ABSTRACT

VINCENT, WILLIAM JACOB. Evaluating Quinclorac for Grass Weed Management in Grain Sorghum in North Carolina. (Under the direction of Wesley J. Everman).

Grain sorghum [*Sorghum bicolor* (L.) Moench] is the sixth most popularly grown cereal grain crop globally behind rice [*Oryza sativa* (L.)], wheat [*Triticum aestivum (*L.)], corn [*Zea mays* (L.)], soybean [*Glycine max* (L.)], and barley [*Hordeum vulgare* (L.)]. Weed management is a concern for grain sorghum growers as few herbicides are developed for grain sorghum use because of its relatively small planted area in the United States compared to corn and soybean. Many herbicides are available to control broadleaf weeds in grain sorghum but few exist for selective annual grass weed management. In 2013, quinclorac previously used in rice, turf, switchgrass [*Panicum virgatum* (L.)], and pre-plant wheat scenarios was registered for in-crop grain sorghum use. Literature review of previous work indicated the susceptibility of many common annual grass weed species to quinclorac. Experiments were conducted to evaluate crop safety and herbicide system strategies for grain sorghum weed management in North Carolina.

Adjuvants are commonly used to enhance the efficacy of postemergence (POST) herbicides. However, discrepancy exists about which products to use with quinclorac. Field and greenhouse experiments were conducted to investigate the impact of quinclorac rate, application timing according to weed growth stage, fertilizer additive, and spray adjuvant on problem weeds and grain sorghum. Increased quinclorac rate proved to be important to weed control when applications were made to weeds beyond 5 cm; otherwise results were not in support of using higher quinclorac rates. In general, oil-based adjuvants enhanced the activity of quinclorac compared with nonionic surfactant. Methylated seed oil increased weed control and resulted in reduced plant height more than when quinclorac was applied

with crop oil concentrate or nonionic surfactant. Quinclorac did not control goosegrass (*Eleusine indica* (L.) Gaertn.), crowfootgrass (*Dactyloctenium aegyptium* (L.) Willd.*)*, and Texas millet (*Urochloa texana* (Buckl.) R. Webster). Grain sorghum yield was influenced most by application timing as applications made to weeds 4 cm tall produced greater yields compared to delayed applications.

The specific relationship of application growth stage, herbicide rate, and targeted weed species are important factors in determining herbicide efficacy. A greenhouse experiment was conducted to determine susceptibility of six common grass species as influenced by growth stage at application and rate of quinclorac. Large crabgrass (*Digitaria sanguinalis* (L.) Scop.), broadleaf signalgrass (*Urochloa platyphylla* (Nash) R.D. Webster*)*, and fall panicum (*Panicum dichotomiflorum* Michx.) were highly susceptible to applications of quinclorac regardless of rate when sprayed when smaller than 5 cm but inconsistent control was observed if sprayed at 10 cm. Texas millet showed signs of susceptibility only for those plants sprayed at 2.5 cm. Goosegrass and crowfootgrass showed minimal growth inhibition and in some cases treated plants were taller and heavier than nontreated plants.

Quinclorac can only be successful in the grain sorghum weed management marketplace if it works additively or synergistically with currently used broadleaf herbicide products. Field studies were implemented in order to evaluate the impact of quinclorac tank mixed with various broadleaf herbicides on crop safety, weed control efficacy, and yield. Quinclorac alone did not injure grain sorghum and provided excellent control of large crabgrass and ivyleaf morningglory (*Ipomoea hederacrea* Jacq.). The addition of atrazine to tank mixtures improved control of several annual grass and broadleaf species and caused slight crop stunting initially but did not impact yield.

Evaluating Quinclorac for Grass Weed Management in Grain Sorghum in North Carolina

by
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A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Masters of Science

Crop Science

Raleigh, North Carolina

2015

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DEDICATION

I thank God for bringing me to North Carolina State University and allowing me the opportunity to conduct research at such an esteemed institution with high caliber advisors and fellow colleagues. My advisor, Dr. Wesley Everman is due many thanks for his trust in me, his unwavering support and his guidance throughout my education at NC State. Zack Taylor, Alex Knight, Eric Paynter, Bryan Hicks, Thierry Besancon, Brandon Schrage, Logan Grier, Anthony Growe, Manish Bansal, John Sanders, Drake Copeland, Adam Blackmore, and Neal O'Quinn are all owed a piece of this thesis as it would not have been possible without them. I was honored to work within the team whose members embodied selfless attitudes and devotion to team play which made my research possible. I have always found much solace and encouragement in the following quote and believe that team members and the dynamic they created embodied this idea, "As iron sharpens iron, so one person sharpens another" Proverbs 27:17 (NIV). I would like to thank my fiancée Amy for her support, encouragement, and love in all aspects of life. Finally, I thank my mother Pat Urquhart, my father Bill Vincent, and my sister Emma Vincent for always believing in me and for their encouragement during my time in graduate school.

BIOGRAPHY

Liam Vincent is from the southeast Michigan area and fostered his passion for agriculture during mission trips to Mexico during which time he was inspired by the impact farming and food have on the world. He pursued his undergraduate education at Iowa State University (ISU) where he received two bachelors of science degrees in Agricultural Business and Agronomy. During his time there, he was an active member of FarmHouse Fraternity. Liam had several on-campus as well as international work opportunities while in school including the United Nations – Food and Agriculture Organization and the ISU Weed Science Department. Working as an hourly laborer for the ISU weed science department, a job turned into a passion for agricultural research. Liam worked for the ISU weed science department for three out of four years of his undergraduate career and became an integral member of the team by managing field and greenhouse trials, communicating with growers/research extension employees, and was involved in documenting resistant weed species throughout the state. It was also at ISU that Liam met the love of his life, Amy. After college, Liam worked for Context Network for a year as a Business Analyst creating quantitative models and compiling and analyzing first source data. It was during this job he realized his need to be around research and closer to the grit and grind of field work and agricultural research. Liam wholeheartedly pursued North Carolina State University for a master's of science degree in Crop Science. In his free time, Liam enjoys playing hockey, lacrosse, reading, and quality time with friends and family.

ACKNOWLEDGMENTS

In addition to those named above in the dedication, I would like to say thank you to all of the professors on my committee and elsewhere for their wisdom helping me to explore my research topics with breadth and depth. Also, none of the research I conducted would have been possible without the help of the staff of the exceptional research stations where we worked; specifically, Central Crops Research Station in Clayton, NC; Upper Coastal Plain Research Station in Rocky Mount, NC; Peanut Belt Research Station in Lewiston-Woodville, NC; and the Caswell Research Farm in Kinston, NC.

TABLE OF CONTENTS

LIST OF TABLES

CHAPTER II

CHAPTER III

CHAPTER IV

CHAPTER 1

Literature Review

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Grain Sorghum *(Sorghum bicolor (L.)* Moench) in the United States

Grain sorghum or milo is the sixth most planted grain crop worldwide behind wheat [*Triticum aestivum* (L.)], corn [*Zea mays* (L.)], rice [*Oryza sativa* (L.)], soybean [*Glycine max* (L.)], and barley [*Hordeum vulgare* (L.)] at 41.1 million harvested hectares in 2010-2013 or 5.5% of world feed grain area and the fourth most planted grain crop in the United States accounting for approximately 2.3% harvested hectares or 2 million hectares in the same period (FAO STAT 2013). Grain sorghum planted acreage in the United States in concentrated in Kansas followed by Texas and Oklahoma where precipitation is limiting for high yielding corn and soybean cultivation (USDA-NASS 2014). Introduction of grain sorghum to North Carolina was spurred on by the demand for feed grains from the local animal industry, for more planted acres and higher yields of corn, wheat, and grain sorghum.

Potential for Grain Sorghum Production in North Carolina

According to the United States Department of Agriculture-National Agricultural Statistics Service (USDA-NASS 2014) estimates from 2014, gross income receipts gained from hogs and broilers for meat ranks North Carolina as third nationally in both categories (USDA-NASS 2014). Before 2012, North Carolina had been importing 5.1 trillion bushels of corn annually, in addition to the 2.5 trillion bushels locally supplied to feed the state's animal industry (Montgomery 2012). Nationally, grain sorghum planted area expanded beginning in the 1960s and peaked in the 1980's at 6.9 million hectares. North Carolina was responsible for growing anywhere from 30,000 to 49,000 hectares of grain sorghum during the same period until grain sorghum declined due to more profitable and drought-tolerant corn and soybean production (USDA-NASS 2014). A majority of row crops such as wheat, corn, soybean, and grain sorghum grown within the state go directly to feeding livestock. Grain sorghum has a nearly equivalent feed value compared to corn and has been known as a desirable silage as well as grain feed (Browning 1966; Myer et al. 2013). Furthermore, Beyer (2012) explained that in terms of nutrient digestibility, nutritional content, and processing ease corn and grain sorghum as feedstuffs for poultry are on an equal playing field.

Grain Sorghum and its Interference with Weeds

Turner et al. (1978) confirmed water use efficiencies of a C4 plant such as grain sorghum compared to a C3 plant. During periods of adequate moisture the two crops performed similarly in terms of osmotic and leaf water potential, photosynthetically active radiation (PAR), and leaf conductance (Turner et al. 1978). In water deficit scenarios, grain sorghum has been shown to produce greater yields compared to soybean (Constable and Hearn 1978) as a result of higher water uptake from dense root systems in the upper 25 cm of soil layers (Burch et al. 1978) and superior water use efficiency during grain fill (Burch et al. 1978). In water limiting scenarios, grain sorghum exhibited more drought tolerance compared to corn mainly due to ability to regulate stomatal closure and water transport system efficiency (Ackerson and Krieg 1977).

Corn and grain sorghum as C4 plants have identical photosynthetic pathways but have different water use efficiencies leading to yield disparities. Schittenhelm et al. (2013) and Zegada-Lizarazu et al. (2012) point to the ability of sweet sorghum to obtain greater plant height and aboveground dry weight compared to corn in medium to dry soil moisture environments. The enhanced drought tolerance of grain sorghum compared to corn in times of water shortage is due to three main factors; more intensive and extensive root penetration (Matsuura et al. 1996), increased water uptake capacity and root length density (Zegada-Lizarazu et al. 2012), and the efficiency with which water is converted to dry matter (Schittenhelm et al. 2013). In addition to the superior drought tolerance of grain sorghum compared to corn, several studies have found that grain sorghum produced greater yields compared to corn (Farre and Faci 2006; Singh and Singh 1995; Staggenborg et al. 2008; Wagner and Knoblauch 2011; Zegada-Lizarazu et al. 2012).

Weeds are more competitive for nutrients, light, and water compared to grain sorghum in early development stages making early season weed control essential to a high yielding grain sorghum crop (Sankaran and Mani 1972). Early season weed competition with grain sorghum has been shown to be greater with grain sorghum than many other row crops (Stahlman and Wicks 2000). One pigweed plant/30 m^2 reduced grain yield 48% compared to one barnyardgrass (*Echinochloa crus-galli* (L.) Beauv.) plant per meter of crop row which reduced yield by 10% (Norris 1980; Shipley and Wiese 1969). It has been shown that the interference of texas millet (*Urochloa texana* (Buckl.) R. Webster), large crabgrass

(*Digitaria sanguinalis* (L.) Scop.), and barnyardgrass reduced yield by about 4% with each week of interference with the crop (Smith et al. 1990).

A large body of research exists concerning the critical weed free period of sorghum. Although estimates differ, it is accepted that sorghum will tolerate weed competition from three to six weeks after crop emergence if the crop stand remains weed free for four weeks after planting (Burnside and Wicks 1967; Feltner 1969). Furthermore, work from Okafor and Zitta (1991) discovered that the critical weed free period of grain sorghum is dependent upon crop fertilization. Unfertilized grain sorghum will not tolerate the presence of weeds if allowed to coexist for any period of time. However, grain sorghum which received 60-120 kg N ha^{-1} could tolerate 7-14 days of weed competition without dramatic yield loss. Stahler (1948) postulated that under sufficient conditions of nutrients and soil moisture, light became the most limiting factor to crop and weed competition. Photosynthetically active radiation (PAR) is the most important factor on plant growth and competitive ability (Graham et al. 1988). Work from Clegg et al. (1974) found that although the upper canopy of grain sorghum consisted of less than half of the plants total leaf area, this region gathered 70-80% of incoming PAR. Palmer amaranth (*Amaranthus palmeri* S. Wats.) competition reduced grain sorghum LAI which resulted in a retarded ability to achieve maximum light absorption. Taller and more competitive pigweed plants were then able to absorb more PAR than the grain sorghum plants leading to decreased head and dry weights (Graham et al. 1988).

Crop competition for water is contingent on three factors; relative growth rate, ability to obtain available soil water and early vigor to establish an extensive root system (Donald 1963). In an experiment by Slayter (1955), grain sorghum developed the most extensive root system and transpired less moisture compared to peanut [*Arachis hypogaea* (L.)] and cotton [*Gossypium hirsutum* (L.)]. Furthermore, Wiese and Vandiver (1970) found that soil moisture conditions dictate the competitive ability of crops and weeds.

Weed Control in Grain Sorghum

Grain sorghum is often planted into fields with minimal tillage increasing grower reliance upon preemergence herbicide use to set weeds back and make the crop more competitive. The innovation of seed safeners to protect grain sorghum seed from chloroacteamide injury has allowed for the use of more versatile preemergence herbicides to be used such as s-metolachlor (Ellis et al. 1980). Herbicide active ingredients such as s-metolachlor, mesotrione, acetochlor, and dimethenamid-P (Everman and Besancon 2011; Ferrell et al. 2012) have excellent to moderate control of grass weed species when applied pre-emergence. However, a preemergence application is often not sufficient to control annual grass weeds throughout the growing season. Burnside (1977) found that atrazine applied at 2.24 kg ai ha^{-1} to 8 cm tall weeds provided total control of broadleaf weeds but only 33% control of green foxtail and large crabgrass. Furthermore, the lack of activating rainfall due to the location of common grain sorghum areas may limit the potential efficacy of preemergence herbicides, especially on grass species (Regehr 2008).

Several herbicide tools exist to address in-crop dicotyledonous weed problems in grain sorghum, but until 2013 no postemergence herbicide tools were available to control monocotyledonous weeds. Much research has been conducted which proves the utility of properly timed post emergence applications of auxin mimic herbicides such as dicamba and 2,4-D in their ability to eliminate broadleaf weeds from in-crop grain sorghum (Dan et al. 2010; Petter et al. 2011; Rosales-Robles et al. 2011). The 2014 version of the North Carolina Agricultural Chemicals Manual along with outside research reveals effective options for broadleaf weed control for in-crop grain sorghum including atrazine (Rosales-Robles et al. 1991), acetochlor (Jackson et al. 1985), prosulfuron (Rosales-Robles et al. 2012), fluthiacet-methyl (Reddy et al. 2014), bentazon (Rosales-Robles et al. 2011), halosulfuron (Hennigh et al. 2010), carfentrazone-ethyl (Hennigh et al. 2010), bromoxynil (Wicks et al. 1994), and bromoxynil + pyrasulfotole (Fromme et al. 2012). None of the herbicides on the aforementioned list along with dicamba and 2,4-D; have an acceptable level of phytotoxic activity on emerged monocotyledonous weed species. Growers have been forced to use paraquat or linuron at the post-directed stage to control monocotyledonous weed problems (Walker et al. 1991).

Results from farmer surveys conducted by the Southern Weed Science Society in 2012 revealed that in each of the grain sorghum producing states surveyed (Alabama, Arkansas, Florida, Georgia, Mississippi, Missouri, and Texas) a grass weed species was ranked the #1 most common and troublesome weed issue in grain sorghum production. Furthermore, in all but one state a grass weed species was named as the second most troublesome weed species as well (Webster 2012). A large gap in grain sorghum weed control exists for postemergence control of grass weed species.

Weed Control Opportunities in Grain Sorghum using Quinclorac

Quinclorac, or 3,7- dichloroquinolinecarboxylic acid has been used as a weed control tool in rice, turf, grass grown for seed, fallow systems, preplant wheat, switchgrass, non-crop area, pasture, rangeland, and in-crop grain sorghum (Anonymous, 2013). Landes et al. (1991) found quinclorac to be efficacious in the control of *Echinochloa* spp., *Digitaria sanguinalis*, *Brachiaria* spp., *Aeschynomene* spp., *Ipomoea* spp., and *Sesbania exaltata* in rice. Previously known as Drive XLR8, Drive, and Paramount; quinclorac has been re-branded and released under the trade name Facet L in 2013 for postemergence weed control of select grass and broadleaf species in grain sorghum.

The mode of action and selectivity of quinclorac are topics of contention amongst some researchers. In susceptible broadleaf species, plant response to quinclorac resembles the visual symptoms seen after applications of 2,4-D or dicamba. However, in susceptible grasses, rapid reddening leading to chlorosis on the youngest expanding leaf is followed by necrosis on the whole plant (Koo et al. 1991). Differences in crop and weed selectivity is dependent upon three factors uptake (Devine, 1989), translocation (Lichtner, 1986), or metabolism (Shaner and Robson, 1985).

Two separate studies were conducted to evaluate the mechanism of selectivity; each one compared a tolerant and sensitive grass species by applying the aforementioned plants with radiolabeled quinclorac to gauge plant response in terms of absorption, translocation, and metabolism (Chism et al. 1991; Zawierucha and Penner 2000). Both studies as well as others examining this topic agree that quinclorac is not well metabolized, including tolerant species (Enloe et al. 1999; Lamoureux and Rusness 1995). Chism et al. (1991) found that quinclorac was taken up rapidly (>66%) by both species whereas Zawierucha and Penner (2000) reported low uptake (<27%). The latter party claim differences in application technique as responsible for discrepancies in results, namely the use of pure methanol as carrier by Chism et al. (1991), which according to Zawierucha and Penner (2000) would amplify the effects of the herbicide beyond commercially feasible replication. In addition, Chism et al. (1991) made the herbicide application to the youngest leaf while Zawierucha and Penner (2000) applied to the most fully expanded mature leaf. In another study, at 128h after treatment, Kentucky bluegrass (*Poa pratensis* L.) (tolerant to quinclorac) was able to move more quinclorac to nontreated portions of the plant more readily than southern crabgrass (*Digitaria ciliaris* (Retz.) Koeler) similar to other tolerant species such as rice (Berghaus and Wuerzer 1987; Chism et al. 1991). Sensitive species do not move quinclorac out of the treated leaf (Berghaus and Retzlaff 1988; Chism et al. 1991; Enloe et al. 1999; Zawierucha and Penner 2000).

Quinclorac is known to be translocated more acropetally than basipetally throughout the plant via foliar as well as soil activity (Williams et al. 2004). Furthermore, Williams et al. (2004) sought to further understand if either form of absorption was more important than another. By exposing torpedograss (*Panicum repens* L.) to various rate and time of exposure periods, it was determined that quinclorac is better absorbed and translocated when it comes in contact with roots compared to foliage. These findings are in agreement with McAvoy et al. (1987). Along with numerous other studies, Williams et al. (2004) pointed out that quinclorac is not well metabolized (Chism et al. 1991; Enloe et al. 1999; Zawierucha and Penner 2000) or translocated (Enloe et al. 1999; Zawierucha and Penner 2000) by sensitive species. These findings suggest that quinclorac remains stable and unmetabolized in the treated leaf of susceptible species, specifically in the youngest tissue and points to soil and root activity as important for weed control. Mechanism of selectivity studies on quinclorac absorption, translocation, and metabolism point to target site interactions as factors to explain quinclorac selectivity (Chism et al. 1991; Zawierucha and Penner 2000). Furthermore, Koo et al. (1997) and Abdallah et al. (2006) proposed that alternate binding site relationships at the target site as the reason for selectivity between tolerant and resistant species.

The mode of herbicidal activity of quinclorac is of contentious debate due to its highly selective nature and variable symptomology in broadleaves and grasses. Berghaus and Wuerzer (1987) found that quinclorac inhibited root growth of cucumbers similar to 2,4-D. It was also discovered that when applied to rice and barnyardgrass that rice was able to distribute the herbicide through its roots and survive while barnyardgrass was not able to transport it and senesced (Berghaus and Wuerzer 1987). Although quinclorac may cause symptoms typical of 2,4-D, such as mesocotyl elongation, the level at which this occurs with quinclorac is significantly less than that of 2,4-D. (Berghaus and Wuerzer 1987 and Koo et al. 1991). Koo et al. (1996) demonstrated on corn roots that quinclorac operates in a unique manner, unlike its structurally similar auxinic counterparts by interfering with cell wall biosynthesis of susceptible grass species. The hemicellulosic and cellulosic portions of the cell wall were rapidly broken down and over increased exposure times and higher herbicide rates, led to root growth inhibition and a decrease in major cell wall constituents such as glucose as seen by Koo et al. (1994). Furthermore, Koo et al. (1994) found that electrolyte leakage amongst the susceptible grasses tested was nearly fivefold greater compared to the tolerant grasses or susceptible broadleaf species. This evidence suggested that electrolyte leakage was a secondary effect of cell wall biosynthesis interruption by quinclorac and that a unique mode of action must exist due to the disparities exhibited by quinclorac between susceptible broadleaf and grass species (Koo et al. 1994).

