ABSTRACT

CONTRERAS GAMERO, DIEGO JOSE. Critical Period of Grass Weed Control in Grain Sorghum (*Sorghum bicolor*) and Wheat (*Triticum aestivum*) (Under the direction of Dr. Wesley J Everman).

North Carolina's livestock production requires around 310 million bushels of grain feed annually. Only 50 % of that is produced in-state, the rest shipped in from other parts of the country with costs in the range of around $200 million per year. This provides local grain growers a with valuable market opportunity. Wheat (3rd) and grain sorghum (6th) are among the most produced cereal crops in the world. In North Carolina, wheat is often used in double-cropping systems with summer crops while grain sorghum has not been grown as extensively. Both are very susceptible to yield losses due to weed competition. Weed control in these crops is challenging mainly due to the limited options for selective grass weed control. An integrated weed management (IWM) system utilizes chemical and non-chemical approaches to control weeds. Some of the components of an IWM system include tillage, planting dates, row widths, crop variety selection and implementation of the critical period of weed control (CPWC).

Italian ryegrass is a grass weed species that consistently ranks as the most troublesome weed for wheat. Grain sorghum is a summer annual therefore it is affected by a wider range of grass weed species. Field studies were conducted at multiple locations and years to determine the CPWC of both crops for grasses that resulted on or less than 5% total yield loss. "Weedy" and "weed-free" treatments were employed during the crops' growing seasons to relate weed removal or establishment to crop yield loss. The CPWC of Italian ryegrass in no-till wheat was from 10.7 – 18.5 weeks after emergence (WAE) in 2017, 11.6 – 17.6 WAE in no-till wheat in 2018 and 12.6 – 15 WAE in 2018 with conservation tillage. Results provided a consistent CPWC

for no-tilled wheat and demonstrated that conservation tillage can be an important factor of an IWM system.

The CPWC for grasses in grain sorghum planted at Clayton, NC in May at 38 cm and 91 cm row spacing were 2.58 - 8.76 WAE and 2.38 - 6.41 WAE respectively. The CPWC for June-planted sorghum in 38 cm and 91 cm rows were 2.62 - 5.85 WAE and 2.22 - 6.21 WAE. At Rocky Mount, NC the CPWC for May-planted sorghum in 38 cm and 91 cm rows were 2.51 - 5.43 WAE and 3.39 – 5.36 WAE. The CPWC for June-planted sorghum was 2.16 – 5.96 WAE and 2.95 – 6.10 WAE. Results suggest that planting arrangements such as planting date and row width may not have a strong influence on the duration CPWC.

Critical Period of Grass Weed Control in Grain Sorghum (*Sorghum bicolor*) and Wheat (*Triticum aestivum*)

by
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BIOGRAPHY

Diego Contreras was born in Honduras, Central America where he was fortunate to live all his life at the campus of a worldwide recognized agricultural school, Zamorano University. His mother, Ligia Contreras, has worked at Zamorano for all of Diego's life, providing him the opportunity to grow in an environment completely surrounded by agriculture. During his childhood Diego would frequently visit the university's animal farms, crop fields and fruit plantations. He was often surrounded by university students and professors that motivated him to pursue agriculture as a career. When the time to make a choice about his future came by, Diego only had Zamorano University in his mind. He received a scholarship to attend Zamorano, and made great use of the opportunity to learn the value of work, understanding and living by the university's motto "Labor Omnia Vincit" or "Work Conquers All". Zamorano's prestigious "learn by doing", program provided Diego with a hands on experience to the whole agricultural production chain throughout his four years. Besides the professional development, Diego made unforgettable memories and friendships that will last a lifetime.

In his senior year, Diego had a life-changing opportunity as he interned during four months at North Carolina State University in the Forage and Grasslands program. During this time, Diego realized about the possibilities and opportunities to learn that came with working in research at a university in the United States, which encouraged him to pursue a graduate degree. After wrapping up his studies in Zamorano, Diego went back to work at the Forage and Grassland's program for five months, before starting his graduate degree in the Weed Science program. His long term goal is to pursue a PhD in weed science and to continue to fulfill his desire to learn.

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Literature Review

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Wheat in the United States

Wheat (*Triticum aestivum* L.) is one of the more widely grown cereals in the world, planted in over 17% of total crop acreage and feeds nearly 40% of the world population (Gupta et al. 2008). In 2004, it was projected that wheat production had to increase at an annual rate of 2.2% to meet growing human demands without using additional land area (Gill et al. 2004). However, up to 2010, wheat productivity was only increasing at a rate of 1.1% (Dixon et al. 2009. In the US wheat production for the 2018-2019 season neared 1.9 billion bushels grown on 45 million acres across the country, a 150 million bushel and 1.8 million acres increase compared to 2017-2018 (Bond, 2020). Ideally, more land could be used for wheat production, but long-term sustainability of the global ecosystem could be affected, therefore the direct solution would be through an increase in productivity (Reynolds et al. 2012).

