98	
W/O ATZ, Tall[2,4]	0	46	73	75	97	93	

[1] With ATZ, Atrazine was applied at 840 g ha^{-1} in the tank mix.

[2] W/O ATZ, No atrazine was applied.

[3] Short, treated when plants were 5 to 10 cm tall.

[4] Tall, treated when plants were 15 to 20 cm tall.

All treatments were applied with crop oil concentrate at 1% v/v and ammonium sulfate at 2,240 g ha^{-1}

Table 3.4 Biomass reduction relative to nontreated control of barnyardgrass, yellow foxtail, wheat, and large crabgrass as affected by nicosulfuron rate averaged across plant height at application and with or without atrazine at 4 WAT.

	Biomass reduction						
	Nicosulfuron rate (g ha^{-1})						
Species	0	4.375	8.8	17.5	35	70	LSD (0.05)
	%						Rate
Barnyardgrass	9	41	41	42	44	44	4
Yellow foxtail	5	40	40	46	50	57	10
Wheat	2	22	24	26	28	30	4
Large crabgrass	3	18	31	45	49	49	4

All treatments were applied with crop oil concentrate at 1% v/v and ammonium sulfate at 2,240 g ha^{-1}

Table 3.5 Visual control of yellow foxtail 4 WAT as affected by grass weed height and nicosulfuron rate averaged over atrazine.

	Visual control						
	Nicosulfuron Rate (g ha^{-1})						
Effect	0	4.375	8.8	17.5	35	70	LSD (0.05)
	%						Rate*Height
Short[1]	7	33	48	85	98	98	21
Tall[2]	17	12	20	56	56	84	

[1] Short, yellow foxtail were treated when plants were 5 to 10 cm tall.

[2] Tall, yellow foxtail were treated when plants were 15 to 20 cm tall.

All treatments were applied with crop oil concentrate at 1% v/v and ammonium sulfate at 2,240 g ha^{-1}

Table 3.6 Yellow foxtail biomass reduction 4 WAT as affected by atrazine and plant height.

Effect	Biomass Reduction
	%
With ATZ, Tall[1,4]	28
W/O ATZ, Tall[2,4]	33
With ATZ, Short[1,3]	45
W/O ATZ, Short[2,3]	52
LSD (0.05) Atz*Height	8

[1] With ATZ, Atrazine was applied at 840 g ha^{-1} in the tank mix.

[2] W/O ATZ, No atrazine was applied.

[3] Short, large crabgrass were treated when plants were 5 to 10 cm.

[4] Tall, large crabgrass were treated when plants were 15 to 20 cm.

All treatments were applied with crop oil concentrate at 1% v/v and ammonium sulfate at 2,240 g ha^{-1}

Table 3.7 Visual control of wheat 4 WAT as affected by plant height at time of application, addition of atrazine, and nicosulfuron rate.

	Visual control						
	Nicosulfuron Rate (g ha^{-1})						
Effect	0	4.4	8.8	17.5	35	70	LSD (0.05)
			%				Atz*Rate*Height
With ATZ, Short[1,3]	6	74	75	81	94	98	17
With ATZ, Tall[1,4]	9	13	26	62	71	90	
W/O ATZ, Short[2,3]	0	8	53	91	97	96	
W/O ATZ Tall[2,4]	0	15	20	53	39	63	

[1] With ATZ, Atrazine was applied at 840 g ha^{-1} in the tank mix.

[2] W/O ATZ, No atrazine was applied.

[3] Short, treated when plants were 5 to 10 cm tall.

[4] Tall, treated when plants were 15 to 20 cm tall.

All treatments were applied with crop oil concentrate at 1% v/v and ammonium sulfate at 2,240 g ha^{-1}

Table 3.8 Wheat biomass reduction as affected by atrazine and plant height at application averaged over nicosulfuron rate, 4 WAT.

Effect	Biomass Reduction	LSD (0.05)
	%	
With ATZ[1]	32	ATZ
W/O ATZ[2]	14	4
Short[3]	30	Height
Tall[4]	16	4

[1] With ATZ, Atrazine was applied at 840 g ha^{-1} in the tank mix.

[2] W/O ATZ, No atrazine was applied.

[3] Short, wheat were treated when plants were 5 to 10 cm.

[4] Tall, wheat were treated when plants were 15 to 20 cm.