Expanded research done by Koo et al. (1997) found rapid cell wall synthesis inhibition due to decreasing levels of glucose incorporation into cell walls on a concentration and time dependent scale. Koo et al. (1997) demonstrated that even in tolerant species, root inhibition was noticed after quinclorac application while the shoots of the same species were unaffected suggesting a tissue specific response at the site of action.

In contrast, work by Grossmann and Kwiatkowski (1993) postulated the similarity in mode of action of quinclorac to other auxinic herbicides by exposing root sections of barnyardgrass to various exposure periods and quinclorac concentrations. Similar to other auxin-type compounds, quinclorac was found to induce the production of the same growth regulator inhibitor compounds and produce a higher level of ethylene in susceptible compared to resistant species, similar to 2,4-D. When quinclorac was applied to the vascular system of barnyardgrass, increases in 1-aminocyclopropane-1-carboxylic acid (ACC) were documented followed by production of ethylene and eventually cyanide as a byproduct of the two previous processes (Grossmann 1998). Cyanide and ethylene levels were respective to exposure time, application rates, and were responsible for a negative correlation between these ACC metabolites and the fresh weights of barnyardgrass (Grossmann and Kwiatkowski 1995). In 2011, Sunoharo et al. found that while cyanide accumulation was a likely and probable explanation for susceptible grass species phytotoxicity brought on by quinclorac application, the inherent ability of a plant species to tolerate reactive oxygen species (ROS) should be considered. Based on GR_{50} values, goosegrass (*Eleusine indica (L.)* Gaertn.) (tolerant) was found to be 313 times more tolerant of quinclorac compared to southern crabgrass (susceptible) when seedlings of each species were exposed to quinclorac. Tolerance to quinclorac by goosegrass of this magnitude has been noted previously (Sunohara et al. 2010, Zawierucha and Penner 2000; Zawierucha and Penner 2001). According to Sunohara et al. (2011), quinclorac application causes overproduction of ROS and the ability of a plant to survive is dependent on its antioxidative capacity to divert high ROS concentrations from interfering with lipids, proteins, and nucleic acids and detoxify potentially phytotoxic levels of cyanide. Both researchers of the two hypotheses, (Koo et al. and Grossmann and Kwiatkowski) agree that the target site is the mechanism of selectivity.

Quinclorac has been shown to be safe on grain sorghum (Grossmann 2000; Koo et al. 1991). Consequently, full knowledge of the weed control spectrum is vital in utilizing quinclorac as a herbicide tool. According to the current Facet L label for in crop grain sorghum, quinclorac is capable of controlling the following grasses; large crabgrass, barnyardgrass, giant foxtail (Setaria faberi), green foxtail (Setaria viridis), yellow foxtail (Setaria pumila), junglerice (*Echinochloa colona (L.) Link*), and broadleaf signalgrass (*Urochloa platyphylla* (Nash) R.D. Webster) when applied to plants shorter than 5 cm. Furthermore, Koo et al. (1991) confirmed efficacy on the aforementioned species as well as fall panicum (*Panicum dichotomiflorum* Michx.*)* and orchardgrass (*Dactylis glomerata* L.*)*.

Effects of Timing, Adjuvants, and Fertilizer Additives along with Quinclorac

Most relevant literature existing about quinclorac regarding crop safety, weed control efficacy, and yield effects is for turfgrass, rice, and pasture crops. Koo et al. (1991) evaluated the differential response of 17 grass and 18 broadleaf crop and weed species to quinclorac and 2,4-D on a scale of complete destruction (100) to no effect (0). Koo showed (quinclorac-tolerant) rice incurred 0% injury at 145 g ai ha^{-1} of quinclorac while grain sorghum exhibited 10% injury at the same level. Goosegrass has been shown to be tolerant to applications of quinclorac and incurred the same low level of injury as grain sorghum. Street and Mueller (1993) and Street et al. (1995) found quinclorac to be a versatile herbicide for use in rice weed control as the crop benefitted from higher yields as a function of improved weed control and increased rate at the preplant incorporated (PPI), preemergence moist (PRE-M), preemergence dry (PRE-D), and early postemergence (EPOST) application timings. Street et al. (1995) found EPOST to be the most efficacious application timing to benefit rice yields and control weeds compared to PPI, PRE-M, or PRE-D. Quinclorac has demonstrated phytotoxicity of emerged weeds in rice crops as well as residual control of weeds emerging 2 to 3 weeks after application (Stauber et al. 1991). However, more important than application timing may be the relationship of herbicidal efficacy and moisture after application. Quinclorac efficacy on barnyardgrass, hemp sesbania (*Sesbania herbacea* (Mill.) McVaugh), and palmleaf morningglory (*Ipomoea wrightii*) as well as rice yield was found to be greatest when applied to moist soil (Street et al. 1994).

Quinclorac requires the addition of a spray adjuvant for optimum weed control. Spray adjuvants can be categorized into two large subgroups; activator and utility adjuvants. Aqueous herbicide- activator adjuvant mixtures are utilized to improve postemergence weed control of hard to kill as well as susceptible species, decrease crop injury, and extend weed control beyond normally susceptible growth stages (Enache and Ilnicki 1991; Street et al. 1995; Zawierucha and Penner 2000). The performance of postemergence adjuvants have been found to be variable in their efficacy dependent upon the weed species, companion herbicide, and application environment (Kent et al. 1991; Manthey et al. 1995; Strahan et al. 2000). Adjuvants allow the herbicide to be more effective via leaf wetting, spreading, and altering epicuticular wax formation (Behrens 1964; Jansen 1964; McWhorter and Azlin 1978). The physical and chemical changes caused by adjuvant use can lead to better weed control because of increased levels of absorption and translocation of herbicides (McWhorter 1982).

It is well documented that activator adjuvants have acted synergistically to improve weed control when combined with a postemergence herbicide and quinclorac is no exception (Manthey et al. 1990; Strahan et al. 2000; Wixson and Shaw 1991). The quinclorac label requires the use of an adjuvant for optimum herbicide efficacy, specifically the inclusion of crop oil concentrate (COC) or methylated seed oil (MSO) while the addition of urea ammonium nitrate (UAN) or ammonium sulfate (AMS) is optional. Quinclorac efficacy is greatly improved in the presence of an oil-based adjuvant compared to a nonionic surfactant (Woznica et al. 2003 and Zawierucha and Penner, 2001). Nonionic surfactant (NIS) with AMS may be included instead of COC or MSO where oil-based adjuvant restrictions apply (Anonymous 2013). Manthey et al. (1995) found that the differential response of several nonionic surfactants combined with various herbicides, including quinclorac show higher hydrophillic : lipophillic balance (HLB) values of surfactants tended to improve phytotoxicity. In addition, Manthey et al. (1995) found that surfactant chemistry as well as individual plant species are just as important to consider when ranking product efficacy.

The addition of COC has been shown to increase weed control efficacy over the companion herbicide applied alone in the following herbicide active ingredients; lactofen, chlorimuron, fomesafen, glyphosate, and quinclorac (Manthey et al. 1990; Sims et al. 1989). Methylated seed oils are another common activator adjuvant which are used extensively in postemergence herbicide-adjuvant aqueous sprays in soybean, small grains, and major grain crops. Manthey et al. (1990) found that MSO reduced shoot fresh weight of certain grass weed species more than refined seed oils or petroleum based oil adjuvants. MSO has been found to synergize nicosulfuron activity when applied together and allow for lower rates of nicosulfuron to be applied (Idziak and Woznica 2013)

Fertilizer additives such as AMS and UAN have shown mixed effects in weed control efficacy. Quinclorac is a weak acid herbicide and alike similar herbicides, its efficacy can be reduced in the presence of certain cations in carrier water. AMS proved to be more effective at overcoming the antagonism of salt cations (not calcium) in well water compared to UAN (Woznica et al. 2003). Woznica et al. (2003) found that the activity of quinclorac was increased if AMS was applied along with COC or MSO when spray carrier water contained certain cations. However, in tap water without antagonistic salts, the addition of either AMS or UAN made no significant difference in green foxtail fresh weight reduction compared to the surfactant alone (Woznica et al. 2003). Pearson et al. (2008) demonstrated that adding UAN to penoxsulam and bispyribac based tank mixes did not improve broadleaf signalgrass control.

Numerous researchers have demonstrated improved herbicide efficacy when targeting shorter, younger monocotyledonous weeds compared to taller, older plants (Anmadi et al. 1980; Beckett et al. 1992; Hager et al. 2003; Kells et al. 1984; Knezevic et al. 2010; Smith 1974). Anmadi et al. (1980) investigated the impacts of glyphosate activity on barnyardgrass plants at 5, 10, 15, and 20 cm plants and found greater amounts of absorption and translocation with 5 and 10 compared to 15 and 20 cm plants. Furthermore, Kells et al. (1984) found less herbicidal activity on five-six leaf quackgrass compared to two-three leaf plants. Grass species have been shown to be best controlled at earlier rather than later application timings (Craigmyle et al. 2013; Ngouajio and Hagood 1993; Smith 1974).

Research has also indicated that higher rates of herbicide applied at earlier stages of crop development can improve weed control and crop yield (Smith 1974). A similar study examined the impacts of herbicide rate and timing of atrazine on southern sandbur (*Cenchrus echinatus L*). and found that the greatest reduction in weed dry weight biomass, height, and seed production occurred when the application was made when first true pair of leaves unfurled compared to the emergence of the second pair of leaves or tillers (Dan et al. 2011). Chism et al. (1992) have confirmed that postemergence applications of quinclorac decrease in herbicide efficacy as southern crabgrass became more mature. Meanwhile the higher rates of quinclorac has demonstrated that the herbicide sometimes improves control (Enanche and Ilnicki 1991; Franetovich and Peeper 1995) and sometimes does not impact weed control (Franetovich and Peeper 1995; Street et al. 1995).

Previous research has not studied quinclorac efficacy as a function of species and application timing within a range of weed sizes of particular interest or importance to agricultural production (Chism et al. 1992; Zawierucha and Penner 2001). Current weed management guidelines from the Facet L label recommend that applications should not be delayed past 5 cm in height for all species. Chism et al. (1992) demonstrated decreased herbicide efficacy as plants aged with *Digitaria* spp. However, the smallest plant size did not equate to the largest reduction in dry weight biomass. The tillering stage of southern crabgrass was shown to be more susceptible per unit of quinclorac compared to pre emergence, first true leaf, and flowering application timings (Chism et al.1992). Goosegrass, a known tolerant species, could not be controlled until application rates reached 2000 g ai ha^{-1}, a rate more than twofold greater than the one time per year application limit (Zawierucha and Penner 2001).

No prior research has used quinclorac on a field study basis to obtain a holistic view of how quinclorac may fit as a postemergence herbicide in grain sorghum weed management. The versatility of quinclorac at several application timings and its efficacy on several important agronomic weeds encountered in crop production warrant its testing. Research results must reveal optimum application timing of quinclorac, appropriate adjuvant combinations, and safe tank mix partners. If quinclorac can be combined with a formidable broadleaf herbicide, a grower should be able to achieve full spectrum, season long weed control and obtain high grain sorghum yields to provide more local feed sources for the animal industry.

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CHAPTER 2

Weed Efficacy and Grain Sorghum Response to Quinclorac Applied with Various Adjuvants.

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Abstract

Grass weed management in grain sorghum is a cause of concern for growers as they are dependent on preemergent herbicides and activating rainfall to achieve grass control. However, the regions in which grain sorghum is best fit to be cultivated, sufficient moisture is not always available. In 2013, quinclorac was released as an option for selective postemergence weed control in grain sorghum. Annual and perennial grasses are difficult to control in grain sorghum and often reduce yield because herbicide options are limited in this crop. Greenhouse evaluations were conducted during 2015 to determine the effect of adjuvant and fertilizer additives on weed control. Field evaluations were conducted during 2014 and 2015 to determine the effect of adjuvant and fertilizer additives on weed control and grain sorghum. Greenhouse experiments included three adjuvants; crop oil concentrate (COC), methylated seed oil (MSO), and nonionic surfactant (NIS); two fertilizer additives: urea ammonium nitrate (UAN) and ammonium sulfate (AMS); and six annual grasses large crabgrass, broadleaf signalgrass, fall panicum, Texas millet, crowfootgrass, and goosegrass. Field experiments included three adjuvants: COC, MSO, and NIS; two weed growth stages: 2.5 – 5 cm and 8 – 10 cm; two herbicide rates: 290 and 420 g ae ha^{-1}, and one fertilizer additive: AMS.

In field experiments, quinclorac did not injure grain sorghum regardless of adjuvant or fertilizer additive. Broadleaf signalgrass was controlled at least 90% regardless of adjuvant in field studies and greenhouse evaluation. Growers should avoid NIS in tank mixtures for control of large crabgrass and fall panicum. Texas millet was best controlled

with MSO but control was less than 15%. Crowfootgrass and goosegrass control never exceeded 4% control in the greenhouse or 46% in the field. In high to moderate yield scenarios, applying quinclorac at the early postemergence timing targeting 2.5 to 5 cm weeds provided significantly greater yields than treatments targeting 8 – 10 cm weeds.

Nomenclature: Broadleaf signalgrass, (*Urochloa platyphylla (Nash) R.D. Webster*); crowfootgrass, (*Dactyloctenium aegyptium* (L.) Willd.*)*; fall panicum, (*Panicum dichotomiflorum* Michx.); grain sorghum, *[Sorghum bicolor* (L.) Moench]; goosegrass, (*Eleusine indica* (L.) Gaertn.*);* large crabgrass, (*Digitaria sanguinalis* (L.) Scop.*);* quinclorac; Texas millet, (*Urochloa texana* (Buckl.) R. Webster).

Key Words: AMS, COC, crop safety, fertilizer additive, MSO, NIS, quinclorac, UAN, weed growth stage, yield.

Postemergence grass weed management in grain sorghum is challenging in part because herbicide options are limited (Walker et al. 1991). Broadleaf signalgrass, large crabgrass, fall panicum, Texas millet, crowfootgrass, and goosegrass have all been named as either a top ten most common or troublesome weed species for grain sorghum growers in the southeastern United States (Webster 2012). Broadleaf signalgrass has demonstrated a highly competitive ability to displace other weed species such as fall panicum and large crabgrass in several important row crops (Johnson and Coble 1986). Large crabgrass has been shown to be an abundant seed producing species that was listed in the top ten most common and troublesome weeds throughout southern grain sorghum production (Webster 2012). Fall panicum has become a problem in corn production as atrazine has been shown to be ineffective at controlling this species (Harvey and Doersch 1974). Fall panicum is tolerant of atrazine, and in the absence of other more competitive weed species, has been allowed to thrive (Parochetti 1974; Schnappinger and Wilson 1972).

Texas millet has been shown to be tolerant of many pre-plant and preemergence herbicides and has become a problem in several row crops throughout the southeast and southwest regions of the United States (Chandler and Santelmann 1969; Grichar 1991). The use of chloroacetamide preemergence herbicides to control certain weeds allowed large seeded species such as Texas millet to grow alongside the crop without the competition of other weed species (Buchanan et al. 1983). Crowfootgrass is drought tolerant, native to Africa and is a major weed problem in the cultivation of several crops in China and India and has become present in certain regions and crops in the United States (Bridges et al. 1994;

Chauhan 2011). Bridges et al. (1994) indicated that crowfootgrass infests up to 75% of the peanut [(*Arachis hypogea* (L.)] production area in Virginia and North Carolina, which is a primary region for renewed interest in grain sorghum production. Goosegrass is one of the world's most troublesome weed species and has been shown to be resistant to several modes of action in the cultivation of many row crops (Heap 2015).

Quinclorac, a postemergence grass product labeled for grain sorghum in 2013, is labeled to control several common and troublesome grass species in the southeastern U.S (Anonymous 2013; Webster, 2012). According to the product label, broadleaf signalgrass and large crabgrass can be controlled by applications of quinclorac up to 5 cm in height. However, the product label does not recognize fall panicum or Texas millet as weed species which are either controlled or suppressed. Koo et al. (1991) demonstrated fall panicum susceptibility to quinclorac when quinclorac was applied at 11 days after planting and visual control estimated 100% complete plant death at 145, 290, 580, 1160, and 2320 g ha^{-1}. Goosegrass control was only achieved with quinclorac rates that fall outside labeled recommendations (Zawierucha and Penner 2001).

The mode of action of quinclorac is unknown but one hypotheses attributes phytotoxicity to cyanide accumulation in susceptible grass species as a result of the over stimulation of ACC synthase (Grossmann and Kwiatkowski 1995). Quinclorac can be applied pre-plant incorporated, (PPI), preemergence (PRE) or postemergence (POST) and has root as well as foliar activity (Street and Teresiak 1994; Williams 2004). Quinclorac activity has been shown to require a spray adjuvant for maximum weed control efficacy

(Enanche and Ilnicki 1991; Manthey et al. 1995; Woznica et al. 2003). Aqueous herbicide activator adjuvant mixtures are utilized to improve postemergence weed control of hard to kill as well as sensitive species, decrease crop injury, and extend weed control beyond previously susceptible growth stages (Enanche and Ilnicki 1991; Street and Teresiak 1994; Zawierucha and Penner 2000). Adjuvants allow the companion herbicide to be more effective via leaf wetting, spreading, and altering epicuticular wax formation (Behrens 1964; Jansen 1964; McWhorter and Azlin 1978). The physical and chemical changes caused by adjuvants use can lead to better weed control due to increased levels of absorption and translocation of herbicides (McWhorter 1982). However spray adjuvants do not always improve weed control efficacy (Bland and Brian 1975; Smith et al. 1966; Temple and Hilton 1963).

Previous research has demonstrated that activator adjuvants have acted synergistically to improve weed control when combined with a postemergence herbicide and quinclorac is no exception (Strahan et al. 2000; Woznica et al. 2003). Efficacy of quinclorac is greatly improved in the presence of an oil-based adjuvant (Woznica et al. 2003; Zawierucha and Penner 2001). Performance of quinclorac is improved with the use of an adjuvant for optimum herbicide efficacy, specifically the inclusion of COC or MSO while the addition of UAN or AMS is optional (Anonymous 2013; Manthey et al. 1990). However, NIS with AMS may be included instead of COC or MSO where oil-based adjuvant restrictions apply (Anonymous 2013). The use and efficacy of NIS is variable depending on the crop and weed species to which it is applied (Nalewaja et al. 1990; Strahan et al. 2000). Nonionic surfactants have been shown to decrease leaf surface tension leading to improved spray droplet adhesion and spray coverage which has been shown to lead to higher amounts of herbicide absorption (De Ruiter et al. 1990; McWhorter and Ouzts 1994; Singh and Mack 1993). Oil-based adjuvants have been shown to be superior in weed control of broadleaf and grass weed species compared to surfactants with the same herbicide (Knezevic et al. 2010; Sharma and Singh 2000; Tonks and Eberlein 2001).

The specific interaction effects of NIS, COC, MSO, and fertilizer additives along with quinclorac on large crabgrass, broadleaf signalgrass, fall panicum, goosegrass, Texas millet, and crowfootgrass have not been previously explored. Therefore the objective of this study is to evaluate the effectiveness of quinclorac alone and in combination with NIS, COC, MSO, AMS, and UAN on six grass weed species to determine which adjuvant(s) or combinations will provide the greatest control of each weed species.

Materials and Methods

Greenhouse Experiments

Greenhouse experiments were conducted to evaluate the impact of various combinations of spray adjuvant and fertilizer additive combinations on quinclorac efficacy applied to six common annual grass weed species in grain sorghum production. The experiment was organized as a three factor factorial with factors consisting of six grass weed species, four adjuvants, and three fertilizer options. Experiments were conducted using a randomized complete block design with six replicates and were repeated twice.