The USDA classifies wheat into five classes which are hard red winter, hard red spring, soft red winter, white, and durum (USDA-ERS, 2020). In the US, 75% of the total wheat production is grown during the winter, while spring wheat accounts for 25%. The southeastern states grow soft red winter wheat, a class that accounts for 11% of the total wheat production (USDA-ERS, 2020). In 2018 in North Carolina, wheat was grown in 185,000 ha producing a total of 21 million bushels. It is typically planted in November and harvested around June in the state (Weisz, 2013). Wheat is often a part of dual-cropping systems rotated with cotton (*Gossypium hirsutum* L.), soybeans [*Glycine max* (L.) Merr.] or peanuts (*Arachis hypogaea* L.) (Culpepper and York, 1997).

Weed interference with wheat

Wheat in North Carolina is grown during the winter, which limits the amount of weed species that compete with it. Broadleaf weed species commonly found in wheat fields include chickweed (*Stellaria media* (L.) Vill.), henbit (*Lamium amplexicaule* L.), and mouse-ear chickweed (*Cerastium vulgatum* Baumg.). Grass weed species often competing with wheat include annual bluegrass (*Poa annua* L.) and Italian ryegrass (*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot). Italian ryegrass is consistently ranked as one of the most troublesome weeds for wheat (Gonzalez-Andujar and Saavedra, 2003; Holm et al. 1977; Paynter and Hills, 2009; Trusler et al. 2007; Webster and MacDonald, 2001). It is an annual grass that germinates during fall and winter and possesses similar physiological and phenotypical growing characteristics to wheat (Concannon, 1987). Italian ryegrass competition with wheat reduces wheat tillering by depletion of nutrients and water (Liebl and Worsham, 1987; Perez-Fernandez and Coble, 1998). This results in reduced wheat yields, as well as reduced grain quality (Hashem et al. 1998; Justice et al. 1994; Kinfe and Peeper, 1991; Liebl and Worsham, 1987; Stone et al. 1998). Wheat producers in North Carolina and Virginia will often abandon wheat production due to severe Italian ryegrass infestations (Bailey and Wilson, 2003). Previous studies conducted at North Carolina indicate that for every ten Italian ryegrass plants per m^2, wheat yields are reduced by 4% (Liebl and Worsham, 1987). Another study demonstrated that 40 plants per m^2 can reduce wheat yield as much as 50% (Stone et al. 1999).

Italian ryegrass control in wheat

Herbicides embody a significant proportion of wheat production costs (Scursoni et al. 2012). Labeled products for wheat weed control include acetyl-CoA-carboxylase-inhibiting

(ACCase) herbicides such as diclofop-methyl and pinoxaden; acetolactate synthase-inhibiting (ALS) herbicides as mesosulfuron-methyl, thifensulfuron-methyl, and pyroxsulam; and a long chain fatty acid inhibitor that is pyroxasulfone. Italian ryegrass resistance to ALS herbicides is becoming widespread in the Southern USA (Bararpour et al. 2018). Populations have been confirmed resistant to ALS herbicides in Arkansas, California, Delaware, Georgia, Idaho, Kentucky, Missouri, North Carolina, and South Carolina (Heap 2020). Pinoxaden is an ACCase inhibitor herbicide labeled for postemergence control of grass weed species in wheat. Unlike diclofop and other labeled herbicides in wheat, pinoxaden is not antagonized by broadleaf herbicides and has a wider window of application (Bararpour et al. 2018). However with the rapid adoption of pinoxaden and subsequent monitoring of ryegrass populations, studies demonstrated that 25% of Italian ryegrass populations are cross-resistant to diclofop and pinoxaden (Bararpour et al. 2018).

Previous studies on cultural practices that compared wheat seeding arrangements, planting densities and the use of more competitive varieties revealed that these strategies did not reduce Italian ryegrass interference with wheat (Appleby and Brewster, 1995; Hashem et al. 1998). Studies have stated that a crop's competitive ability, which is the combination of morphological traits that allow a crop to utilize a greater proportion of resources than neighboring weeds, can be an important component of integrated weed management systems (Blackshaw and Brandt, 2008; Worthington et al. 2014). Tillage is also an important component of an integrated weed management system. Conservation tillage promotes accumulation of plant residue, which reduces soil temperatures (Bararpour et al. 2018). Conservation and zero tillage are becoming a commonly used tactic for weed management compared to conventional tillage in wheat (Bond et al. 2014; Carpenter and Gianessi, 1999; Cerdeira and Duke, 2006; Taylor and

Coats, 1996;). This approach also increases availability of soil nutrients resulting from enhanced microbial activities as well as increased soil moisture (Service, 2007). Weed control from reduced tillage has produced inconsistent results. Previous studies have mentioned zero tillage could give way to a rapid increase in soil seedbank and variable Italian ryegrass control (Cerdeira and Duke, 2006; Vencill and Banks, 1994;). However a more recent study stated greater benefits from zero tillage as Italian ryegrass populations were reduced (Bararpour et al. 2018).