All treatments were applied with crop oil concentrate at 1% v/v and ammonium sulfate at 2,240 g ha^{-1}

Table 3.9 Large crabgrass visual control 4 WAT as affected by atrazine, height, and nicosulfuron rate.

	Visual Control						
	Nicosulfuron Rate (g ha^{-1})						
Effect	0	4.375	8.8	17.5	35	70	LSD (0.05)
	%						ATZ*Rate
With ATZ[1]	1	5	20	57	71	77	8.08
W/O ATZ[2]	0	10	17	44	67	80	
Short[3]	1	7	15	53	77	87	Rate*Height
Tall[4]	0	8	22	48	61	70	9

[1] With ATZ, Atrazine was applied at 840 g ha^{-1} in the tank mix.

[2] W/O ATZ, No atrazine was applied.

[3] Short treated when plants were 5 to 10 cm tall.

[4] Tall, treated when plants were 15 to 20 cm tall.

All treatments were applied with crop oil concentrate at 1% v/v and ammonium sulfate at 2,240 g ha^{-1}

Table 3.10 Maximum height of grass weed species 35 g ha^{-1} nicosulfuron will control effectively, according to Zest herbicide label (Anonymous 2017).

Grasses	Maximum height
	cm
Barnyardgrass	10
Broadleaf signalgrass	5
Large crabgrass	5
Foxtail spp.	10
Itchgrass	15
Panicum spp.	10
Ryegrass spp.	15
Sandbur spp.	7
Wild oat	10
Wild proso millet	10
Witchgrass	15
Volunteer cereals	15

[1] Foxtail spp. (bristly, giant, green, and yellow)

[2] Panicum spp. (fall, Texas, browntop)

[3] Ryegrass spp. (Italian, perennial)

[4] Sandbur spp. (field, longspine)

Appendix A - Supplemental Tables

Appendix A.1: Weed control with the following herbicides treatments at 1 and 2 weeks after postemergence treatment at Manhattan and Hutchinson in 2015.

	Manhattan						Hutchinson			
	Large crabgrass		Stinkgrass		Palmer Amaranth		Large crabgrass		Yellow Foxtail	
Herbicide Treatment[a]	1 WAT	2 WAT	1 WAT	2 WAT	1 WAT	2 WAT	1 WAT	2 WAT	1 WAT	2 WAT
	--% Control--------------------------------------									
1. Rimsulfuron + thifensulfuron[b] fb nicosulfuron	69 b	70 b	56 b	66 b	81 ns	50 d	76 b	56 d	80 b	62 bc
2. Rimsulfuron + thifensulfuron + *S*-metolachlor& atrazine fb nicosulfuron	99 a	99 a	99 a	99 a	75 ns	99 a	91 a	89 a	97 a	93 a
3. *S*-metolachlor & atrazine fb nicosulfuron	99 a	99 a	99 a	99 a	99 ns	99 a	90 a	86 ab	96 a	91 a
4. Rimsulfuron + thifensulfuron + *S*-metolachlor & atrazine[d]	99 a	99 a	99 a	99 a	95 ns	94 a	15 b	44 d	84 b	46 c
5. Nicosulfuron[c]	55 c	59 c	40 c	51 c	73 ns	54 cd	75 a	51 d	80 b	61 bc
6. Nicosulfuron + bromoxynil & pyrasulfotole[c]	56 c	56 c	40 c	49 c	87 ns	73 b	78 a	49 d	80 b	59 bc
7. Nicosulfuron + dicamba[c]	62 bc	59 c	35 c	51 c	65 ns	69 bc	74 a	58 cd	79 b	72 b
8. *S*-metolachlor & atrazine[d]	99 a	99 a	99 a	99 a	99 ns	99 a	25 b	44 d	79 b	49 c
9. *S*-metolachlor & atrazine fb nicosulfuron + bromoxynil & pyrasulfotole	99 a	99 a	99 a	99 a	77 ns	99 a	81 a	71 bc	88 ab	71 b
10. *S*-metolachlor & atrazine fb nicosulfuron + dicamba	99 a	99 a	99 a	99 a	99 ns	99 a	89 a	91 a	95 a	93 a

[a] fb, followed by, herbicides before fb were applied preemergence herbicides after fb were applied postemergence

[b] Early Preplant 15 days before planting before fb

[c]Postemergence only treatment

[d]Preemergence only treatment

Values in a column with the same letter were not different at p=0.05. NS- not significant

&= indicates commercial prepackages mixture of active ingredients

Appendix A.2 Volunteer wheat, conventional sorghum, and Palmer amaranth control with the following herbicide treatments 1 and 2 weeks after the postemergence treatments at Manhattan and Hutchinson in 2016.