Crowfootgrass, large crabgrass, goosegrass, and fall panicum seed were collected in the fall of 2013 from a fallow field at Central Crops Research Station in Clayton, NC and Texas millet seed was collected from a field near Wallace, NC. Seed of broadleaf signalgrass were purchased from Azlin Seed Services (Azlin Seed Services, 112 Lilac Dr, Leland, MS 38756). Germination procedures such as freezer storage, seed scarification, and shallow planting were employed according to species to promote vigorous germination. Large crabgrass, goosegrass, broadleaf signalgrass, fall panicum, Texas millet, and crowfootgrass seeds were sown into 7.62 cm tall by 7.62 cm wide plastic pots (Wyatt-Quarrels, 730 US-70, Garner, NC 27529). Each species was planted into moist soil medium (4P Fafard Growing Mix, (43-53% Canadian sphagnum peat moss, pine bark, vermiculite, perlite, dolomitic wetting agent), Sun Gro Horticulture Ltd. 52130 RR 65, PO Box 189, Seba Beach, AB T0E 2BO Canada) and according to species-specific planting depth guidelines and watered afterwards in order to ensure optimum seed-soil contact, germination, and emergence (Buhler and Hoffman 1999).

Seedlings were thinned to one plant per pot within two days after emergence and were irrigated in order to allow for rapid growth. Natural sunlight was augmented by 1000W metal halide lamps of 16 hour photoperiods, providing a daily photon flux of 455.8 μ mol m^{-2} s^{-1} (BT-56, Philips Lighting Company, 200 Franklin Square Drive Somerset, NJ 08875). Daily greenhouse temperatures were maintained at 37 ± 4 C while nightly temperatures were 17 ± 3 C.

Applications were made with a roller track sprayer calibrated to deliver 140 L ha^{-1} through a TeeJet XR 8002 flat fan nozzle (TeeJet Technologies, 200 W. North Ave. Glendale Heights, IL 60139) at 207 kPA administered by compressed air with city tap water used as a carrier (Table 1).

Quinclorac was applied at 290 g ha^{-1} to all species at 4 cm. Four adjuvants were included: no adjuvant, COC applied at 2.34 L ha^{-1}, MSO applied at 2.34 L ha^{-1}, and NIS applied at 0.35 L ha^{-1}. Fertilizers included no fertilizer additive, AMS at 1.43 kg ha^{-1} (Fisher Scientific, 300 Industry Drive Pittsburgh, PA 15275) and 28% UAN at 2.34 L ha^{-1} (UAN 28, Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268). A full list of treatments can be found in Table 2.

Weed heights were recorded for each pot the day of application (0 DAT), 7 days after treatment (7 DAT), and 14 days after treatment (14 DAT). Heights were measured from the soil surface to the growing point of each plant which varied by species due to erect versus decumbent growth habits. Plant height and dry weight were expressed as a percentage of height and dry weight reduction versus the nontreated check using the formula:

% dry weight or height reduction = ((check value – treatment value) / check value)

In addition, visual estimations of control were recorded at 7 DAT and 14 DAT using a 0 (not affected) to 100 (complete plant death) scale based on the percent of the plant affected compared to the nontreated check. Finally, at 14 DAT plants were cut at the soil surface, put into paper bags (PFS Sales Company, 4701 Beryl Rd, Raleigh, NC 27606) and dried in an oven at 60 C for 72 hours to ensure uniform dry weight.

Data were subjected to ANOVA with the use of PROC GLM in SAS 9.3 (SAS Institute, 100 SAS Campus Dr, Cary, NC 27513) and means were separated using Fisher's Protected LSD test with a probability level of 95%. Runs and replications were considered to be random effects.

Field Experiments

Field studies were conducted at North Carolina Department of Agriculture and Consumer Services (NCDA&CS) research stations in 2015 to evaluate the impact of quinclorac applied with various combinations of spray adjuvants and fertilizer additives on grain sorghum crop safety, weed control, and yield. In 2015, studies were conducted at the Peanut Belt Research Station in Lewiston-Woodville, NC (36.1323875, -77.1705763), and at the Upper Coastal Plain Research Station near Rocky Mount, NC (35.8942103, -77.6801122). The study at Rocky Mount was planted on Norfolk loamy sand soil (fine-loamy, kaolinitic, thermic Typic Kandiudults) and Goldsboro fine sandy loam soil (fine-loamy, siliceous, subactive, thermic Aquic Paleudults). At the Peanut Belt Research Station in Lewiston-Woodville, NC the experiment was planted on Lynchburg sandy loam soil (fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults) as well as Goldsboro fine sandy loam soil (fine-loamy, siliceous, subactive, thermic Aquic Paleudults). Soil types were identified using the USDA web soil survey (USDA-NRCS 2013).

All 2015 locations were planted on 91 cm rows. The fields at Rocky Mount and Lewiston-Woodville were planted with a 4 row John Deere 7300 VaccuumMax MaxEmerge vacuum-metered planter. Plot sizes were 2.4 m wide by 9.1 m long regardless of year or location. DeKalb ‘DKS53-67’ grain sorghum was planted on raised beds to a depth of 2 cm on June 13, 2015 at a plant population of 247,000 seeds ha^{-1} at Rocky Mount, respectively. Pioneer ‘84P80’ grain sorghum was planted on raised beds at a depth of 2 cm on June 24, 2015 at 247,000 seeds ha^{-1} at Lewiston-Woodville. All fields were conventionally tilled prior to planting. Standard fertilization and insect management practices as recommended by the North Carolina Cooperative Extension Service were followed. In 2015, the Rocky Mount field was irrigated throughout the growing season due to lack of rainfall. No other fields were irrigated.

Twenty five treatments were applied in a randomized complete block design with four replications. The study was arranged as a four factor factorial with two quinclorac rates, three adjuvants, two fertilizer additives, two weed growth stages, plus a nontreated check. All plots received a preemergence application of atrazine at 560 g ai ha^{-1} to suppress broadleaf weeds and allow grass weeds to emerge uninhibited. Quinclorac was applied at 290 g ha^{-1} or 420 g ha^{-1} to all plots. Three adjuvants were included; COC applied at 2.34 L ha^{-1}, MSO applied at 2.34 L ha^{-1}, and NIS applied at 0.35 L ha^{-1}. Fertilizers included spray grade AMS was added at 1.43 kg ha^{-1} as well as UAN which was added at 2.34 L ha^{-1}. Applications were made at two growth stages targeting weed species at 3 – 5 cm and 8 – 10 cm, respectively. A complete list of treatments can be found in Table 3. Treatments were applied using a CO_2-

pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 207 kPa with TeeJet flat fan XR11002 nozzles. Grain sorghum heights at the time of application ranged from 15 to 41 cm, depending on application timing and location although the quinclorac label listing the maximum height of grain sorghum at application to be no taller than 30 cm (Anonymous 2013). These applications were made in order to spray weeds at specific heights.

Visual estimations of crop injury and weed control for all species were made 14, 28, and 42 days after postemergence application. Crop height measurements were recorded at the time of visual weed control ratings. Weed control, relative to the nontreated check, was estimated visually at 14, 28, and 42 days after postemergence application. Visual estimation of weed control at 14 and 42 DAT have been omitted from discussion. Visual weed control estimates were based on a scale of 0-100% where 0 = no weed control and 100 = complete weed control.   A detailed list of weed species present and evaluated at each location in this study can be found in Table 4. A small plot combine was used to harvest yield.

Statistical analyses were carried out in SAS 9.3 organized as a full factorial. Environments and replications were considered to be random effects. ANOVA was conducted using the PROC GLM procedure and means were separated using Fisher's Protected LSD test with a significance level of 5%.

Results and Discussion

Results from greenhouse evaluation

Fertilizer additive had no effect on any parameter (Table 5). Furthermore, there was no significant interaction between fertilizer additive x species, fertilizer additive x adjuvant, or fertilizer additive x species x adjuvant. Both runs of this experiment used spray carrier water low in antagonistic characteristics such as iron, calcium carbonate, and chloride (Table 1). Similarly, when Woznica et al. (2003) used tap water compared to well water, no added benefit of fertilizer additive was observed. Beckett et al. (1992) concluded that ammonium fertilizers combined with quizalofop and sethoxydim exerted no impact on the control of corn [*Zea mays* (L.)] or giant foxtail [*Setaria faberi* Herrm].

A significant species by adjuvant interaction, averaged over fertilizer, was observed for quinclorac control, height reduction, and dry weight reduction (Table 5 & 6). Quinclorac did not control crowfootgrass or goosegrass with any adjuvant combination at 7 or 14 DAT (Table 6). Similarly, control of Texas millet was not significantly different from crowfootgrass or goosegrass, with the greatest control, 14%, observed when quinclorac was applied with the low rate of MSO. Large crabgrass control 7 DAT was at least 91% when quinclorac was applied with MSO (Table 6). Control of large crabgrass was significantly reduced to 79% when COC was substituted, and further reduced to 37% when NIS was used as the adjuvant. Broadleaf signalgrass control was also greatest where quinclorac was applied with MSO, again with significant reduction in control for using COC, and further reduction with NIS. Fall panicum also followed similar trends, although control never exceeded 58% 7

DAT. Species differences in response to quinclorac were more pronounced at 14 DAT, with control of Texas millet, crowfootgrass, and goosegrass being less than 14%, while control of broadleaf signalgrass, fall panicum, and large crabgrass was greater than 83% for the high rate of MSO (Table 6).Control of broadleaf signalgrass was statistically similar, regardless of adjuvant applied. Large crabgrass and fall panicum control was significantly reduced when NIS was used as the adjuvant, with all other combinations resulting in similar control. These results indicate that quinclorac may not be an acceptable option for control of goosegrass, crowfootgrass, or Texas millet, however control of large crabgrass, fall panicum, and broadleaf signalgrass with MSO as an adjuvant will be an option for growers.

Plant height reduction following quinclorac application also showed a significant species by adjuvant interaction, averaged over fertilizer, and followed the same general trend as the control data (Table 5 & 6). The greatest height reductions were observed where quinclorac was applied to large crabgrass with MSO or COC. Height reductions were not significantly different from the highest (92%) for all adjuvants on broadleaf signalgrass, and for COC or MSO applied with quinclorac on fall panicum. Similarly to the control data, height reductions were not as great when NIS was applied on fall panicum or large crabgrass when compared to either MSO or COC. Height reductions of Texas millet were 42 and 45% for quinclorac plus MSO low and high rates, respectively. COC or NIS added to quinclorac resulted in less than 15% height reduction of Texas millet, both significantly lower than MSO. Crowfootgrass and goosegrass had shown tolerance to quinclorac regardless of adjuvant when evaluated visually. Height reductions were negative for these species, indicating they had grown taller than the nontreated check. The increase in height was fairly uniform for both species, averaging 11 to 24% taller plants. Work by Zawierucha and Penner (2000) have confirmed that goosegrass is tolerant to applications of quinclorac and that although an adjuvant was shown to lower GR_{50} compared to when used without an adjuvant; there were no statistical differences among adjuvants.

Analysis of the dry weight reduction identified a significant main effect of species following application with quinclorac (Table 5 & 6). There were no differences in dry weight reduction within species but significant differences existed between species. Control and height reduction of broadleaf signalgrass, large crabgrass, and fall panicum was greater than 90% when MSO was applied in combination with quinclorac. Dry weight reductions were significantly lower for Texas millet, ranging from 40 to 62%, and reductions were essentially zero or even negative for goosegrass and crowfootgrass, again indicating greater growth when these grasses were treated compared to the nontreated.

Previous research as well as the results from this experiment points to improved weed control efficacy with the use of oil based adjuvants compared to nonionic surfactants. The addition of COC has been shown to increase weed control efficacy of herbicides when compared to a nonionic surfactant in a wide range of herbicide site of action groups (Nalewaja et al. 1990; Sims et al. 1989). Manthey et al. (1990) found that MSO reduced shoot fresh weight of certain grass weed species more than refined seed oils or petroleum based oil adjuvants. Previous research with MSO has demonstrated enhanced weed control (Knezevic et al. 2010; Sharma and Singh 2000; Tonks and Eberlein 2001) and greater plant biomass reductions (Manthey et al. 1990; Nalewaja et al. 1990; Young and Hart 1998) compared to NIS and sometimes COC.

Results from field evaluation

Although large crabgrass was observed at both Rocky Mount and Lewiston-Woodville, there was no statistical significance observed.

Control of Texas millet 28 DAT was analyzed by the main effect of application timing (Table 8). Overall control of this weed species with quinclorac was low as observed in previous chapter as plants sprayed at 2.5 -5 cm resulted in 16% control compared to the nontreated check whereas those sprayed at 8 – 10 cm resulted in only 4% control. Texas millet control at Lewiston-Woodville was less than expected from typical applications which are believed to be due to the high plant density present in the plots which may have severely inhibited root absorption. This lapse in control may be explained by Williams et al. (2004) who found that foliar and soil and soil only application of quinclorac significantly reduced fresh weight foliage of torpedograss (*Panicum repens* L.) compared to foliage only applications. Even at the earliest of applications quinclorac should not be expected to control Texas millet.

Broadleaf signalgrass control 28 DAT in Rocky Mount 2015 was analyzed by the main effect of growth stage (Table 8). Earliest applications to 2.5 – 5 cm plants resulted in 80% control which was significantly better than delayed applications to 8 – 10 cm plants which resulted in 70% control.

Broadleaf signalgrass control 28 DAT in Rocky Mount 2015 was influenced by weed growth stage, quinclorac rate, and adjuvant (Table 9). Response to quinclorac rate, growth stage, and adjuvant resulted in greater control when application was delayed to 8-10 cm timing. No significant differences were observed among quinclorac applications at 290 g ha^{-1} plus MSO or NIS or at 420 g ha^{-1} plus COC applied to 8 – 10 cm weeds. All other treatments were significantly lower and less than 90%.

The interaction of adjuvant by fertilizer additive, averaged over quinclorac rate and growth stage, was significant for broadleaf signalgrass 28 DAT in Rocky Mount 2015 (Table 10). Broadleaf signalgrass control 28 DAT was greater when AMS was applied with COC or MSO, but lower when applied with NIS. The greatest control was observed with COC plus AMS or NIS applied alone.

Yield was collected for each study and data were analyzed by the main effect of application timing pooled over environment as well as by the interaction of environment, adjuvant, and fertilizer additive (Tables 8 and 11). The earliest application made to 2.5 – 5 cm weeds resulted in significantly greater yield at 3389 kg ha^{-1} compared to delayed application to 8 – 10 cm weeds at 3076 kg ha^{-1}. These data indicate the importance of making quinclorac applications before weed size exceeds 5 cm.

Analysis of yield also included the interaction of environment, spray adjuvant, and fertilizer additive (Table 11). There was no benefit of adding AMS to any adjuvant tested. In general yields were higher when AMS was not included. The use of MSO resulted in the greatest yields regardless of location. When AMS was excluded from the tank mix, the use of MSO produced significantly greater yields compared to NIS at both Rocky Mount and Lewiston while MSO and COC gave comparable results.

Based on the results of field and greenhouse experiments, broadleaf signalgrass, large crabgrass, and fall panicum should be considered susceptible to quinclorac. Conversely, Texas millet, crowfootgrass, and goosegrass should be considered tolerant. These data suggest that adjuvant selection can be an important decision when considering applying quinclorac, particularly when fall panicum and large crabgrass are present. If these species are present, one should not include NIS as the adjuvant choice, and instead use COC or MSO. If fall panicum is present MSO should be added instead of COC. Furthermore, there was no statistically significant benefit of using the high rate (2.34 L ha^{-1}) of MSO over the low rate (1.17 L ha^{-1}) in greenhouse studies. Texas millet height reductions as well as visual estimation of control were greater with MSO and in general COC and NIS were not significantly different. Dry weight reduction of Texas millet (54%) was not differentially impacted by adjuvant but as a species was significantly lower than broadleaf signalgrass (98%), large crabgrass (95%), and fall panicum (84%). Also, overall reduction of these parameters suggests that Texas millet is not controlled well by quinclorac or any adjuvant combination thereof. Crowfootgrass and goosegrass can be considered in the same category and one should not rely on quinclorac to control these species.

Fertilizer additives such as AMS and UAN had limited impact on any weed species evaluated in greenhouse or field studies. Previous works have shown mixed effects of fertilizer additives in weed control efficacy. Quinclorac is a weak acid herbicide and like similar herbicides, its efficacy can be reduced in the presence of certain cations in spray carrier water (Stahlman and Phillips 1979). AMS proved to be more effective at overcoming the antagonism of salt cations (not calcium) in well water compared to UAN (Woznica et al. 2003). Woznica et al. (2003) found that the activity of quinclorac was increased if AMS was applied along with COC or MSO when spray carrier water contained certain cations. However, in tap water without antagonistic salts, the addition of either AMS or UAN made no significant difference in green foxtail fresh weight reduction compared to the surfactant alone (Woznica et al. 2003). Additionally, UAN has been shown to be ineffective at providing additional control of several weed species in tank mixtures (Pearson et al. 2008; Young and Hart 1998). Visual estimation, height and dry weight reduction of broadleaf signalgrass, large crabgrass, fall panicum, Texas millet, and goosegrass were often significantly improved with COC or MSO compared to NIS giving a general efficacy trend of NIS ≤ COC ≤ MSO. Street and Teresiak (1994) found similar results regarding the relationship between nonionic surfactants and quinclorac, resulted in less barnyardgrass control and lower rice yields compared to other adjuvants. Young et al. (2007) concluded similar results when testing various HPPD herbicides with commercial adjuvants on several grass weed species.

Finally, where high yield potential is expected there is a significant advantage to applying quinclorac on 2.5 – 5 cm weeds as compared to waiting to apply to 8 – 10 cm weeds. Quinclorac is an effective tool in postemergence annual grass weed control of certain species in grain sorghum if applications are made early with the use of suitable oil-based adjuvants.

Acknowledgements

Funding for this research originates from the North Carolina Small Grain Growers Association.

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Table 1. The pH, electrical conductivity (EC), and ion concentration in water sources from Raleigh, NC during the months of February and March, 2015.

Month	pH[a,b]	EC	$CaCO_3$	Fe	Cl^-	Fl^-
		uS cm^{-1}		mg L^{-1}		
February	8.4	223	27.8	0.1	-	0.79
March	8.4	225	26.9	0.1	13.7	0.74

[a] Abbreviations: $CaCO_3$, calcium carbonate; Cl^-, chloride; EC, electrical conductivity; Fe, iron; Fl^-, fluoride; uS cm^{-1}, microsiemens per centimeter; mg L^{-1}, milligrams per liter.

[b] Information retrieved from EM Johnson Water Plant Finished Water Quality Report, March 2015.

Table 2. Treatment list for greenhouse study investigating grass weed control with quinclorac as affected by adjuvant and fertilizer.

Quinclorac rate[a]	Adjuvant	Adjuvant Rate	Fertilizer Additive	Fertilizer Rate[b]	Application Timing
g ae ha^{-1}		L ha^{-1}			cm
290	COC	2.34	-	-	3.8
290	COC	2.34	UAN	2.34	3.8
290	COC	2.34	AMS	1.43	3.8
290	MSO	1.17	-	-	3.8
290	MSO	1.17	UAN	2.34	3.8
290	MSO	1.17	AMS	1.43	3.8
290	MSO	2.34	-	-	3.8
290	MSO	2.34	UAN	2.34	3.8
290	MSO	2.34	AMS	1.43	3.8
290	NIS	0.35	-	-	3.8
290	NIS	0.35	UAN	2.34	3.8
290	NIS	0.35	AMS	1.43	3.8
290	-	-	-	-	3.8
Nontreated	-	-	-	-	3.8

[a] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; MSO, methylated seed oil; NIS, nonionic surfactant; UAN, urea ammonium nitrate.

[b] Fertilizer rate expressed in terms of kg ha^{-1} for AMS and L ha^{-1} for UAN.

Table 3. Treatment list for field study investigating crop response, weed control, and yield response of quinclorac in combination with various spray adjuvant combinations.