Grain Sorghum in the United States

Sorghum (*Sorghum bicolor* (L.) Moench) is the sixth most planted crop in the world and 4th most planted grain in the US (USDA-NASS, 2020). It is a summer cereal crop with a high tolerance to harsh abiotic factors such as drought and heat (Stalhman and Wicks, 2000; Ottman and Olsen, 2009; Ghani et al. 2015). It is considered a vital crop in arid regions due to its lower requirements for water and improved tolerance to high temperatures compared to other cereal crops (Ghani et al. 2015). Sorghum produces high quality grains for feed as well as nutritious fodder (Ghani et al. 2015) that can be used for livestock feed. Sorghum varieties that have been developed for a higher grain production are denominated as grain sorghum. Sorghum grains contain 10-13% protein, 2-3% fat and 70-80% carbohydrates, providing excellent nutritional values for dairy cattle and poultry (Ghani et al. 2015).

Despite its agronomic potential, the total area under grain sorghum production has declined around the world due to management challenges, especially in Asia and the United States (Kumar et al. 2012; USDA-NASS, 2020). In an effort to increase production in the Mid-Atlantic, in 2012, Smithfield Hog Production Division introduced programs that incentivized growers to produce grain sorghum. Four years later, total acreage of grain sorghum in Virginia and North Carolina had tripled (Balota et al. 2018). However, production in the US and in North Carolina has seen a sharp decline over the last two years. North Carolina farmed 18,000 ha of grain sorghum in 2016 but reduced that area to 7000 ha in 2018 (USDA-NASS, 2020). This is a direct result of sugarcane aphids (*Melanaphis sacchari* (Zehntner) (Hemiptera: Aphididae)), which in 2015 could be found in 98% of the total production areas of the US (USDA-NASS, 2020). Excessive aphid infestations on pre-flowering sorghum and infestations present during grain development can reduce yield through reduction in number of heads, reduced seed weight, delayed development and maturity, and plant death (Bowling et al. 2016). It is expected that with recent developments in sugarcane aphid tolerant varieties grain sorghum production will increase again (Bowling et al. 2016).

Weed influence on Sorghum

Another major obstacle for grain sorghum production is weed control (Geier et al. 2009). The economic losses due to weed competition with sorghum in the US was reported to be greater than $100 million annually (Bridges, 1992; Walker et al. 2005). Yield losses due to heavy weed infestations in grain sorghum can range from 40% to 97% (Magani, 2008; Peerzada et al. 2017; Smith and Scott, 2010; Stalhman and Wicks, 2000). Weed competition during the first two weeks after crop emergence does not reduce wheat yield, on the other hand weed competition beyond that point contributes to grain sorghum yield losses (Burnside et al. 1964; Feltner et al. 1969; Smith et al. 1990). The arid environments in which grain sorghum is usually grown can have limited water availability, which may restrict timely preemergence herbicide activation, reducing control efficacy (Hennin et al. 2010). Furthermore, most of the postemergence options labeled for wheat target broadleaf species and usually have inadequate grass control (Werle et al. 2016). Yet grasses can be the most common and troublesome weeds for grain sorghum (Elmore, 1988). Previous studies on grass interference in grain sorghum showed that one barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.) per meter squared could reduce yields by 10%, and populations greater than 170 barnyardgrass plants per meter could reduce more than 50% of the total yield. Another study documented the effect that three separate grass species (barnyardgrass, large crabgrass [*Digitaria sanguinalis* (L.) Scop.], and Texas panicum [*Urochloa texana* (Buckley) R. Webster]) had on grain sorghum yields, and found that there was a 2.6% yield loss for each week of weed interference regardless of the grass species (Smith et al. 1990).

Weed control in grain sorghum

The most common weed control practices for grain sorghum in Asia and other semi-arid tropical region are hand weeding and mechanical cultivation (Mishra et al. 2015). Labor scarcity and high cost of cultivation equipment limits these strategies on large scale productions (Peerzada et al. 2017). Moreover, the high cost of manual labor in the United States eliminates hand weeding as an option for weed control in non-specialty crops such as grain sorghum.