Herbicide Treatment[a]	Manhattan				Hutchinson			
	Wheat		Conv. sorghum		Palmer amaranth		Conv. sorghum	
	1 WAT	2 WAT	1 WAT	2 WAT[h]	1 WAT	2 WAT	1 WAT	2 WAT
	-------------------------------% Control----------------------------------							
1. Rimsulfuron + thifensulfuron fb nicosulfuron	24 abc	67 b	36 b	30	74 ab	61 c	99 a	99 a
2. Rimsulfuron + thifensulfuron + *S*-metolachlor & atrazine fb nicosulfuron	30 ab	93 a	41 ab	30	89 a	90 a	99 a	99 a
3. *S*-metolachlor & atrazine fb nicosulfuron	43 a	98 a	46 ab	30	74 ab	80 ab	99 a	99 a
4. Rimsulfuron + thifensulfuron + *S*-metolachlor & atrazine[d]	0 c	2.5 c	0 c	30	20 c	20 d	28 b	24 b
5. Nicosulfuron[c]	19 abc	81 ab	40 ab	30	83 ab	76 b	99 a	99 a
6. Nicosulfuron + bromoxynil & pyrasulfotole[c]	28 ab	92 a	45 a	30	82 ab	93 a	99 a	99 a
7. Nicosulfuron + dicamba[c]	30 ab	79 ab	40 ab	30	83 ab	91 a	99 a	99 a
8. *S*-metolachlor & atrazine + nicosulfuron[c]	43 a	98 a	40 ab	30	66 b	85 ab	98 a	99 a
9. *S*-metolachlor & atrazine[d]	13 bc	5 c	0 c	0	28 c	20 d	4 c	0 c
10. *S*-metolachlor & atrazine fb nicosulfuron + bromoxynil & pyrasulfotole	40 a	96 a	45 a	0	80 ab	88 ab	91 a	99 a
11. *S*-metolachlor & atrazine fb nicosulfuron + dicamba	39 ab	87 ab	45 a	0	85 ab	91 a	97 a	99 a

[a] fb, followed by, herbicides before fb were applied preemergence herbicides after fb were applied postemergence
[c] Postemergence only treatment
[d] Preemergence only treatment
[e] WHT, volunteer wheat
[f] AMAPA, Palmer amaranth
[g] Conv. Sorg., conventional sorghum
[h] column non-significant p value 0.93
Values in a column with the same letter were not different at p=0.05
&= indicates commercial prepackages mixture of active ingredients

Appendix A.3 Grain sorghum head number ha^{-1} at Hutchinson and grain sorghum head number ha^{-1} along with grain berry number per head at Manhattan among herbicide treatments in 2015.

Herbicide Treatment[a]	Hutchinson Heads ha^{-1}	Manhattan Heads ha^{-1}	Manhattan Grain head^{-1}
	Head no.	Head no.	Berry no.
1. Rimsulfuron + thifensulfuron[b] fb nicosulfuron	109,503	93,860	4014
2. Rimsulfuron + thifensulfuron + *S*-metolachlor & atrazine fb nicosulfuron	92,213	100,447	6000
3. *S*-metolachlor & atrazine fb nicosulfuron	103,740	103,740	4255
4. Rimsulfuron + thifensulfuron + *S*-metolachlor & atrazine[d]	102,917	105,387	4388
5. Nicosulfuron[c]	92,213	88,920	4728
6. Nicosulfuron + bromoxynil & pyrasulfotole[c]	97,153	105,387	4651
7. Nicosulfuron + dicamba[c]	92,213	111,973	5128
8. *S*-metolachlor & atrazine[d]	95,507	111,973	3825
9. *S*-metolachlor & atrazine fb nicosulfuron + bromoxynil & pyrasulfotole	92,213	118,560	4803
10. *S*-metolachlor & atrazine fb nicosulfuron + dicamba	86,450	111,973	4518
11. Nontreated Check	90,567	74,100	2645

[a] fb, followed by, herbicides before fb were applied preemergence herbicides after fb were applied postemergence.

[b] Early Preplant 15 days before planting before fb

[c]Postemergence only treatment

[d]Preemergence only treatment

&= indicates commercial prepackages mixture of active ingredients