Quinclorac rate[a,b]	Adjuvant	Adjuvant Rate[c]	Fertilizer Additive	Fertilizer Rate[d]	Target Weed Height
g ae ha^{-1}		L ha^{-1}		kg ha^{-1}	cm
290	COC	2.34	-	-	2.5-5
290	MSO	2.34	-	-	2.5-5
290	NIS	0.35	-	-	2.5-5
290	COC + AMS	2.34	AMS	1.43	2.5-5
290	MSO + AMS	2.34	AMS	1.43	2.5-5
290	NIS + AMS	0.35	AMS	1.43	2.5-5
420	COC	2.34	-	-	2.5-5
420	MSO	2.34	-	-	2.5-5
420	NIS	0.35	-	-	2.5-5
420	COC + AMS	2.34	AMS	1.43	2.5-5
420	MSO + AMS	2.34	AMS	1.43	2.5-5
420	NIS + AMS	0.35	AMS	1.43	2.5-5
290	COC	2.34	-	-	8-10
290	MSO	2.34	-	-	8-10
290	NIS	0.35	-	-	8-10
290	COC + AMS	2.34	AMS	1.43	8-10
290	MSO + AMS	2.34	AMS	1.43	8-10
290	NIS + AMS	0.35	AMS	1.43	8-10
420	COC	2.34	-	-	8-10
420	MSO	2.34	-	-	8-10
420	NIS	0.35	-	-	8-10
420	COC + AMS	2.34	AMS	1.43	8-10
420	MSO + AMS	2.34	AMS	1.43	8-10
420	NIS + AMS	0.35	AMS	1.43	8-10
Nontreated	None	-	-	-	-

[a] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; MSO, methylated seed oil; NIS, nonionic surfactant.

Table 4. Weed species present at two environments in the field evaluation of quinclorac rate, spray adjuvant, and fertilizer.

Lewiston-Woodville 2015	Rocky Mount 2015
Weed Species	
Texas millet	Broadleaf signalgrass
Large crabgrass	Large crabgrass

Table 5. Analysis of variance of control, height, and dry weight reduction for greenhouse study investigating grass weed species control with quinclorac as affected by adjuvant and fertilizer.

			p-value		p-value
Source	df	F-value Control 7 DAT	Control 7 DAT	F-value Height Reduction 7 DAT	Height Reduction 7 DAT
Species (Sp)	5	18.89	0.0029*	68.50	0.0001*
Adjuvant (Adj)	3	111.59	0.0014*	4.22	0.1340
Sp * Adj	15	2.81	0.0271*	2.46	0.0457*
Fertilizer (Fert)	2	1.70	0.3689	2.71	0.2698
Fert * Sp	10	2.93	0.0523	1.06	0.4653
Fert * Adj	6	0.51	0.7860	1.09	0.4596
Sp * Fert * Adj	30	0.91	0.6040	0.71	0.8272
Run	1	69.37	<0.0001	4.37	0.0369
Sp * Run	5	25.28	<0.0001	5.35	<0.0001
Adj * Run	3	0.56	0.6442	2.37	0.0694
Sp * Adj * Run	15	4.79	<0.0001	1.42	0.1304
Fert * Run	2	0.59	0.5567	0.32	0.7288
Sp * Fert * Run	10	0.63	0.7917	0.43	0.9331
Adj * Fert * Run	6	2.02	0.0609	1.13	0.3417
Sp * Adj * Fert * Run	30	1.21	0.2019	0.85	0.7044
Rep (Run)	10	2.13	0.0204	4.15	<0.0001

[a] An asterisk denotes significance at the $\alpha = 0.05$ level according to Fisher's Protected LSD.

Table 5. Analysis of variance of control, height, and dry weight reduction for greenhouse study investigating quinclorac as affected by species, adjuvant, and fertilizer.

			p-value[a]		p-value
Source	df	F-value Control 14 DAT	Control 14 DAT	F-value Height Reduction 14 DAT	Height Reduction 14 DAT
Species (Sp)	5	49.85	0.0003*	36.01	0.0006
Adjuvant (Adj)	3	64.28	0.0032*	15.51	0.0248*
Sp * Adj	15	2.93	0.0226*	2.72	0.0309*
Fertilizer (Fert)	2	0.37	0.7311	0.82	0.5492
Fert * Sp	10	1.73	0.2008	0.72	0.4636
Fert * Adj	6	0.24	0.9452	0.20	0.9656
Sp * Fert * Adj	30	0.53	0.9574	0.35	0.9974
Run	1	35.92	<0.0001	6.26	0.0126
Sp * Run	5	13.38	<0.0001	12.32	<0.0001
Adj * Run	3	0.72	0.5405	1.13	0.3366
Sp * Adj * Run	15	5.18	<0.0001	1.33	0.1786
Fert * Run	2	0.57	0.5661	0.61	0.5420
Sp * Fert * Run	10	0.52	0.8773	0.32	0.9764
Adj * Fert * Run	6	1.17	0.3212	0.88	0.5057
Sp * Adj * Fert * Run	30	1.77	0.0075	1.29	0.1422
Rep (Run)	10	1.54	0.1219	9.77	<0.0001

[a] An asterisk denotes significance at the $\alpha = 0.05$ level according to Fisher's Protected LSD.

Table 5. Analysis of variance of control, height, and dry weight reduction for greenhouse study investigating quinclorac as affected by species, adjuvant, and fertilizer.

			p-value
Source	df	F-value Dry Weight Reduction	Dry Weight Reduction
Species (Sp)	5	15.55	0.0046*
Adjuvant (Adj)	3	2.34	0.2505
Sp * Adj	15	1.78	0.1374
Fertilizer (Fert)	2	1.39	0.4175
Fert * Sp	10	0.93	0.5457
Fert * Adj	6	0.62	0.7122
Sp * Fert * Adj	30	1.00	0.5032
Run	1	27.49	<0.0001
Sp * Run	5	26.01	<0.0001
Adj * Run	3	2.10	0.0988
Sp * Adj * Run	15	1.15	0.3074
Fert * Run	2	0.52	0.5966
Sp * Fert * Run	10	1.84	0.0503
Adj * Fert * Run	6	1.36	0.2302
Sp * Adj * Fert * Run	30	1.32	0.1199
Rep (Run)	10	5.30	<0.0001

Table 6. Effect of quinclorac and spray adjuvants on control and height reduction of six common grass weed species in a greenhouse environment.

Species	Adjuvant[a,b] L ha^{-1}	Control 7 DAT[c]	Height Reduction 7 DAT	Control 14 DAT	Height Reduction 14 DAT
		-------%-------			
Broadleaf signalgrass	NIS 0.35	44 d	83 a	90 a	92 a
	COC 2.34	62 c	82 a	92 a	92 a
	MSO 1.17	76 b	83 a	95 a	92 a
	MSO 2.34	79 b	85 a	96 a	94 a
Large crabgrass	NIS 0.35	37 de	73 ab	40 d	70 b
	COC 2.34	79 b	89 a	75 ab	91 a
	MSO 1.17	91 a	92 a	96 a	98 a
	MSO 2.34	94 a	92 a	97 a	98 a
Fall panicum	NIS 0.35	21 f	48 b	29 e	50 c
	COC 2.34	31 e	77 ab	59 c	84 ab
	MSO 1.17	42 c	72 ab	69 b	88 a
	MSO 2.34	58 c	80 a	83 ab	92 a
Texas millet	NIS 0.35	3 h	7 c	5 f	-5 e
	COC 2.34	3 h	15 c	8 f	-1 e
	MSO 1.17	12 fg	42 b	14 f	20 d
	MSO 2.34	4 gh	45 b	5 f	21 d
Crowfootgrass	NIS 0.35	0 h	-11 d	0 fg	-2 e
	COC 2.34	0 h	-24 d	0 fg	-7 e
	MSO 1.17	0 h	-17 d	1 fg	-3 e
	MSO 2.34	0 h	-18 d	0 fg	5 e
Goosegrass	NIS 0.35	0 h	-17 d	2 fg	-14 ef
	COC 2.34	0 h	-17 d	4 fg	-10 ef
	MSO 1.17	0 h	-18 d	3 fg	-14 ef
	MSO 2.34	0 h	-11 d	0 fg	-10 ef

Table 6. Continued

[a] Abbreviations: COC, crop oil concentrate; DAT, days after treatment; MSO, methylated seed oil; NIS, nonionic surfactant;.

[b] Quinclorac rate for all treatments = 290 g ae ha^{-1}.

[c] Data in the same column followed by the same letter are not significantly different according to Fisher’s Protected LSD ($P \leq 0.05$)

Table 7. Effect of quinclorac on dry weight reduction as influenced by six common grass weed species in a greenhouse environment averaged over spray adjuvant and fertilizer additive.

	Dry Weight Reduction[a]
Weed Species	---%---
Broadleaf signalgrass	98 a
Large crabgrass	95 a
Fall panicum	84 b
Texas millet	54 c
Crowfootgrass	-5 d
Goosegrass	-17 e

[a] Data in the same column followed by the same letter is considered to not be significantly different according to Fisher's Protected LSD ($P \leq 0.05$).

Table 8. Effect of quinclorac on weed control and yield as influenced by growth stage in a field environment averaged over fertilizer additive, spray adjuvant, and herbicide rate.

	Broadleaf signalgrass 28 DAT[b]	Texas millet 28 DAT	Yield
Growth Stage	--	%--	
cm			kg ha^{-1}
2.5 - 5	80 a	16 a	3389 a
8 -10	70 b	4 b	3076 b

[a] Abbreviations: DAT, days after treatment.

[b] Means within the same evaluation date followed by the same letter should not be considered statistically different according to Fisher's Protected LSD test at P ≤ 0.05.

Table 9. Effect of quinclorac on weed control as influenced by growth stage, herbicide rate, and spray adjuvant in a field environment averaged over fertilizer additive.

			Rocky Mount, 2015
Growth stage	Quinclorac Rate	Adjuvant[a,b]	Broadleaf signalgrass 28 DAT[c]
cm	g ae ha^{-1}		
2.5 - 5	290	COC	86 b
		MSO	81 c
		NIS	77 cd
	420	COC	80 c
		MSO	79 c
		NIS	80 c
8 - 10	290	COC	88 b
		MSO	94 a
		NIS	94 a
	420	COC	95 a
		MSO	85 b
		NIS	76 cd

[a] Abbreviations: COC, crop oil concentrate; DAT, days after treatment; MSO, methylated seed oil; NIS, nonionic surfactant.

[b] Adjuvant application rates: COC = 2.34 L ha^{-1}, MSO = 2.34 L ha^{-1}, NIS = 0.35 L ha^{-1}.

[c] Means followed by the same letter within one rating date column should not be considered statistically different according to Fisher's Protected LSD test at $P \leq 0.05$.

Table 10. Effect of quinclorac on weed control as influenced by spray adjuvant and fertilizer additive in a field environment averaged over growth stage and herbicide rate.

		Rocky Mount, 2015
Adjuvant[a,b]	Fertilizer Additive[c]	Broadleaf signalgrass 28 DAT[d]
		-----------%----------
COC	None	85 b
	AMS	90 a
MSO	None	80 c
	AMS	84 b
NIS	None	88 a
	AMS	75 d

[a] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; DAT, days after treatment; MSO, methylated seed oil; NIS, nonionic surfactant.

[b] Adjuvant application rates: COC = 2.34 L ha^{-1}, MSO = 2.34 L ha^{-1}, NIS = 0.35 L ha^{-1}.

[c] Rate of AMS = 1.43 kg ha^{-1}.

[d] Means within the same evaluation date followed by the same letter should not be considered statistically different according to Fisher's Protected LSD test at $P \leq 0.05$.

Table 11. Effect of quinclorac on yield as influenced by spray adjuvant and fertilizer additive in a field environment averaged over growth stage and herbicide rate.

		Yield[d]	
Adjuvant[a,b]	Fertilizer Additive[c]	Rocky Mount	Lewiston-Woodville
		kg ha^{-1}	
COC	None	2321 bc	4039 AB
	AMS	2498 b	3881 B
MSO	None	2781 a	4164 A
	AMS	2201 c	4194 A
NIS	None	2422 b	3998 B
	AMS	2288 bc	3893 B

[a] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; DAT, days after treatment; MSO, methylated seed oil; NIS, nonionic surfactant.

[b] Adjuvant application rates: COC = 2.34 L ha^{-1}, MSO = 2.34 L ha^{-1}, NIS = 0.35 L ha^{-1}.

[c] Rate of AMS = 1.43 kg ha^{-1}.

[d] Means within the same evaluation date followed by the same letter should not be considered statistically different according to Fisher's Protected LSD test at $P \leq 0.05$.

CHAPTER 3

Effect of Quinclorac Rate and on Control of Six Grass Weed Species at Two Growth Stages.

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Abstract

The objective of this experiment was to evaluate the impact of quinclorac rate and growth stage at application on control of six common and troublesome grass species common to grain sorghum in the southeastern United States. When quinclorac was applied to broadleaf signalgrass, large crabgrass, and fall panicum dry weight reduction ranged from 95 to 99% when plants were sprayed at less than 5 cm. Texas millet control was moderate and was only obtained at this level when applications were made at 2.5 cm. Crowfootgrass and goosegrass were not controlled by quinclorac. The effect of growth stage was most important in the control of broadleaf signalgrass, large crabgrass, fall panicum, and Texas millet. Increasing herbicide rate improved height and dry weight reduction of plants sprayed at 5 and 10 cm but not 2.5 cm. This research encourages application to plants no taller than 5 cm.

Nomenclature: Broadleaf signalgrass, (*Urochloa platyphylla (*Nash) R.D. Webster); crowfootgrass, (*Dactyloctenium aegyptium* (L.) Willd.); fall panicum, (*Panicum dichotomiflorum* Michx.); goosegrass, (*Eleusine indica* (L.) Gaertn.); grain sorghum, *[Sorghum bicolor* L. Moench]; large crabgrass, (*Digitaria sanguinalis (*L.) Scop.); quinclorac; Texas millet, (*Urochloa texana* (Buckl.) R. Webster); weed control.

Key Words: Annual grass control, dry weight reduction, height reduction, herbicide rate, weed control.

In the southern United States, monocotyledonous weeds are more common and troublesome than most broadleaf weeds present in conventional grain sorghum (Elmore 1987; Webster 2012). In particular, broadleaf signalgrass has become a serious problem for growers in Alabama, Arkansas, and Mississippi because of its ability to outcompete other weed species (Johnson and Coble 1986; Webster 2012). Large crabgrass has proven to be a prolific seed producer with seed that can germinate throughout a growing season and also poses control issues for grain sorghum growers in all seven major grain sorghum producing states in the southeastern United States surveyed by the Southern Weed Science Society in 2012 (Johnson and Coble 1986; Webster 2012). Fall panicum, another annual weedy grass, has become an issue in corn production as it may be tolerant to atrazine and has been mentioned by grain sorghum growers in Mississippi and Missouri as a tough to control weed species (Parochetti 1974; Webster 2012). Texas millet control has become more of a problem as its hardiness in droughty environments combined with late season germination habits and the lack of activity by several preemergence herbicides makes it a formidable opponent in grain sorghum weed management (Chandler and Santelmann 1969; Grichar 1991; Schroeder et al. 1990). Furthermore, Texas millet has been listed as either a top ten most common or troublesome weed for grain sorghum growers in Texas, Georgia, Alabama, and Florida (Webster 2012). Crowfootgrass has been known to be a troublesome weed for peanut production in Virginia and North Carolina (Bridges et al. 1994), part of the area of renewed interest in grain sorghum production. Goosegrass has been documented worldwide in numerous agricultural settings as a troublesome weed with biotypes resistant to several herbicidal modes of action (Heap 2015). Therefore, with these weed species present in the southeastern United States and its diverse cropping systems, they are inevitably bound to emerge in grain sorghum production as well.

Fortunately for growers, many herbicide products exist which can be used safely to eliminate broadleaf weeds from a grain sorghum crop but none for selective in-crop annual grass weed control (Everman and Besancon 2013). Historically, growers have relied on preemergence herbicides and atrazine to control monocotyledonous weeds although poor control often results (Ellis et al. 1980; Walker et al. 1991). In 2013, the release of quinclorac provided a solution for control of certain annual grass and broadleaf species. Quinclorac has been shown to control large crabgrass, broadleaf signalgrass, and some research points to the susceptibility of fall panicum to the herbicide as well (Koo et al 1991; Landes et al. 1994). In contrast, goosegrass, a known tolerant species, could not be controlled until application rates reached 2000 g ae ha^{-1}, a rate more than twofold greater than the one time per year application limit (Zawierucha and Penner 2001). There is no available literature on the susceptibility of Texas millet or crowfootgrass to quinclorac.

Numerous researchers have demonstrated improved herbicide efficacy when targeting shorter, younger monocotyledonous weeds compared to taller, older plants (Anmadi et al. 1980; Beckett et al. 1992; Hager et al. 2003; Kells et al. 1984; Knezevic et al. 2010; Smith 1974). Anmadi et al. (1980) investigated the impacts of glyphosate activity on barnyardgrass plants at 5, 10, 15, and 20 cm and found greater amounts of absorption and translocation with 5 and 10 compared to 15 and 20 cm plants. Furthermore, Kells et al. (1984) found less herbicidal activity of fluazifop on five to six leaf quackgrass compared to two to three leaf plants. Grass species have been shown to be best controlled at earlier rather than later application timings (Craigmyle et al. 2013; Ngouajio and Hagood 1993; Smith 1974).

Research has also indicated that higher rates of propanil applied at earlier stages of crop development can improve control of grass weed species and crop yield (Smith 1974). A similar study was done to examine the impacts of atrazine rate and timing on southern sandbur (*Cenchrus echinatus L*). Results indicated that the greatest reduction in plant dry weight biomass, plant height, and seed production was observed when the first true pair of leaves unfurled compared to the emergence of the second pair of leaves or tillers (Dan et al. 2011). Chism et al. (1992) confirmed herbicide efficacy decreases as postemergence applications of quinclorac are applied after southern crabgrass has become more mature. Previous works indicate that higher rates of quinclorac sometimes improve control (Enanche and Ilnicki 1991; Franetovich and Peeper 1995) and sometimes does not impact weed control (Franetovich and Peeper 1995; Street et al. 1995).

Thus far, research has not explored the interactions between doses and timings of quinclorac to broadleaf signalgrass, fall panicum, Texas millet, or crowfootgrass. Furthermore, previous research has not studied quinclorac efficacy as a function of species and growth stage within a range of weed sizes of importance to agricultural production (Chism et al. 1992; Zawierucha and Penner 2001). Current weed management guidelines for quinclorac use recommend that applications should not be after weeds reach 5 cm in height for all species (Anonymous 2013). Different from the previous chapter, results will uncover detailed height and dry weight reduction response of six common annual grass weeds to three growth stages and two herbicide rates.

Materials and Methods

General Greenhouse Procedures.

Greenhouse studies were conducted to evaluate the impact of quinclorac applied at various rates and growth stages on control of annual grass weed species common to grain sorghum (*Sorghum bicolor* L. Moench) production in North Carolina. The experiment was organized as a thee factor factorial with factors consisting of six grass weed species, three growth stages, and two herbicide rates. Weed species evaluated included broadleaf signalgrass, crowfootgrass, fall panicum, goosegrass, large crabgrass, and Texas millet. Quinclorac was applied at 290 g ae ha^{-1} rate or 420 g ae ha^{-1} to weeds when they were 2.5, 5, or 10 cm. Experiments were conducted using a randomized complete block design with six replicates and was repeated twice.

Crowfootgrass, large crabgrass, goosegrass, and fall panicum seed was collected in the fall of 2013 from a fallow field at Central Crops Research Station in Clayton, NC and Texas millet seed was collected from a miscanthus field near Wallace, NC. Seed of broadleaf signalgrass were purchased from Azlin Seed Services (Azlin Seed Services, 112 Lilac Dr, Leland, MS 38756). Broadleaf signalgrass, large crabgrass, broadleaf signalgrass, fall panicum, Texas millet, crowfootgrass, and goosegrass seeds were sown into 10 cm tall by 10 cm wide plastic pots (Wyatt-Quarrels, 730 US-70, Garner, NC 27529). Each species was planted into moist soil medium (4P Fafard Growing Mix, (43-53% Canadian sphagnum peat moss, pine bark, vermiculite, perlite, dolomitic wetting agent), Sun Gro Horticulture Ltd. 52130 RR 65, PO Box 189, Seba Beach, AB T0E 2BO Canada) and according to species-specific planting depth guidelines and watered afterwards in order to ensure optimum seed-soil contact, germination, and emergence (Buhler and Hoffman 1999).

Seedlings were thinned to one plant per pot within two days after emergence and were irrigated in order to allow for rapid growth. Natural sunlight was augmented by 1000W metal halide lamps of 16 hour photoperiods, providing a daily photon flux of 455.8 µ mol m^{-2} s^{-1} (BT-56, Philips Lighting Company, 200 Franklin Square Drive Somerset, NJ 08875). Daily greenhouse temperatures were maintained at 37 ± 4 C while nightly temperatures were 17 ± 3 C.

A roller track sprayer was calibrated to deliver 140 L ha^{-1} through a TeeJet XR 8002 flat fan nozzle (TeeJet Technologies, 200 W. North Ave. Glendale Heights, IL 60139) at 207 kPA administered by compressed air. Mix sizes were 100 mL and tap water was used as a carrier. Tap water from Raleigh, NC was used and chemical composition analysis detected low levels of antagonistic salts (Table 1).

The study was arranged as a three factor factorial with six weed species, three growth stages, and two herbicide rates. Quinclorac (Facet L®, BASF Agricultural Products Group, 26 Davis Drive, Research Triangle Park, NC 27709) was applied at 290 or 420 g ha^{-1} at 2.5, 5, and 10 cm. All treatments included crop oil concentrate (COC) at 2.34 L ha^{-1} (Crossfire®, Cardinal Chemical Inc., 2905 Yukon Road, Kinston, NC 27893).

Weed heights were recorded for each pot the day of application (0 DAT), 7 days after treatment (7 DAT), and 14 days after treatment (14 DAT) in order to observe potential stunting effects of herbicide treatments. Heights were measured from the soil surface to the growing point of each plant which varied by species due to erect versus decumbent growth habits. In addition, visual estimations of weed control were recorded at 7 DAT and 14 DAT. Visual weed control ratings were made using a 0 (not affected) to 100 (complete plant death) scale based on the percent of the plant affected compared to the nontreated check. Finally, at 14 DAT plants were cut at the soil surface, put into paper bags (PFS Sales Company, 4701 Beryl Rd, Raleigh, NC 27606) and dried in an oven at 60 C for 72 hours to ensure uniform dry weight. After sufficient drying time, samples were weighed and recorded in grams.

Data were subjected to ANOVA using the PROC GLM procedure in SAS 9.3 at the 95% probability level in order to separate means (SAS Institute, 100 SAS Campus Dr, Cary, NC 27513). Runs and replications (nested within runs) and all their interactions were considered random while species, timing, and rate were considered fixed effects.

Plant height and dry weight was compared as a percentage of height and dry weight reduction versus the nontreated check. Each percentage was calculated by comparing the treatment of interest to the nontreated check value within the appropriate repetition and run. The following formula was used to calculate these values:

% dry weight or height reduction = ((check value – treatment value) / check value)

Results and Discussion

Main effects of species, growth stage, and the interaction of species and growth stage were significant for weed control at 7 DAT, height reduction at 7 and 14 DAT, as well as dry weight reduction (Table 2). Broadleaf signalgrass, large crabgrass, and fall panicum control at 7 DAT were significantly improved when applications were made at 2.5 cm compared to later growth stages (Table 3). A significant quinclorac rate by growth stage interaction was also observed for weed control and height reduction at 7 DAT (Table 2). When averaged over species, the greatest control was also observed when weeds were treated at 2.5 cm when compared to 5 cm or 10 cm, regardless of rate (Table 4). Height reduction was similar to weed control at 7 DAT, with greater reduction when quinclorac was applied when weeds were 2.5 cm, when averaged over species (Table 4). Greater than 50% height reduction was observed for broadleaf signalgrass, fall panicum, and large crabgrass at 7 DAT for all combinations with the interaction of species and growth stage averaged over quinclorac rate. Conversely, height reduction 7 DAT was less than 50% for crowfootgrass, goosegrass, and Texas millet for all growth stages, averaged over quinclorac rates (Table 3).

Texas millet, crowfootgrass, and goosegrass control ranged from 0 to 12% 7 DAT and never exceed 44% (Table 3). Low levels of weed control of Texas millet (2-12%) were observed at all growth stages. Crowfootgrass exhibited no phytotoxic symptoms in response to quinclorac application. Furthermore, if no visual symptoms of chlorosis or necrosis are noticed, it can be expected that quinclorac will not be effective in eliminating this weed species (Grossmann 1998). Similar to crowfootgrass, control of goosegrass was low (≤ 8%) and more often than not was absent. At 7 DAT, height was reduced more at the 5 cm timing (3%) than 2.5 cm (1%) (Table 3). Consistent with Chism et al. (1992), smaller goosegrass plants were more susceptible to quinclorac than more mature ones as reflected in dry weight reduction, to an extent (Table 3). However, height reduction did not exceed 8% and dry weight reduction was less than 15%, regardless of growth stage. Furthermore, weed control of Texas millet, crowfootgrass, and goosegrass was not different by growth stage (Table 3).

A difference in species interaction with growth stage at time of quinclorac application, averaged over rates, was also observed for height reduction at 14 DAT (Table 2). Quinclorac was more effective at reducing height 14 DAT, averaged over rates, on 2.5 and 5 cm weeds within species for broadleaf signalgrass, fall panicum, and large crabgrass (Table 3). Plant height decreased, often significantly, as plants were sprayed at less mature growth stages, compared to the nontreated check for broadleaf signalgrass, large crabgrass, fall panicum, and Texas millet. At both evaluation dates, the 2.5 and 5 cm growth stages height reduction was not statistically different for broadleaf signalgrass, large crabgrass, or fall panicum. At 7 DAT, height reduction for broadleaf signalgrass and large crabgrass were statistically the same regardless of growth stage. Delaying application until fall panicum was 10 cm in height resulted in significant differences from the earliest two growth stages when evaluated 7 DAT. By 14 DAT, only broadleaf signalgrass height reduction was still statistically similar regardless of growth stage. Large crabgrass height reduction was statistically different between 2.5 cm (96%) and 10 cm (70%) but both were similar to the 5 cm growth stage (82%). Fall panicum height reduction was the same amongst 2.5 and 5 cm growth stages but different from both at the 10 cm growth stage when evaluated at 14 DAT (Table 3).

Dry weight reduction was analyzed by the interaction of species and growth stage, averaged over herbicide rates (Table 2). Levels of dry weight reduction were greatest with broadleaf signalgrass followed closely by large crabgrass and fall panicum, particularly when plants were sprayed at 2.5 cm (Table 3). Making an application on plants of this stature caused between 98-99% dry weight reductions for the three aforementioned species. Dry weight reduction of Texas millet for plants sprayed at 2.5 cm was similar to that of broadleaf signalgrass, large crabgrass, and fall panicum. Furthermore, even the two latter growth stages of Texas millet yielded dry weight reduction results similar to that observed from large crabgrass and fall panicum sprayed at 10 cm. The highest dry weight reduction of Texas millet was achieved when plants were treated at 2.5 cm as those treated later accumulated more plant biomass. If application is delayed to 5 cm, biomass reduction slips from 80% to 67% and eventually to 61% if treated at 10 cm. Dry weight reduction of broadleaf signalgrass, large crabgrass, fall panicum, and Texas millet shared similar results at 14 DAT but each species and results from each of its growth stages demonstrated significantly greater reduction compared to crowfootgrass or goosegrass. Dry weight reduction of crowfootgrass was greatest at 10 cm (9%) and the other two growth stages actually increased crowfootgrass weight compared to the check.

The interaction of growth stage and herbicide rate was significant for weed control and height reduction at 7 DAT and data were pooled over species (Table 2). Control and height reduction at 7 DAT at the earliest growth stage (2.5 cm) was significantly greater when the low rate of quinclorac was used (Table 4). At the 5 cm growth stage an increased herbicide rate did not impact weed control or height reduction. By the final growth stage of 10 cm, applying quinclorac at 420 g ha^{-1} significantly enhanced control and height reduction. Control increased from 27% to 38% when 290 and 420 g ha^{-1} were applied, respectively. Height reduction followed a similar trend as control increased from 32% to 42% when 290 and 420 g ha^{-1} were applied, respectively.

Visual estimation of control and height reduction at 7 DAT results stressed the importance of applying quinclorac when weed height is less than or equal to 5 cm. Height reduction obtained with the low rate of quinclorac at 2.5 cm was highest of the remaining observations at 53%. Quinclorac applied at 420 g ha^{-1} at 2.5 cm achieved height reduction which was similar to plants at 5 cm at both herbicide rates and height from the high rate at 10 cm. However, when plants were sprayed at 10 cm with 290 g ha^{-1} height reduction and weed control suffered significantly compared to all other growth stages and herbicide rates. Furthermore, regardless of growth stage, all height reduction results at the 420 g ha^{-1} rate were statistically similar and in a range from 42% to 44%. Simultaneously, regardless of growth stage, all height reduction results at the 290 g ha^{-1} rate were all statistically different from each other and in a range from 32% to 53% in the sequence of 10, 5, and 2.5 cm (Table 4).

Visual control at 7 DAT was significantly greater at the 2.5 cm growth stage compared to other timings, regardless of herbicide rate (Table 4). Irrespective of growth stage, all weed control results at the low rate of quinclorac were all statistically different from each other representing a range from 27% to 50% control for 10, 5, and 2.5 cm, respectively. However, at the high rate of quinclorac control from plants sprayed 5 and 10 cm responded similarly at 39 and 38% control, respectively. In contrast, plants sprayed at 2.5 cm demonstrated 48% control which was significantly greater than the two latter growth stages. These results indicate that at earlier growth stages, less herbicide is required to achieve similar weed control and height reduction as at higher rates of quinclorac.

Growth stage impact on dry weight reduction was not an important factor within species but was important amongst species (Table 3). The effect of growth stage had no impact on broadleaf signalgrass dry weight reduction, similar to large crabgrass and fall panicum which all recorded a reduction in the range of 79% to 99% . Dry weight reduction compared to the nontreated check did not differ between any of the growth stages of fall panicum as plants sprayed at 2.5 cm and 5 cm (98% and 95%) were lighter compared to those sprayed at 10 cm (79%).

Analysis indicated a species by growth stage by herbicide rate interaction was significant for weed control at 14 DAT (Table 2 & 5). For the two earliest growth stages, control with the high rate of quinclorac 420 g ha^{-1} was greater than or equal to control obtained at the lower rate for broadleaf signalgrass, large crabgrass, fall panicum, Texas millet, and crowfootgrass. Weed control of broadleaf signalgrass, large crabgrass, and fall panicum at all growth stages and herbicide rates was significantly greater compared to any treatment with Texas millet, crowfootgrass, or goosegrass. Control of broadleaf signalgrass, large crabgrass, and fall panicum was similar amongst species at the 2.5 cm growth stage with control ranging from 82-98%. Although control was equal or slightly greater with the high rate of herbicide, differences were not significant. Weed control of the three species at 5 cm was similar to that observed at 2.5 cm with a slight response to rate for broadleaf signalgrass. Control at 5 cm was not significantly different by herbicide rate for broadleaf signalgrass, large crabgrass, or fall panicum nor was it different from control obtained at the 2.5 cm timing. Weed control obtained from the low rate of herbicide at the 10 cm growth stage of broadleaf signalgrass, large crabgrass, and fall panicum was statistically different from the same rate of plants sprayed at 2.5 cm for each species. There was no significant difference by rate for broadleaf signalgrass, large crabgrass, or fall panicum within the 10 cm timing. However, using a higher rate of quinclorac on large crabgrass and fall panicum may have some benefit over the low rate as weed control levels increased to statistically similar levels of the 2.5 and 5 cm growth stages (Table 5).

Broadleaf signalgrass and large crabgrass exhibited similar responses in weed control, height, and dry weight reductions with respect to timing of applications. Initial ratings of broadleaf signalgrass weed control showed that applications made at 2.5 cm displayed typical visual symptoms by 7 DAT (Table 3). However, visual symptoms were delayed for other timings until 14 DAT and the level of control became equal for plants treated at 2.5 and 5 cm. Height reductions revealed greater decreases in plant stature by

14 DAT for later applications while the earliest application exhibited rapid height reduction by 7 DAT (Table 5). Delaying application timing to 10 cm resulted in more biomass production compared to the earlier timings (Table 3). Plant visual ratings demonstrated a negative relationship between height and weed control at all rating dates. Control of fall panicum at 7 and 14 DAT showed difference between 2.5 cm and the two later timings and similar results at the 5 and 10 cm timings. By 14 DAT, all timings adhered to the following sequence in order of decreasing levels of control; 2.5 cm, 5 cm, and 10 cm. The first plant height measurements showed that although plants sprayed at 2.5 cm reduced height more than 10 cm timing, the first timing was not different from the second. At 14 DAT, height reduction revealed that the 2.5 cm and 5 cm timings reduced height similarly and greater than the 10 cm timing. Meanwhile, dry weight reduction was found to be similar regardless of growth stage although a large drop in biomass production was observed from 5 to 10 cm (Table 3).

Texas millet should be considered moderately tolerant to quinclorac as the weed species shows symptoms of temporary height reduction with magnitude dependent upon growth stage at which it is applied. In addition, if sprayed at 2.5 cm the species demonstrated an ability to reduce dry weight by 80% compared to the nontreated check. Applications made to plants taller than 2.5 cm were not as efficacious dropping rapidly in effectiveness. Crowfootgrass and goosegrass responded similarly to each other in that weed control was not existent in the former and limited to 8% for the latter. Overall, less mature, shorter plants were better controlled than taller plants on a height and dry weight reduction basis (Table 3).

A general trend did exist where increasing herbicide rate led to frequently significantly greater levels of weed control. However, the factor of quinclorac rate may not prove to be as important as growth stage within the specific protocol tested as rate was important initially but to a lesser degree by 14 DAT. Both control and height reduction at 7 DAT was analyzed by the interaction of growth stage and quinclorac rate indicating some initial stunting and suppression. Rate response was critically important when the high rate improved control and height reduction of the 10 cm growth stage to levels which were statistically similar to earlier, less mature growth stages for some weed species. The one instance of significantly greater control as a result of higher herbicide rate occurred with Texas millet at 2.5 cm for which control was enhanced from 3 to 21% by increasing herbicide rate from 290 to 420 g ha^{-1}. Before 5 cm there is no statistically significant benefit to using the high rate of quinclorac (Table 4). However, if application is delayed to a weed height of 10 cm, increased rate may improve weed control of broadleaf signalgrass, large crabgrass, and fall panicum.

For all species tested except crowfootgrass and goosegrass, the earlier quinclorac is applied; greater weed control, height, and dry weight reductions were observed compared to later growth stages. These data pinpoint the importance of applying quinclorac before weed height exceeds 5 cm as the efficacy in height and dry weight reduction for broadleaf signalgrass, large crabgrass, fall panicum, and Texas millet drops significantly afterwards. In general, the following order for quinclorac herbicidal efficacy in relation to growth stage for the selected species is true; 2.5 cm $\geq$ 5 cm $\geq$ 10 cm and overall quinclorac at a rate of 290 g ha^{-1} was sufficient for control of large crabgrass, broadleaf signalgrass, and fall panicum.

Acknowledgements

Funding was provided by the North Carolina Small Grain Growers Association.

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Table 1. The pH, electrical conductivity (EC), and ion concentration in water sources from Raleigh, NC during the months of February and March, 2015.

Month	pH[a,b]	EC	$CaCO_3$	Fe	Cl^-	Fl^-
		uS cm^{-1}	mg L^{-1}			
February	8.4	223	27.8	0.1	-	0.79
March	8.4	225	26.9	0.1	13.7	0.74

[a] Abbreviations: Cl^-, chloride; $CaCO_3$, calcium carbonate; EC, electrical conductivity; Fl^-, fluoride; Fe, iron; uS cm^{-1}, microsiemens per centimeter; mg L^{-1}, milligrams per liter.

[b] Information retrieved from EM Johnson Water Plant Finished Water Quality Report, March 2015.

Table 2. Analysis of variance of weed control and height reduction for quinclorac + COC at three growth stages and two herbicide rates on six weed species in a greenhouse environment.

Source[a]	DF	F-value Height Reduction 7 DAT	p-value Height Reduction 7 DAT	F-value Control 7 DAT	p-value Control 7 DAT
Species (Sp)	5	168.06	<0.0001*	181.38	<0.0001*
Growth Stage (GS)	2	6.95	0.0011*	45.19	<0.0001*
Sp * GS	10	2.13	0.0218*	7.92	<0.0001*
Rate	1	0.01	0.9154	1.11	0.2920
Rate * Sp	5	0.95	0.4518	0.76	0.5782
Rate * GS	2	4.75	0.0093*	4.82	0.0086*
Rate * Sp * GS	10	0.53	0.8699	1.26	0.2509
Run	1	10.38	0.0014	48.03	<0.0001
Sp * Run	5	1.03	0.3983	8.25	<0.0001
GS * Run	2	0.64	0.5294	9.09	0.0001
Sp * GS * Run	10	1.96	0.0375	3.16	0.0007
Rate * Run	1	0.18	0.6756	0.12	0.7301
Sp * Rate * Run	5	0.83	0.5266	0.95	0.4495
GS * Rate * Run	2	0.68	0.5084	0.60	0.5491
Sp * GS * Rate * Run	10	1.61	0.1027	1.11	0.3540
Rep(Run)	10	1.22	0.2775	2.03	0.0297

[a] Abbreviations: COC, crop oil concentrate; DAT, days after treatment.

Table 2. Analysis of variance of weed control and height reduction for quinclorac + COC at three growth stages and two herbicide rates on six weed species in a greenhouse environment.

Source[a]	DF	F-value Height Reduction 14 DAT	p-value Height Reduction 14 DAT	F-value Control 14 DAT	p-value Control 14 DAT
Species (Sp)	5	203.37	<0.0001*	235.04	<0.0001*
Growth Stage (GS)	2	27.49	<0.0001*	28.78	<0.0001*
Sp * GS	10	1.98	0.0349*	4.93	<0.0001*
Rate	1	2.52	0.1137	3.16	0.0762
Rate * Sp	5	0.60	0.7034	1.57	0.1665
Rate * GS	2	2.60	0.0755	3.79	0.0236*
Rate * Sp * GS	10	0.27	0.9873	2.41	0.0088*
Run	1	7.30	0.0072	49.18	<0.0001
Sp * Run	5	2.48	0.0319	12.48	<0.0001
GS * Run	2	1.35	0.2599	0.91	0.4029
Sp * GS * Run	10	0.56	0.8487	2.31	0.0121
Rate * Run	1	2.68	0.1029	1.49	0.2236
Sp * Rate * Run	5	1.03	0.3988	0.59	0.7091
GS * Rate * Run	2	0.03	0.9673	0.33	0.7181
Sp * GS * Rate * Run	10	1.14	0.3327	1.48	0.1460
Rep(Run)	10	1.47	0.1480	0.95	0.4876

[a] Abbreviations: COC, crop oil concentrate; DAT, days after treatment.

Table 2. Analysis of variance of dry weight reduction for quinclorac + COC at three growth stages and two herbicide rates on six weed species in a greenhouse environment.

Source[a]	DF	F-value Dry Weight Reduction	p-value Dry Weight Reduction
Species (Sp)	5	255.64	<0.0001*
Growth Stage (GS)	2	4.89	0.008*
Sp * GS	10	3.36	0.0003*
Rate	1	0.48	0.4892
Rate * Sp	5	0.41	0.8436
Rate * GS	2	0.33	0.7170
Rate * Sp * GS	10	0.47	0.9058
Run	1	0.04	0.8371
Sp * Run	5	2.07	0.0689
GS * Run	2	1.09	0.3381
Sp * GS * Run	10	1.91	0.0424
Rate * Run	1	0.03	0.8699
Sp * Rate * Run	5	0.29	0.9160
GS * Rate * Run	2	0.65	0.5242
Sp * GS * Rate * Run	10	0.42	0.9362
Rep(Run)	10	1.14	0.3336

[a] Abbreviations: COC, crop oil concentrate; DAT, days after treatment.

Table 3. Effect of quinclorac on weed control, height, and dry weight reduction as influenced by species and growth stage in a greenhouse environment averaged over herbicide rate.

Species	Growth Stage	Control 7 DAT[a,b]	Height Reduction 7 DAT	Height Reduction 14 DAT	Dry Weight Reduction
		---	%	--	
	cm				
Broadleaf signalgrass	2.5	78 b	89 a	97 a	99 a
	5	40 d	76 a	91 a	98 a
	10	39 d	70 ab	77 ab	92 a
Large crabgrass	2.5	92 a	89 a	96 a	99 a
	5	66 c	82 a	82 ab	96 a
	10	57 c	69 ab	70 b	83 ab
Fall panicum	2.5	78 b	80 a	98 a	98 a
	5	38 d	74 ab	89 a	95 a
	10	38 d	58 b	66 b	79 ab
Texas millet	2.5	12 e	44 b	44 c	80 ab
	5	8 e	33 c	34 c	67 b
	10	4 e	26 cd	7 d	61 b
Crowfootgrass	2.5	0 ef	-14 de	2 d	-15 d
	5	0 ef	-8 d	-1 d	-5 cd
	10	0 ef	2 d	1 d	9 c
Goosegrass	2.5	0 ef	1 d	8 d	0 c
	5	0 ef	3 d	-1 d	14 c
	10	1 e	-3 d	-15 de	-7 cd

[a] Abbreviations: DAT, days after treatment.

[b] Data within the same column followed by the same letter is considered to not be significantly different according to Fisher's Protected LSD test $P \leq 0.05$.

Table 4. Effect of quinclorac on height reduction and weed control 7 DAT as influenced by growth stage and quinclorac rate in a greenhouse environment averaged over weed species.

		Control 7 DAT[a,b]	Height Reduction 7 DAT
Growth Stage	Quinclorac Rate	----------------------%-------------------------	
cm	g ae ha^{-1}		
2.5	290	50 a	53 a
	420	48 b	44 b
5	290	37 c	43 b
	420	39 c	43 b
10	290	27 d	32 c
	420	38 c	42 b

[a] Abbreviations: DAT, days after treatment.

[b] Data in the same column followed by the same letter is considered to not be significantly different according to Fisher's Protected LSD test $P \leq 0.05$.

Table 5. Effect of quinclorac on weed control 14 DAT as influenced by grass species, growth stage, and herbicide rate in a greenhouse environment.

			Control 14 DAT[a,b]
Species	Growth Stage	Quinclorac Rate	-------------%------------
	cm	g ae ha^{-1}	
Broadleaf signalgrass	2.5	290	91 a
		420	91 a
	5	290	77 ab
		420	93 a
	10	290	53 b
		420	60 b
Large crabgrass	2.5	290	85 a
		420	98 a
	5	290	67 ab
		420	70 ab
	10	290	50 b
		420	70 ab
Fall panicum	2.5	290	82 a
		420	92 a
	5	290	67 ab
		420	70 ab
	10	290	50 b
		420	70 ab
Texas millet	2.5	290	3 d
		420	21 c
	5	290	1 d
		420	10 cd
	10	290	2 d
		420	2 d
Crowfootgrass	2.5	290	0 d
		420	0 d
	5	290	0 d
		420	0 d
	10	290	0 d
		420	0 d
Goosegrass	2.5	290	0 d
		420	0 d
	5	290	8 cd
		420	0 d
	10	290	1 d
		420	0 d

Table 5. Continued

[a] Abbreviations: DAT, days after treatment.

[b] Data in the same column followed by the same letter is considered to not be significantly different according to Fisher's Protected LSD test $P \leq 0.05$.

CHAPTER 4

Grain Sorghum Response, Weed Control, and Yield following Quinclorac Application with Various Herbicides.

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Abstract

Field studies were conducted at three locations in North Carolina in 2015 to evaluate weed control efficacy as well as grain sorghum crop safety and yield response to POST applications of quinclorac alone and in combination with several common grain sorghum broadleaf herbicides. Control of large crabgrass, broadleaf signalgrass, and ivyleaf morningglory was greater than 82% when a preemergence herbicide was followed by a postemergence herbicide including quinclorac. The addition of atrazine was important for extended control of broadleaf signalgrass, large crabgrass, Texas millet, goosegrass, crowfootgrass, and palmer amaranth. Goosegrass and crowfootgrass control was greater than 99% when a PRE was applied, otherwise control was sporadic at the POST only stage. Quinclorac is not a suitable option alone to control palmer amaranth as results varied from 47 to 65% depending on location. Crop safety concerns were minimal for the quinclorac alone treatment further demonstrating its safety to grain sorghum as there were no observations of crop injury. However, treatments including atrazine caused slight decreases in plant height compared to treatments which did not include atrazine in early ratings. Treatments at the PRE fb POST timing had significantly greater yields compared to POST only treatments at all locations. Addition of atrazine to the tank mix did not negatively impact yield of PRE fb POST treatments but in each treatment at the POST only timing it significantly increased yield over similar treatments without atrazine. The highest yielding treatment received a PRE of *s*-metolachlor and atrazine as well as a POST of quinclorac and 2,4-D. These results indicate that quinclorac can safely be used in grain sorghum to improve weed control efficacy and crop yield

when tank mixed with broadleaf herbicides which are commonly used in grain sorghum production.

Nomenclature: Atrazine; broadleaf signalgrass, (*Urochloa platyphylla* (Nash) R.D. Webster); crowfootgrass, (*Dactyloctenium aegyptium* (L.) Willd.); goosegrass, (*Eleusine indica* (L.) Gaertn.); grain sorghum, (*Sorghum bicolor* (L.) Moench); ivyleaf morningglory, (*Ipomoea hederacea* Jacq.); large crabgrass, (*Digitaria sanguinalis* (L.) Scop.; palmer amaranth, (*Amaranthus palmeri* S. Wats.); s-metolachlor; Texas millet, (*Urochloa texana* (Buckl.) R. Webster).

Key Words: Crop safety, preemergence followed by postemergence, herbicide tank mixes, weed control efficacy.

Grain sorghum, a cereal crop predominantly grown in the High Plains of the United States has garnered revitalized interest in North Carolina in response to the need to provide more local grain supply for livestock feedstocks. In 2011, approximately 2,000 hectares of grain sorghum were grown in North Carolina and a year later planted area increased ten-fold (Montgomery 2012).

Several herbicide options exist to control broadleaf weed problems in grain sorghum but few tools exist for in crop grain sorghum weed management of grass weed species (Walker et al. 1991). Furthermore, many herbicide options which are available for grain sorghum weed management often have long rotation restrictions (Everman and Besancon 2012). Quinclorac has been proven to be safe on grain sorghum and to control select grass and broadleaf species (Koo et al. 1991; Landes et al. 1994). However, there are species outside of the spectrum of control of quinclorac.

A major benefit of grain sorghum is the ability to integrate modes of action into the weed management plan that cannot be used in sensitive crops such as soybean [*Glycine max* (L.) Merr.] and cotton [*Gossypium hirsutum* (L.)] to eliminate tough to control weeds. Several tank mix partners are recommended for use with quinclorac to control broadleaf weed species. For example, the current published section 2 Facet L® label recommends the following herbicides as tank mix partners to control weeds for in-crop grain sorghum; 2,4-D, atrazine, dicamba, prosulfuron, and bromoxynil.

Auxinic growth regulator herbicides such as 2,4-D and dicamba can safely be applied to grain sorghum before plants reach 30 cm in height (Phillips 1960). These two herbicides have demonstrated an exceptional ability to control *Amaranthus spp.*

(Merchant et al. 2013 and Jha and Norsworthy 2012). The presence of herbicide resistant palmer amaranth (*Amaranthus palmeri* S.Wats) populations in North Carolina make auxinic herbicides a useful tool in reducing seedbank populations for subsequent crop years (Jha and Norsworthy 2012; Poirier et al. 2014). However, there is evidence of antagonism of dicamba and 2,4-D when combined with some products for grass control (Flint and Barrett 1989; Merchant et al. 2013).

Atrazine can be considered the backbone of grain sorghum weed management as it is commonly used preemergence, postemergence, or both but should be utilized carefully. Chamberlain et al. (1970) found that applications of atrazine to 2.54 and 7.62 cm tall grain sorghum plants resulted in significant yield losses compared to plants sprayed at 15 cm. Although atrazine is most efficacious in suppressing broadleaf species, its control of grass weed species is variable (Geier et al. 2009; Grichar et al. 2004; Walker et al. 1991). Ramakrishna et al. (1991) found that atrazine reduced the height of grain sorghum regardless of application rate (0.5, 0.75, and 1 kg ai ha^{-1}) compared to other treatments. Dowler and Wright (1995) found that crowfootgrass and Texas millet can be sufficiently controlled with postemergence applications of atrazine in pearl millet. Plants applied with the low rate of atrazine recovered and yielded similar to those treatments which did not receive atrazine. The combination of quinclorac + atrazine POST is the current recommendation on the Facet L® label.

Prosulfuron has been shown to be less phytotoxic on grain sorghum and offer similar control of palmer amaranth and other broadleaf weeds compared to 2,4-D (Rosales-Robles et al. 2014; Rosales-Robles et al. 2011). Abit et al. (2011) demonstrated that the combination of quizalofop and prosulfuron provided greater than 90% control of palmer amaranth, puncturevine (*Tribulus terrestris* L.), and tumble pigweed (*Amaranthus albus* L.) proving a broad spectrum of control of dicotyledonous weeds.

Bromoxynil inhibits photosystem II within the nitrile chemical family which is safe to apply to corn and grain sorghum as well as offers excellent control of broadleaf weed species, including palmer amaranth (Rosales-Robles et al. 2011). However, many have found that bromoxynil causes antagonism when tank mixed with graminicides such as fluazifop-methyl, quizalofop, and clethodim (Corkern et al. 1998; Grey et al. 1993; Jordan et al. 1993). A relatively new pre-mixed herbicide containing bromoxynil + pyrasulfotole (Huskie®) has been registered for use in wheat, barley, and grain sorghum. Pyrasulfotole is from the pyrazole herbicide family and inhibits 4-hydoxyphenylpyruvate dioxygenase (HPPD) enzyme synthesis (Reddy et al. 2013). Combinations of photosystem II and HPPD inhibitors have been shown to have synergistic herbicide effects providing increased levels of control of susceptible and resistant weed populations (Abendroth et al. 2006; Walsh et al. 2012). Injury from this herbicide can be expected but symptoms are transient by 3-4 weeks after application (Reddy et al. 2013). Recommendations from the label suggest adding atrazine for added and expanded weed control.

Due to the diverse cropping systems present in North Carolina, the cohort of weed species which grain sorghum growers must control are artifacts of weed seedbanks left uncontrolled by previous crops. Broadleaf signalgrass (*Urochloa platyphylla (*Munro ex C. Wright), large crabgrass (*Digitaria sanguinalis (*L.) Scop.), Texas millet (*Urochloa* *texana (*Buckl.) R. Webster), crowfootgrass (*Dactyloctenium aegyptium* Willd.), and goosegrass (*Eleusine indica (*L.) Gaertn.) have all been named by grain sorghum growers in the southeastern United States as tough to control weed species (Webster 2012). Broadleaf signalgrass has been shown to outcompete other vigorously growing weeds such as large crabgrass and fall panicum (*Panicum dichotomiflorum* Michx.*)*, (Johnson and Coble 1986). Large crabgrass has demonstrated a strong ability to reproduce as one plant may create 150,000 seeds in a growing season. The species will also germinate in several flushes throughout the growing season (Johnson and Coble 1986). Several preplant and preemergence herbicides are ineffective at controlling Texas millet (Chandler and Santelmann 1969; Grichar 1991). The use of some herbicide chemistries, particularly the chloroacetamides have allowed the large seeded species to emerge without competition from other more commonly smaller annual grass seeds (Buchanan et al. 1983). Crowfootgrass, native to Africa has been known to inhabit 25-75% of the peanut production area in North Carolina and Virginia making it a potential weed management issue for grain sorghum (Bridges et al. 1994). Goosegrass is a weed species identified globally as a major pest in crop production with biotypes resistant to several modes of action (Heap 2015).

The herbicidal relationships from the aforementioned broadleaf products tank mixed with quinclorac have not been explored previously. Suitable options for broad spectrum weed control need to be evaluated for quinclorac to become fully integrated as a herbicide option in the minds of grain sorghum growers. Additionally, quinclorac efficacy must be tested against weed species common to areas of grain sorghum production in North Carolina.

The objective of this study was to evaluate grain sorghum crop safety, weed control, and grain yield as affected by application timing and the influence of commonly used herbicides when tank mixed with quinclorac in grain sorghum weed management.

Materials and Methods

Field studies were conducted to evaluate the impact of various combinations of herbicide tank mixes on grain sorghum crop safety, weed control, and yield. Studies were conducted at the Central Crops Research Station in Clayton, NC (35.6663036, -78.4995275), the Peanut Belt Research Station in Lewiston-Woodville, NC (36.1323875, -77.1705763), and at the Upper Coastal Plain Research Station in Rocky Mount, NC (35.8942103, -77.6801122) in 2015. The soil type at Clayton and Rocky Mount was a Norfolk loamy sand which are fine-loamy, kaolinitic, thermic Typic Kandiudults. At the Peanut Belt Research Station in Lewiston-Woodville, NC the experiment was planted on Lynchburg sandy loams which are fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults. Soil types were identified using the USDA web soil survey (USDA-NRCS 2013).

Grain sorghum was planted in conventionally tilled soils at 247,000 seeds ha^{-1} on 91 cm rows in plots 2.4 m x 9.1 m, regardless of location. Clayton was planted using a 2 row John Deere 7100 VaccuumMax MaxEmerge vacuum-metered planter while Rocky Mount and Lewiston-Woodville were planted with a 4 row John Deere 7300

VaccuumMax MaxEmerge vacuum-metered planter. DeKalb 'DKS53-67' grain sorghum was planted on raised beds to a depth of 1.9 cm on June 11, 2015 and June 13, 2015 at Clayton and Rocky Mount, respectively. Pioneer '84P80' grain sorghum was planted on raised beds at a depth of 1.9 cm on June 24, 2015 at Lewiston-Woodville. Standard fertilization and insect management practices as recommended by the North Carolina Cooperative Extension Service were followed. The study at Rocky Mount was irrigated as needed during the summer due to lack of rainfall.

The experiment was arranged in a randomized complete block design with a two factor factorial. Preemergence herbicide options were *s*-metolachlor + atrazine at 1078 g ai ha^{-1} plus 1392 g ai ha^{-1} (Bicep II Magnum, Syngenta Crop Protection, Greensboro, NC), respectively, or no preemergence herbicide. POST herbicide options included quinclorac (Facet L®, BASF Agricultural Products, Research Triangle Park, NC) at 290 g ae ha^{-1} plus crop oil concentrate (COC) was included in all postemergence treatments at 2.34 L ha^{-1} (Crossfire®, Cardinal Chemical Company, Wilson, NC). A full list of treatments can be found in Table 1.

Treatments were applied using a CO_2-pressurized backpack sprayer calibrated to a pressure of 207 kPa, delivering 140 L ha^{-1} with TeeJet flat fan XR11002 nozzles (TeeJet Technologies Inc., Wheaton, IL 60187).

Visual estimation of crop safety and weed control was made 14, 28, and 42 days after the appropriate postemergence application. Crop response evaluations recorded at 42 days as well as weed control at 14 and 42 days after treatment are omitted from the discussion due to potential confounding weed competition effects. Crop height measurements as well as visual estimation of crop stunting were recorded simultaneously with visual weed control ratings. Weed control, relative to the nontreated check, was estimated visually at 14, 28, and 42 days after postemergence application. Visual weed control estimates were based on a scale of 0-100% where 0 = no weed control and 100 = complete weed control. A full list of weed species present at each of the locations where this study was conducted can be found in Table 2. A small plot combine was used to harvest yield.

Data were subjected to ANOVA with the use of PROC GLM in SAS 9.3 (SAS Institute, 100 SAS Campus Dr, Cary, NC 27513) and means were separated using Fisher's Protected LSD test with a probability level of 95%. Runs and replications were considered to be random effects.

Results and Discussion

Crop response

A significant interaction of environment and postemergence herbicide, pooled over preemergence was observed for chlorosis 14 DAT (Table 3). There was no chlorosis noted by quinclorac alone and in most treatments evidence of chlorosis could not be detected. However, 3% crop chlorosis was noted at Clayton and Lewiston-Woodville for the quinclorac + pyrasulfotole + bromoxynil treatment. Chlorosis was significantly reduced with quinclorac + pyrasulfotole + bromoxynil + atrazine to 1% at Clayton and no injury was observed at Lewiston-Woodville. It has been widely noted that the pyrasulfotole + bromoxynil pre-mix causes temporary chlorosis, which becomes transient soon after application and typically did not negatively impact yield (Fromme et al. 2012; Reddy et al. 2013). Crop stunting was evaluated at each rating date but no necrosis injury was observed.

Crop stunting was evaluated by the main effect of environment at 14 DAT (Table 4). Significantly greater stunting was observed at Clayton (8%) at 14 DAT compared to Rocky Mount (4%) or Lewiston-Woodville (3%) (Table 4). Stunting was also significant due to the interaction of environment and preemergence herbicide at 28 DAT (Table 5). At all locations grain sorghum plants which received a PRE application were significantly less stunted compared to those plants which did not receive a PRE. Stunting increased for treatments which only received a POST at all locations. Crop stunting was also significant by the interaction of PRE and POST herbicide, pooled over environment at 14 and 28 DAT (Table 6). Visual estimation of stunting of PRE fb POST treatments may more accurately depict herbicidal impact on the crop as effects observed at the POST only timing may be confounded by weed pressure rather than treatment effect, especially in later ratings. At 14 DAT, treatments with the highest level of crop stunting included those which contained prosulfuron, particularly prosulfuron + atrazine. Quinclorac + 2,4-D or dicamba did not differ from quinclorac alone in the amount of stunting exhibited which was not more than 3%. At 28 DAT, quinclorac alone stunted the crop approximately 3%, at the lowest level of observed among treatments. Similarly, quinclorac + atrazine resulted in 6% stunting while atrazine alone showed 14% stunting, among the highest observed. Treatments at the PRE fb POST timing with the greatest amount of stunting include atrazine alone, quinclorac + pyrasulfotole + bromoxynil +

atrazine, and quinclorac + prosulfuron + atrazine. Again, adding 2,4-D and dicamba at the PRE fb POST timing exhibited a similar level of crop stunting compared to quinclorac alone.

Crop height data were significantly impacted by the interaction of environment and PRE herbicide at 14 and 28 DAT as well as the interaction of environment and POST herbicide at 14 DAT (Tables 7 & 8). Crop height 14 DAT as affected by environment and POST herbicide showed the addition of atrazine generally produced shorter plants compared to their identical treatment without atrazine at all locations (Table 7). In Clayton, each time atrazine was added, crop height was reduced significantly compared to quinclorac alone and compared to its identical treatment pair without atrazine. Further, plants treated with quinclorac + pyrasulfotole + bromoxynil + atrazine were significantly shorter than quinclorac alone. Plants treated with quinclorac + prosulfuron were significantly shorter than all other POST herbicide treatments. At Rocky Mount, the addition of atrazine did not have as strong an impact as only atrazine alone and quinclorac + prosulfuron + atrazine were significantly shorter than quinclorac alone. The addition of 2, 4-D to quinclorac increased crop height compared to quinclorac alone while the addition of dicamba to quinclorac did not impact crop height. Plant measurements taken at Lewiston-Woodville demonstrated that only quinclorac + atrazine resulted in reduced crop height compared to quinclorac alone (Table 7).

The significant environment by PRE herbicide interaction revealed crop height at Clayton was greatest, followed by Rocky Mount and Lewiston-Woodville at both 14 and

28 DAT (Table 8). Treatments which received a PRE application were significantly taller than those which only received a POST application.

Large crabgrass control

The 28 DAT rating required analysis of the interaction between environment, PRE, and POST herbicide (Table 9). Large crabgrass control ranged from 95-100% for treatments which received a PRE for all three locations. However, for those treatments which only received a POST, control was greatest at Clayton with the lowest control at Lewiston-Woodville. Aside from one treatment at Clayton, all POST only treatments gave greater than 97% control of large crabgrass, similar to PRE fb POST treatments. The treatment of quinclorac + pyrasulfotole + bromoxynil resulted in reduced control of large crabgrass when compared to all other POST treatments. The addition of atrazine to quinclorac + pyrasulfotole + bromoxynil significantly increased large crabgrass control. At Rocky Mount, efficacy on large crabgrass was diminished compared to Clayton as no POST only treatments were statistically similar to their PRE fb POST treatment pair. However, the addition of atrazine to quinclorac, quinclorac + prosulfuron, and quinclorac + pyrasulfotole + bromoxynil provided significantly greater large crabgrass control compared to the same treatments without atrazine. The addition of 2, 4-D or dicamba resulted in significantly greater control compared to quinclorac alone. Efficacy at Lewiston-Woodville was slightly reduced compared to Rocky Mount at 28 DAT but the trend with increased control due to the addition of atrazine was present. Quinclorac alone gave significantly greater control of large crabgrass compared to treatments which included 2, 4-D, dicamba, prosulfuron, or pyrasulfotole + bromoxynil without atrazine.

Broadleaf signalgrass control

Broadleaf signalgrass control was significant by the interaction of PRE and POST herbicides, pooled over environment as well as the interaction of environment and PRE herbicide at 28 DAT (Tables 10 and 11).

Control of broadleaf signalgrass was greatest for those treatments which included quinclorac and atrazine which provided significantly improved control over either of the two treatments alone 28 DAT at the POST only timing (Table 10). Treatments which included quinclorac + atrazine significantly increased control compared to those which did not contain atrazine. Although all PRE fb POST treatments gave statistically similar control amongst treatments including the PRE only treatment, a few POST only treatments gave similar control to PRE fb POST treatments. Quinclorac + atrazine at the PRE fb POST and POST only timings gave statistically similar weed control results. Furthermore, quinclorac + pyrasulfotole + bromoxynil + atrazine and quinclorac + prosulfuron + atrazine demonstrated statistically similar levels of broadleaf signalgrass control compared to a PRE fb POST treatment. Quinclorac + 2, 4-D, dicamba, and + prosulfuron provided significantly greater control of broadleaf signalgrass than quinclorac alone at the POST only timing. All those treatments which included quinclorac + atrazine at the POST only timing significantly increased broadleaf signalgrass control.

In general, broadleaf signalgrass was better controlled at Clayton, followed by Rocky Mount, followed by Lewiston-Woodville (Table 11).

Texas millet control

Control of Texas millet was significant by the interaction of environment, preemergence, and postemergence herbicide at 28 DAT (Table 9). Quinclorac alone at the PRE fb POST timing at Clayton and Rocky Mount gave similar levels of control compared to PRE only but were different by location; 55% for the former and 94% for the latter. All PRE fb POST treatments save atrazine alone at Rocky Mount exhibited similar levels of control amongst treatments which ranged from 92-100%. Atrazine alone gave significantly lower Texas millet control compared to quinclorac alone or quinclorac + atrazine at both locations at the PRE fb POST timing. Adding atrazine to quinclorac, quinclorac + pyrasulfotole + bromoxynil, and quinclorac + prosulfuron significantly improved control of Texas millet at the PRE fb POST and POST only timings at Clayton and for the POST only treatments at Rocky Mount. Quinclorac + 2, 4-D and quinclorac + dicamba offered excellent control at 86 and 90%, respectively at the PRE fb POST timing.

For those treatments which only received a POST, the efficacy of quinclorac alone was minimal as control at Clayton was 40% and 10% control at Rocky Mount (Table 9). Atrazine alone at the POST only timing significantly increased Texas millet control at both locations compared to quinclorac alone. Dowler and Wright (1995) observed greater than 80% levels of control of Texas millet when atrazine was applied postemergence. The combination of quinclorac + atrazine increased Texas millet control at both locations but only at Rocky Mount was that increase significant. Similar to observations made previously at 14 DAT the addition of atrazine to quinclorac alone, quinclorac + pyrasulfotole + bromoxynil, and quinclorac + prosulfuron significantly increased Texas millet control at Clayton and Rocky Mount. Quinclorac + pyrasulfotole + bromoxynil + atrazine provided 99% control of Texas millet at 28 DAT, the sole treatment to reach statistically similar levels of control compared to their PRE fb POST treatment pair.

Goosegrass control

Goosegrass control was analyzed at 28 DAT by the interaction between PRE and POST herbicide treatments, pooled over environment (Table 10). Control remained exceptional at 100% for those treatments which received a PRE, including the PRE only treatment. The PRE only treatment performed differently between the two locations, at Rocky Mount goosegrass control was 100% compared to Clayton where control was only 75%. However, by 28 DAT the PRE only treatment gave 100% control at both locations. Goosegrass control in POST only treatments was increased significantly when atrazine was included. Quinclorac alone provided 20% control at both locations similar to that of quinclorac + prosulfuron. Quinclorac + atrazine or atrazine alone provided significantly greater control between 69 and 72%. Treatments including the premixed herbicide of pyrasulfotole + bromoxynil gave higher levels of weed control without atrazine compared to any of the other treatments at the POST only timing.

The importance of a residual herbicide either at the preemergence or postemergence timing proved to be a crucial factor in successful goosegrass control. Treatments which received the preemergence application of s-metolachlor + atrazine provided exceptional control. A trend emerged from the POST only treatments revealing that the addition of atrazine significantly increased control of goosegrass at all rating dates. Additionally, the premixed herbicide of pyrasulfotole + bromoxynil demonstrated some grass activity.

Crowfootgrass control

Control of crowfootgrass at 28 DAT were pooled over environment and revealed the importance of a PRE herbicide to control of this species (Table 10). All treatments which received a PRE obtained 100% control, including the PRE only treatment which exhibited levels of control superior to any POST only treatment. Quinclorac alone gave low levels of crowfootgrass control (20%). Every other treated plot gave significantly greater control compared to quinclorac alone. Atrazine alone and quinclorac + atrazine provided 72% control of crowfootgrass which was found to be statistically similar to quinclorac + prosulfuron + atrazine. The addition of the pre-mixed pyrasulfotole + bromoxynil treatment without atrazine gave the highest level of control compared to any treatment without atrazine. However, with atrazine that treatment demonstrated 91% control of crowfootgrass. Without atrazine control ranged from 20-53% while the addition of atrazine improved weed control from 69-91%. Furthermore, the addition of atrazine to the tank mixes gave significantly greater control than treatments without it. Quinclorac + 2, 4-D and dicamba gave significantly greater levels of control compared to quinclorac alone.

Palmer amaranth control

Palmer amaranth control at 28 DAT was analyzed by the significant interaction of PRE and POST herbicide pooled over environment as well as the significant interaction of environment and PRE herbicide. Control was also evaluated by the interaction of environment and POST herbicide treatment at 28 DAT (Tables 10, 11, and 12).

Treatments which received a PRE followed by a POST gave control ranging from 91-100% and where a PRE was not applied weed control was unacceptable for palmer amaranth (Tables 10 and 11). The spectrum of broadleaf herbicides included allowed for excellent control (95%) of palmer amaranth even without a PRE with several POST only treatments. Treatments which only received a POST ranged from 47-98% control. In general, the addition of atrazine did not improve control of palmer amaranth at the PRE fb POST timing except for the quinclorac + prosulfuron treatment. However, the addition of atrazine improved control of palmer amaranth for each treatment at the POST only timing allowing some treatments to reach levels of control seen in the PRE fb POST timing including atrazine, quinclorac + atrazine, quinclorac + pyrasulfotole + bromoxynil + atrazine, and quinclorac + prosulfuron + atrazine. In addition to the previously mentioned list, the two auxin mimic growth regulators 2, 4-D and dicamba provided greater than 80% control regardless of timing or rating date. The POST only timing with dicamba provided significantly greater control of palmer amaranth compared to 2,4-D.

Control of palmer amaranth was analyzed by the interaction of environment and postemergence herbicide pooled over the effect of a preemergence herbicide (Table 12). Treatments which included atrazine in the postemergence herbicide tank mix provided the greatest levels of weed control. Furthermore, quinclorac alone should not be considered as an option to provide an acceptable level of palmer amaranth control.

Ivyleaf morningglory control

Weed control of ivyleaf morningglory was analyzed by the significant interaction of environment, PRE and POST herbicide treatment (Table 9). Levels of control were at least 80% for the PRE fb POST and POST only timings and lagged for treatments which did not include quinclorac. Quinclorac alone without a PRE provided at least 88% control of ivyleaf morningglory at each of the three study locations. When a PRE was present quinclorac alone provided at least 96% control.

Yield

Yield data were also analyzed by the interaction of the main effects of PRE and POST herbicide treatments, pooled over environment which revealed the importance of a PRE in successful grain sorghum production (Table 10). With the exception of one treatment, PRE fb POST treatments gave significantly greater yield than their POST only counterpart. All plots which received herbicide achieved higher yield compared to the nontreated check. According to the current quinclorac product label, optimal in crop annual grass control can be gained with the use of quinclorac at 290 – 420 g ha^{-1} along with atrazine at 560-1120 g ha^{-1} (Anonymous 2013). The combination of quinclorac plus atrazine provided statistically similar yield results with or without the presence of a PRE. Overall, adding atrazine to the tank mix did not increase yield for treatments at the PRE fb POST timing. Furthermore, the treatment which received only a preemergence herbicide and no postemergence herbicide yielded similarly at 3830 kg ha^{-1} to all PRE fb POST treatments except for quinclorac + 2,4-D (4080 kg ha^{-1}) and quinclorac + atrazine

(3570 kg ha^{-1}). The highest yielding treatment was at the PRE fb POST timing with a POST treatment including quinclorac + 2,4-D.

The interaction of environment and PRE herbicide treatment were analyzed which indicated that treatments which included a preemergence herbicide had significantly higher yields than those without a preemergence herbicide (Table 11). Lewiston-Woodville and Clayton gave nearly identical yields for the PRE followed by POST (PRE fb POST) timing at 4650 and 4640 kg ha^{-1}, respectively. However, those treatments at the POST only timing were significantly different between the two locations. Plots receiving only a POST at Clayton gave 2909 kg ha^{-1} while those at Lewiston-Woodville at the same timing gave 3710 kg ha^{-1}. Rocky Mount PRE fb POST treatments yielded 2090 kg ha^{-1} while those at the POST only timing gave 1710 kg ha^{-1}.

Although the POST only treatments were applied at early postemergence (EPOST) the lack of PRE initially caused significant loss in yield potential. Only the quinclorac + atrazine treatment gave yield results similar to the PRE only treatment, all others were significantly lower. POST only treatments which included atrazine achieved significantly greater results than those which did not include atrazine.

Quinclorac, when applied with common grain sorghum herbicides such as 2,4-D and atrazine exhibited no adverse effects. These data suggest the importance of a preemergence herbicide for optimal weed control and a high yielding grain sorghum crop. Although some highly susceptible weed species such as large crabgrass and broadleaf signalgrass were controlled without a PRE application, other more tough to control weed species such as goosegrass, Texas millet, goosegrass, and palmer amaranth were able to thrive and decrease crop yields. Particularly for those treatments which only received a postemergence herbicide application, adding atrazine along quinclorac to the tank mix aided in provided residual control of some weed species. For Texas millet, crowfootgrass, and goosegrass where quinclorac applications alone were not efficacious, the addition of atrazine significantly improved control of these species over the same treatments without atrazine. This effect carried over to yield as those treatments which included atrazine regularly obtained significantly higher yield than treatments without it, particularly at the POST only timing. All but one treatment at the POST only timing displayed significantly lower yields compared to the PRE only treatment. However, the highest yielding treatment overall received a PRE and a POST of quinclorac + 2,4-D.

Acknowledgements

Appreciation for this research goes to Anthony Growe, Brandon Schrage, Drake Copeland, Manish Bansal, John Sanders, and Neal O'Quinn for technical support. Additionally, this research would not have been possible without funding from the North Carolina Small Grain Growers Association.

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Table 1. Treatment list.

PRE Herbicide[a]	Rate	POST Herbicide	Rate
	g ai ha^{-1}		g ai ha^{-1}
No PRE		quinclorac	290
No PRE		atrazine	560
No PRE		quinclorac + atrazine	290 + 560
No PRE		quinclorac + pyrasulfotole + bromoxynil	290 + 290
No PRE		quinclorac + pyrasulfotole + bromoxynil + atrazine	290 + 290 + 560
No PRE		quinclorac + prosulfuron	290 + 10
No PRE		quinclorac + prosulfuron + atrazine	290 + 10 + 560
No PRE		quinclorac + 2,4-D	290 + 140
No PRE		quinclorac + dicamba	290 + 280
No PRE		No POST	-
S-metolachlor + atrazine	1078 + 1392	quinclorac	290
S-metolachlor + atrazine	1078 + 1392	atrazine	560
S-metolachlor + atrazine	1078 + 1392	quinclorac + atrazine	290 + 560
S-metolachlor + atrazine	1078 + 1392	quinclorac + pyrasulfotole + bromoxynil	290 + 290
S-metolachlor + atrazine	1078 + 1392	quinclorac + pyrasulfotole + bromoxynil + atrazine	290 + 290 + 560
S-metolachlor + atrazine	1078 + 1392	quinclorac + prosulfuron	290 + 10
S-metolachlor + atrazine	1078 + 1392	quinclorac + prosulfuron + atrazine	290 + 10 + 560
S-metolachlor + atrazine	1078 + 1392	quinclorac + 2,4-D	290 + 140
S-metolachlor + atrazine	1078 + 1392	quinclorac + dicamba	290 + 280
S-metolachlor + atrazine	1078 + 1392	No POST	-

[a] Abbreviations: POST; postemergence herbicide; PRE, preemergence herbicide.

Table 2. Weed species present at three environments in the field evaluation of quinclorac as a part of various herbicide tank mixes.

Clayton 2015	Lewiston-Woodville 2015	Rocky Mount 2015
Weed Species		
Large crabgrass	Large crabgrass	Large crabgrass
Broadleaf signalgrass	Broadleaf signalgrass	Broadleaf signalgrass
Ivyleaf morningglory	Ivyleaf morningglory	Ivyleaf morningglory
Palmer amaranth		Palmer amaranth
Texas millet		Texas millet
Goosegrass		Goosegrass
Crowfootgrass		Crowfootgrass

Table 3. Effect of quinclorac and various herbicide tank mixes on crop chlorosis at 14 DAT as a influenced by environment and postemergence herbicide treatment in a field study.

POST Treatment			
	Chlorosis[a,b]		
	Clayton	Rocky Mount	Lewiston-Woodville
	--------------------%-------------------		
quinclorac	0 c	0 c	0 c
atrazine	0 c	1 b	1 b
quinclorac + atrazine	0 c	0 c	0 c
quinclorac + pyrasulfotole + bromoxynil	3 a	0 c	3 a
quinclorac + pyrasulfotole + bromoxynil + atrazine	1 b	0c	0 c
quinclorac + prosulfuron	0 c	0 c	0 c
quinclorac + prosulfuron + atrazine	0 c	0 c	0 c
quinclorac + 2,4-D	0 c	0 c	0 c
quinclorac + dicamba	1 b	0 c	0 c
No POST	0 c	0 c	0 c

[a] Abbreviations: DAT, days after treatment

[b] Means followed by the same letter should not be considered statistically different according to Fisher's Protected LSD test P $\leq$ 0.05.

Table 4. Effect of quinclorac and various herbicide tank mixes on crop stunting at 14 DAT as influenced by the main effect of environment in a field study.

Environment	Crop Stunting[a,b]
	---------%---------
Clayton	8 a
Rocky Mount	4 b
Lewiston-Woodville	3 b

[a] Abbreviations: DAT, days after treatment.

[b] Means followed by the same letter should not be considered statistically different according to Fisher's Protected LSD $P \leq 0.05$.

Table 5. Effect of quinclorac and various herbicide tank mixes on crop stunting at 28 DAT as influenced by environment and preemergence herbicide in a field study.

	Crop Stunting[a,b]	
Environment	28 DAT	
	PRE fb POST	POST only
	---------------------------%---------------------------	
Clayton	6 b	10 a
Rocky Mount	5 b	10 a
Lewiston-Woodville	6 b	9 a

[a] Abbreviations: DAT, days after treatment; PRE, preemergence; fb, followed by; POST, postemergence.

[b] Means followed by the same letter within the same evaluation timing should not be considered statistically different according to Fisher's Protected LSD P $\leq$ 0.05.

Table 6. Effect of quinclorac and various herbicide tank mixes on crop stunting as influenced by preemergence and postemergence herbicide treatment, pooled over environment in a field study.

		Crop Stunting[a,b]	
Treatment		14 DAT	28 DAT
PRE Trt	POST Trt	---------------%-------------	
PRE	quinclorac	2 fg	3 f
PRE	atrazine	8 c	14 b
PRE	quinclorac + atrazine	3 f	6 e
PRE	quinclorac + pyrasulfotole + bromoxynil	3 f	4 ef
PRE	quinclorac + pyrasulfotole + bromoxynil + atrazine	6 d	10 c
PRE	quinclorac + prosulfuron	9 b	9 d
PRE	quinclorac + prosulfuron + atrazine	10 b	13 b
PRE	quinclorac + 2,4-D	3 f	3 f
PRE	quinclorac + dicamba	1 g	5 ef
PRE	No POST	3 f	4 f
No PRE	quinclorac	2 fg	8 d
No PRE	atrazine	4 e	10 c
No PRE	quinclorac + atrazine	7 cd	7 de
No PRE	quinclorac + pyrasulfotole + bromoxynil	1 g	6 e
No PRE	quinclorac + pyrasulfotole + bromoxynil + atrazine	8 c	5 e
No PRE	quinclorac + prosulfuron	2 fg	7 de
No PRE	quinclorac + prosulfuron + atrazine	11 a	8 d
No PRE	quinclorac + 2,4-D	3 f	4 f
No PRE	quinclorac + dicamba	3 f	7 de
No PRE	No POST	8 c	16 a

[a] Abbreviations: DAT, days after treatment; Trt, treatment.

[b] Means within the same rating column followed by the same letter should not be considered statistically different according to Fisher's Protected LSD test P $\leq$ 0.05.

Table 7. Effect of quinclorac and various herbicide tank mixes on crop height at 14 DAT as influenced by environment and postemergence herbicide treatment in a field study.

POST Treatment	Crop Height[a,b]		
	Clayton	Rocky Mount	Lewiston-Woodville
	-----------------cm-----------------		
quinclorac	76 a	69 e	67 ef
atrazine	71 d	66 f	67 ef
quinclorac + atrazine	75 b	69 e	64 g
quinclorac + pyrasulfotole + bromoxynil	73 c	69 e	67 ef
quinclorac + pyrasulfotole + bromoxynil + atrazine	66 f	67 ef	66 f
quinclorac + prosulfuron	68 e	67 ef	67 ef
quinclorac + prosulfuron + atrazine	64 g	66 f	67 ef
quinclorac + 2,4-D	73 c	72 c	66 ef
quinclorac + dicamba	70 d	67 e	67 ef
No POST	76 a	63 h	65 fg

[a] Abbreviations: DAT, days after treatment; POST, postemergence herbicide.

[b] Means followed by the same letter should not be considered statistically different according to Fisher's Protected LSD test $P \leq 0.05$.

Table 8. Effect of quinclorac and various herbicide tank mixes on crop height at 14 and 28 DAT as influenced by location and preemergence herbicide in a field study.

	Crop Height[a,b]			
Environment	14 DAT		28 DAT	
	PRE fb POST	POST only	PRE fb POST	POST only
	--------------------------------cm---------------------------------			
Clayton	75 a	67 d	99 a	90 b
Rocky Mount	73 b	64 e	78 c	77 cd
Lewiston-Woodville	69 c	62 e	78 c	72 d

[a] Abbreviations: DAT, days after treatment; PRE, preemergence; fb, followed by; POST, postemergence.

[b] Means followed by the same letter within the same rating date should not be considered statistically different according to Fisher's Protected LSD $P \leq 0.05$.

Table 9. Effect of quinclorac and various herbicide tank mixes on weed control 28 DAT as influenced by environment, preemergence, and postemergence herbicide treatment in a field study.

		Weed Control							
Treatment		Ivyleaf morningglory[a,b]			Large crabgrass			Texas millet	
PRE Trt	POST Trt	Clayton	Rocky Mount	Lewiston-Woodville	Clayton	Rocky Mount	Lewiston-Woodville	Clayton	Rocky Mount
		---%							---
PRE	quinclorac	100 a	100 a	96 b	100 a	100 a	95 ab	55 e	94 a
PRE	atrazine	100 a	69 e	92 b	100 a	100 a	100 a	41 f	72 c
PRE	quinclorac + atrazine	100 a	100 a	53 h	100 a	100 a	97 ab	66 d	98 a
PRE	quinclorac + pyrasulfotole + bromoxynil	100 a	100 a	82 d	100 a	99 a	100 a	76 c	100 a
PRE	quinclorac + pyrasulfotole + bromoxynil + atrazine	100 a	100 a	89 c	100 a	100 a	100 a	92 ab	93 ab
PRE	quinclorac + prosulfuron	100 a	100 a	88 c	100 a	97 a	96 ab	86 b	92 ab
PRE	quinclorac + prosulfuron + atrazine	100 a	100 a	96 b	100 a	100 a	100 a	97 a	92 ab
PRE	quinclorac + 2,4-D	100 a	100 a	90 c	100 a	100 a	100 a	90 ab	98 a
PRE	quinclorac + dicamba	100 a	100 a	90 c	100 a	100 a	100 a	86 b	99 a
PRE	No POST	87 cd	62 g	50 i	100 a	100 a	97 a	55 e	95 a
No PRE	quinclorac	100 a	100 a	90 c	97 a	52 g	47 h	40 f	10 hi
No PRE	atrazine	100 a	66 f	40 j	100 a	41 i	34 j	70 cd	50 e
No PRE	quinclorac + atrazine	100 a	100 a	90 c	98 a	85 c	65 e	80 b	71 cd

No PRE	quinclorac + pyrasulfotole + bromoxynil	100 a	100 a	88 c	47 h	75 d	37 ij	32 g	40 f
No PRE	quinclorac + pyrasulfotole + bromoxynil + atrazine	100 a	100 a	89 c	97 a	90 b	49 h	54 e	99 a
No PRE	quinclorac + prosulfuron	100 a	100 a	90 c	100 a	84 c	34 j	29 g	29 g
No PRE	quinclorac + prosulfuron + atrazine	100 a	100 a	90 c	98 a	89 b	57 f	77 c	70 cd
No PRE	quinclorac + 2,4-D	100 a	100 a	92 b	100 a	84 c	39 i	72 c	65 d
No PRE	quinclorac + dicamba	100 a	100 a	93 b	100 a	85 c	35 j	86 b	65 d
No PRE	No POST	0 l	22 k	0 l	10 l	21 k	3 m	0 i	0 i

[a] Abbreviations: PRE, preemergence herbicide; POST, postemergence herbicide.

[b] Means followed by the same letter are not considered to be different according to Fisher's Protected LSD test P ≤ 0.05.

Table 10. Effect of quinclorac and various herbicide tank mixes on weed control and yield as influenced by preemergence and postemergence herbicide, pooled over environment in a field study.

Treatment		Broadleaf signalgrass 28 DAT[a]	Palmer amaranth 28 DAT	Goosegrass 28 DAT	Crowfootgrass 28 DAT	Yield
PRE Trt	POST Trt	--------------------------	----%	----------------------		kg ha^{-1}
PRE	quinclorac	99 a	100 a	100 a	100 a	3640 bc
PRE	atrazine	99 a	100 a	100 a	100 a	3830 b
PRE	quinclorac + atrazine	96 ab	100 a	100 a	100 a	3570 c
PRE	quinclorac + pyrasulfotole + bromoxynil	97 a	98 a	100 a	100 a	3640 bc
PRE	quinclorac + pyrasulfotole + bromoxynil + atrazine	99 a	100 a	100 a	100 a	3890 b
PRE	quinclorac + prosulfuron	99 a	91 bc	100 a	100 a	3890 b
PRE	quinclorac + prosulfuron + atrazine	97 a	100 a	100 a	100 a	3700 bc
PRE	quinclorac + 2,4-D	99 a	100 a	100 a	100 a	4080 a
PRE	quinclorac + dicamba	99 a	100 a	100 a	100 a	3760 b
PRE	No POST	98 a	100 a	100 a	100 a	3830 b
No PRE	quinclorac	67 d	59 e	20 g	20 h	2760 ef
No PRE	atrazine	39 f	95 b	72 c	72 c	3010 e
No PRE	quinclorac + atrazine	82 b	91 bc	69 c	72 c	3640 bc
No PRE	quinclorac + pyrasulfotole + bromoxynil	58 e	71 d	53 d	53 d	2700 f
No PRE	quinclorac + pyrasulfotole + bromoxynil + atrazine	79 bc	96 ab	91 b	91 b	3260 d
No PRE	quinclorac + prosulfuron	72 c	73 d	22 g	22 g	2380 g
No PRE	quinclorac + prosulfuron + atrazine	82 b	98 a	69 c	69 c	2760 ef
No PRE	quinclorac + 2,4-D	74 c	85 c	39 e	39 e	2700 f
No PRE	quinclorac + dicamba	72 c	92 b	29 f	29 f	2890 e
No PRE	No POST	0 g	43 f	3 h	3 i	2010 h

[a] Abbreviations: DAT, days after treatment; POST, postemergence herbicide; Trt, treatment.

Table 10. Continued

[b] Means within the same rating column followed by the same letter should not be considered statistically different according to Fisher's Protected LSD test $P \leq 0.05$.

Table 11. Effect of quinclorac and various herbicide tank mixes on weed control and yield as influenced by the interaction of environment and preemergence herbicide in a field study.

	Palmer amaranth 28 DAT		Broadleaf signalgrass 28 DAT		Yield	
Environment	PRE	No PRE	PRE	No PRE	PRE	No PRE
	---------------------------%-------------------------				kg ha^{-1}	
Clayton, 2015	99 a	92 b	95 a	82 b	4600 a	2900 c
Lewiston-Woodville, 2015	-	-	99 a	40 d	4600 a	3700 b
Rocky Mount, 2015	98 a	69 c	99 a	71 c	2100d	1700 e

[a] Abbreviations: DAT, days after treatment; PRE, preemergence herbicide.

[b] Only means within the same species and/or timing should be evaluated together.

[c] Means followed by the same letter are not considered to be different according to Fisher’s Protected LSD test P ≤ 0.05.

Table 12. Effect of quinclorac and various herbicide tank mixes on weed control at 28 DAT as influenced by environment and postemergence herbicide treatment in a field study.

	Environments	
	Clayton[a,b]	Rocky Mount
	Palmer amaranth 28 DAT	
POST Treatment	----------------------%-------------------------	
quinclorac	83 cd	76 d
atrazine	100 a	95 b
quinclorac + atrazine	100 a	91 bc
quinclorac + pyrasulfotole + bromoxynil	96 ab	66 e
quinclorac + pyrasulfotole + bromoxynil + atrazine	100 a	96 ab
quinclorac + prosulfuron	100 a	65 e
quinclorac + prosulfuron + atrazine	100 a	98 a
quinclorac + 2,4-D	98 a	87 c
quinclorac + dicamba	100 a	93 b
No POST	84 c	59 f

[a] Abbreviations: DAT, days after treatment; POST, postemergence herbicide.

[b] Means within the same rating date columns followed by the same letter should not be considered statistically different according to Fisher's Protected LSD test $P \leq 0.05$.

APPENDICES

CHAPTER II ANOVA TABLES

Table 1. Analysis of variance of Texas millet control.

			p-value[a]
Source	df[a]	F-value Texas millet 28 DAT[b]	Texas millet 28 DAT
Timing	1	10.97	0.0019
Rate	1	3.75	0.0595
Timing * Rate	1	0.27	0.6042
Adjuvant (Adj)	2	0.08	0.9277
Timing * Adj	2	0.53	0.5922
Rate * Adj	2	0.15	0.8617
Timing*Rate*Adj	2	0.47	0.6257
Fertilizer (Fert)	1	1.34	0.2539
Timing*Fert	1	0.45	0.5047
Rate*Fert	1	0.36	0.5508
Timing*Rate*Fert	1	1.31	0.2585
Adj*Fert	2	0.24	0.7892
Timing*Adj*Fert	2	0.61	0.5467
Rate*Adj*Fert	2	0.86	0.4299
Timing*Rate*Adj*Fert	2	0.13	0.8744

[a] Abbreviations: df, degrees of freedom.

[b] Uses Fisher's Protected LSD ($P \leq 0.05$).

Table 2. Analysis of variance of broadleaf signalgrass control.

Source	df[a]	F-value Broadleaf signalgrass 28 DAT[b]	p-value[a] Broadleaf signalgrass 28 DAT
Timing	1	10.14	0.0028
Rate	1	0.48	0.4908
Timing * Rate	1	0.03	0.8555
Adjuvant (Adj)	2	1.80	0.1785
Timing * Adj	2	1.13	0.3336
Rate * Adj	2	0.87	0.4252
Timing*Rate*Adj	2	3.28	0.0479
Fertilizer (Fert)	1	3.18	0.0735
Timing*Fert	1	1.42	0.2406
Rate*Fert	1	3.20	0.0567
Timing*Rate*Fert	1	0.47	0.4968
Adj*Fert	2	3.80	0.0310
Timing*Adj*Fert	2	0.26	0.7710
Rate*Adj*Fert	2	2.24	0.1198
Timing*Rate*Adj*Fert	2	0.85	0.3615

[a] Abbreviations: df, degrees of freedom.

[b] Uses Fisher's Protected LSD ($P \leq 0.05$).

Table 3. Analysis of variance of large crabgrass control.

Source	df[a]	F-value Large crabgrass 28 DAT[b]	p-value Large crabgrass 28 DAT
Timing	1	1.57	0.2124
Rate	1	2.69	0.1032
Timing * Rate	1	0.22	0.6399
Adjuvant (Adj)	2	0.74	0.4777
Timing * Adj	2	0.61	0.5432
Rate * Adj	2	0.10	0.9071
Timing*Rate*Adj	2	0.09	0.9098
Fertilizer (Fert)	1	0.05	0.8245
Timing*Fert	1	0.30	0.5840
Rate*Fert	1	0.12	0.7336
Timing*Rate*Fert	1	0.45	0.5057
Adj*Fert	2	0.23	0.7917
Timing*Adj*Fert	2	0.37	0.6883
Rate*Adj*Fert	2	1.83	0.1651
Timing*Rate*Adj*Fert	2	0.32	0.723
Environment (Env)	1	365.1	<0.0001
Env*Timing	1	0.93	0.3371
Env*Rate	1	0.8	0.3715
Env*Timing*Rate	1	0.29	0.5891
Env*Adj	2	0.49	0.6155
Env*Timing*Adj	2	0.46	0.6316
Env*Rate*Adj	2	1.13	0.3251
Env*Timing*Rate*Adj	2	2.46	0.0897
Env*Fert	1	3.05	0.0834
Env*Timing*Fert	1	1.60	0.2085
Env*Rate*Fert	1	0.45	0.5014
Env*Timing*Rate*Fert	1	0.05	0.8167
Env*Adj*Fert	2	1.90	0.1533
Env*Timing*Adj*Fert	2	0.77	0.4649
Env*Rate*Adj*Fert	2	2.95	0.0561
Env*Timing*Rate*Adj*Fert	2	0.10	0.9038

[a] Abbreviations: df, degrees of freedom.

[b] Uses Fisher's Protected LSD ($P \leq 0.05$).

Table 4. Analysis of variance of yield.

Source	df[a]	F-value Yield[b]	p-value Yield
Timing	1	19.00	<0.0001
Rate	1	0.03	0.8690
Timing * Rate	1	0.22	0.6427
Adjuvant (Adj)	2	2.34	0.1007
Timing * Adj	2	1.69	0.1888
Rate * Adj	2	1.35	0.2623
Timing*Rate*Adj	2	0.18	0.8377
Fertilizer (Fert)	1	2.88	0.0922
Timing*Fert	1	1.31	0.2540
Rate*Fert	1	0.21	0.6449
Timing*Rate*Fert	1	0.14	0.7130
Adj*Fert	2	1.11	0.3318
Timing*Adj*Fert	2	0.11	0.8987
Rate*Adj*Fert	2	0.47	0.6277
Timing*Rate*Adj*Fert	2	0.21	0.8095
Environment (Env)	1	445.01	<0.0001
Env*Timing	1	0.63	0.4302
Env*Rate	1	0.01	0.9106
Env*Timing*Rate	1	0.19	0.6647
Env*Adj	2	0.28	0.7547
Env*Timing*Adj	2	0.25	0.7789
Env*Rate*Adj	2	1.40	0.2512
Env*Timing*Rate*Adj	2	0.59	0.5561
Env*Fert	1	0.45	0.5052
Env*Timing*Fert	1	0.25	0.6165
Env*Rate*Fert	1	0.51	0.4747
Env*Timing*Rate*Fert	1	0.82	0.3679
Env*Adj*Fert	2	3.13	0.0475
Env*Timing*Adj*Fert	2	0.28	0.7581
Env*Rate*Adj*Fert	2	1.85	0.1614
Env*Timing*Rate*Adj*Fert	2	0.05	0.9509

[a] Abbreviations: df, degrees of freedom.

[b] Uses Fisher’s Protected LSD ($P \leq 0.05$)

CHAPTER 4 ANOVA TABLES

Table 1. Analysis of variance for crop stunting for a field study investigating quinclorac impact on sorghum crop safety, weed control, and yield.

			p-value		p-value
Source	DF[a]	F-value Stunting 14 DAT[b]	Stunting 14 DAT	F-value Stunting 28 DAT	Stunting 28 DAT
PRE	1	0.00	0.9080	1	0.5015
POST	9	7	<0.0001*	5	<0.0001*
PRE*POST	9	2	0.0173*	5	<0.0001*
ENV	2	15	0.0015*	1	0.9614
ENV*PRE	2	3	0.0816	5	0.0147*
ENV*POST	18	1	0.1070	2	0.1556
ENV*PRE*POST	18	1	0.1654	1	0.0971

[a] Abbreviations: DF, degrees of freedom; DAT, days after treatment; PRE, preemergence herbicide; POST, postemergence herbicide; ENV, environment.

[b] An asterisk denotes significance at the $\alpha = 0.05$ level according to Fisher's Protected LSD.

Table 2. Analysis of variance for plant chlorosis for a field study investigating quinclorac impact on sorghum crop safety, weed control, and yield.

			p-value		p-value
Source	DF[a]	Chlorosis 14 DAT[b]	Chlorosis 14 DAT	Chlorosis 28 DAT	Chlorosis 28 DAT
PRE	1	2	0.2611	0	0.9999
POST	9	2	0.0522	0	0.8075
PRE*POST	9	1	0.8585	0	0.8017
ENV	2	3	0.1003	0	0.8000
ENV*PRE	2	1	0.7176	0	0.8787
ENV*POST	18	4	0.0030*	0	0.8026
ENV*PRE*POST	18	1	0.8480	0	0.9102

[a] Abbreviations: DF, degrees of freedom; DAT, days after treatment; PRE, preemergence herbicide; POST, postemergence herbicide; ENV, environment.

[b] An asterisk denotes significance at the $\alpha = 0.05$ level according to Fisher's Protected LSD.

Table 3. Analysis of variance for crop height for a field study investigating quinclorac impact on sorghum crop safety, weed control, and yield.

Source	DF[a]	F-value Height 14 DAT[b]	p-value Height 14 DAT	F-value Height 28 DAT	p-value Height 28 DAT
PRE	1	89	0.0001*	2	0.1825
POST	9	3	0.0059*	2	0.1402
PRE*POST	9	1	0.8015	2	0.0567
ENV	2	20	0.0004*	89	0.0001*
ENV*PRE	2	4	0.0436*	13	0.0003*
ENV*POST	18	3	0.001*	1	0.2583
ENV*PRE*POST	18	1	0.2364	1	0.4690

[a] Abbreviations: DF, degrees of freedom; DAT, days after treatment; PRE, preemergence herbicide; POST, postemergence herbicide; ENV, environment.

[b] An asterisk denotes significance at the α = 0.05 level according to Fisher's Protected LSD

Table 4. Analysis of variance for control of ivyleaf morningglory for a field study investigating quinclorac impact on sorghum crop safety, weed control, and yield.

Source	DF[a]	F-value Ivyleaf morningglory 28 DAT[b]	p-value Ivyleaf morningglory 28 DAT
PRE	1	102	<0.0001*
POST	9	16	<0.0001*
PRE*POST	9	2	0.0480*
ENV	2	149	<0.0001*
ENV*PRE	2	71	<0.0001*
ENV*POST	18	7	<0.0001*
ENV*PRE*POST	18	4	<0.0001*

[a] Abbreviations: DAT, days after treatment; DF, degrees of freedom; PRE, preemergence herbicide; POST, postemergence herbicide; ENV, environment.

[b] An asterisk denotes significance at the $\alpha = 0.05$ level according to Fisher's Protected LSD.

Table 5. Analysis of variance for control of large crabgrass for a field study investigating quinclorac impact on sorghum crop safety, weed control, and yield.

			p-value
Source	DF[a]	F-value Large crabgrass 28 DAT[b]	Large crabgrass 28 DAT
PRE	1	95	<0.0001*
POST	9	13	<0.0001*
PRE*POST	9	14	<0.0001*
ENV	2	8	0.0107*
ENV*PRE	2	8	0.0039*
ENV*POST	18	2	0.0066*
ENV*PRE*POST	18	2	0.0025*

[a] Abbreviations: DAT, days after treatment; DF, degrees of freedom; PRE, preemergence herbicide; POST, postemergence herbicide; ENV, environment.

[b] An asterisk denotes significance at the $\alpha = 0.05$ level according to Fisher's Protected LSD.

Table 6. Analysis of variance for control of palmer amaranth for a field study investigating quinclorac impact on sorghum crop safety, weed control, and yield.

			p-value
Source	DF[a]	F-value Palmer amaranth 28 DAT[b]	Palmer amaranth 28 DAT
PRE	1	94	<0.0001*
POST	9	7	<0.0001*
PRE*POST	9	7	<0.0001*
ENV	1	35	0.0011*
ENV*PRE	1	31	0.0001*
ENV*POST	9	3	0.0123*
ENV*PRE*POST	9	1	0.2373

[a] Abbreviations: DAT, days after treatment; DF, degrees of freedom; PRE, preemergence herbicide; POST, postemergence herbicide; ENV, environment.

[b] An asterisk denotes significance at the $\alpha = 0.05$ level according to Fisher's Protected LSD.

Table 7. Analysis of variance for control of goosegrass for a field study investigating quinclorac impact on sorghum crop safety, weed control, and yield.

			p-value
Source	DF[a]	Goosegrass 28 DAT[b]	Goosegrass 28 DAT
PRE	1	293	0.0001*
POST	9	9	0.0001*
PRE*POST	9	9	0.0001*
ENV	1	2	0.1447
ENV*PRE	1	2	0.1447
ENV*POST	9	1	0.5381
ENV*PRE*POST	9	1	0.5592

[a] Abbreviations: DAT, days after treatment; DF, degrees of freedom; PRE, preemergence herbicide; POST, postemergence herbicide; ENV, environment

[b] An asterisk denotes significance at the $\alpha = 0.05$ level according to Fisher's Protected LSD.

Table 8. Analysis of variance for control of crowfootgrass for a field study investigating quinclorac impact on sorghum crop safety, weed control, and yield.

			p-value
Source	DF[a]	F-value Crowfootgrass 28 DAT[b]	Crowfootgrass 28 DAT
PRE	1	270	0.0001*
POST	9	9	0.0001*
PRE*POST	9	9	0.0001*
ENV	1	2	0.1893
ENV*PRE	1	2	0.1893
ENV*POST	9	1	0.4392
ENV*PRE*POST	9	1	0.4596

[a] Abbreviations: DAT, days after treatment; DF, degrees of freedom; PRE, preemergence herbicide; POST, postemergence herbicide; ENV, environment.

[b] An asterisk denotes significance at the $\alpha = 0.05$ level according to Fisher's Protected LSD.

Table 9. Analysis of variance for control of Texas millet for a field study investigating quinclorac impact on sorghum crop safety, weed control, and yield.

Source	DF[a]	F-value Texas millet 28 DAT[b]	p-value Texas millet 28 DAT
PRE	1	30	<0.0001*
POST	9	8	<0.0001*
PRE*POST	9	1	0.3227
ENV	1	19	0.0006
ENV*PRE	1	8	0.0031*
ENV*POST	9	3	<0.0001*
ENV*PRE*POST	9	3	<0.0001*

[a] Abbreviations: DAT, days after treatment; DF, degrees of freedom; PRE, preemergence herbicide; POST, postemergence herbicide; ENV, environment.

[b] An asterisk denotes significance at the $\alpha = 0.05$ level according to Fisher's Protected LSD test.

Table 10. Analysis of variance for control of broadleaf signalgrass and yield for a field study investigating quinclorac impact on sorghum crop safety, weed control, and yield.

			p-value		p-value
Source	DF[a]	F-value Broadleaf signalgrass 28 DAT[b]	Broadleaf signalgrass 28 DAT	F-value YIELD	YIELD
PRE	1	63	<0.0001*	32	<0.0001*
POST	9	7	<0.0001*	1	0.3412
PRE*POST	9	7	<0.0001*	2	0.0424*
ENV	2	7	0.0132*	45	<0.0001*
ENV*PRE	2	10	0.0012*	5	0.0162*
ENV*POST	18	1	0.3454	1	0.1831
ENV*PRE*POST	18	1	0.4507	1	0.2718

[a] Abbreviations: DAT, days after treatment; DF, degrees of freedom; PRE, preemergence herbicide; POST, postemergence herbicide; ENV, environment.

[b] An asterisk denotes significance at the $\alpha = 0.05$ level according to Fisher's Protected LSD test.