Weed control in grain sorghum can become a challenge for growers due to the lack of availability as well as high cost of herbicides, herbicide resistance evolution, and the lack of an adequate knowledge of appropriate timing of weed control (Gholami et al. 2013; Mishra et al. 2015). Selective grass control herbicides are particularly limited. In 2013, quinclorac was presented as Facet L for use in conventional sorghum grass weed control. Timely applications of quinclorac revealed excellent control in some grass species (large crabgrass, broadleaf signalgrass [*Urochloa platyphylla* (Nash) R.D. Webster], fall panicum [*Panicum* *dichotomiflorum* Michx.]) but inconsistent or no control on later applications and other grass species, which usually infest grain sorghum fields in the Southern USA such as Texas millet [*Urochloa texana* Buckl.], goosegrass [*Eleusine indica* (L.) Gaertn.], and crowfoot grass [*Dactyloctenium aegyptium* (L.) Willd]. ALS herbicides are typically not used in conventional sorghum productions due to its susceptibility. However a wild sorghum accession with tolerance to ALS herbicides was identified in 2004 as part of a sorghum germplasm exploration for herbicide tolerant traits done at Kansas State University (Tuinstra and Al-Khatib, 2007). The trait was used to develop ALS-tolerant hybrids suited for sorghum producing areas (Tuinstra and Al-Khatib, 2007; Tuinstra et al. 2009). This trait was later acquired by DuPont®, which labeled the technology as Inzen (Werle et al. 2017). These varieties contain a double mutation in the ALS gene, Val560Ile and Trp574Leu, which confer tolerance to the sulfonylurea and imidazolinone families (Tuinstra and Al-Khatib, 2007; Werle et al. 2016). The active ingredients corresponding to former family were nicosulfuron and rimsulfuron, and both of these herbicides provide excellent grass control as postemergence options (Henning et al. 2010). DuPont® registered nicosulfuron as “zest” for the use in grain sorghum (DuPont, Corteva Agrosciences).

An integrated weed management plan includes non-chemical tactics to improve crop competition with weeds. The selection of a competitive grain sorghum cultivar can suppress weed growth without sacrificing crop yield (Frick, 2000). Some of the characteristics that improve the crop’s competitive potential include rapid emergence and biomass accumulation, and favorable leaf characteristics, canopy structure and height for enhanced light interception (Buhler, 2002). Higher leaf area indexes and increased shading by sorghum cultivars results in reduced weed biomass and seed production (Traore et al. 2003). Row spacing can be manipulated in grain sorghum to increase productivity and reduce weed emergence (Holt, 1995).

Typically grain sorghum has been grown in 76 cm wide rows to facilitate mechanical cultivation (Schatz et al. 1990). Nonetheless, row spacing in grain sorghum may range from 15 cm to 100 cm with a variety of planting configurations (Ottman and Olsen, 2009; Vanderlip et al. 1998). Narrow-row crops improve crop yield by allowing it to perceive more light, nutrients and moisture than weeds (Hozayn et al. 2012). Besides its increased yield, grain sorghum grown in narrow rows, especially with high densities, has been documented to reduce weed populations because of the shading conditions it creates, negatively influencing light interception by weeds (Al-Bedairy et al. 2013; Bishnoi et al. 1990; Gholami et al. 2013; Smith et al. 1990; Stalhman and Wicks, 2000). Lower sorghum populations provide weeds with a more favorable environment to become more competitive with the crop resulting in yield losses. Optimal plant populations are vital to achieve maximum yields in sorghum (Linneman, 2011). Decreased weed growth was observed at 207,000 plants per ha compared to 120,000 plants (Burnside, 1977). The optimum population to maximize yields in grain sorghum is around 250,000 plants per ha (Ottman and Olsen, 2009).

Critical period of weed control

It is crucial to develop weed management strategies based on a better understanding of weed-crop interactions (Scursoni et al. 2012). Effective weed control requires knowledge of weed population dynamics and competition (Scursoni et al. 2012). The time during the growing season when weeds compete with the crop can have a direct impact on crop yields. This time has been explored in many different crops and defined as the critical period of weed control (CPWC). The CPWC represents the time interval between two separately-measured crop-weed competition components known as the critical time for weed removal (CTWR) and the critical weed-free period (CWFP) (Knezevic et al. 2002). The CTWR, also known as weedy curve, is used to determine the begging of the CPWC and the CWFP, or the weed-free curve, and is used to define the end of the CPWC (Knezevic et al. 2002). When trying to define a CPWC, one must have and acceptable yield loss (AYL) threshold. Theoretically, weed control before and after the CPWC does not influence crop-yield potential (Knezevic and Datta 2015). Critical periods of weed control are subject to biological factors such as crop species and weed species as well as abiotic factors including temperature, precipitation, and cultural practices implemented (Hall et al. 1992).

Studies on the CPWC of wheat have not been done previously in the United States. Two studies have been conducted in Asia (Chaudhary et al. 2008; Chopra et al. 1998), but because of their geography, growing conditions and varieties, they are not applicable to the US. Studies about the CPWC in grain sorghum indicate a CPWC between the 3rd and 6th week after crop emergence (Burnside and Wicks, 1964; Feltner, 1969). Other studies provided insights about the effect of N fertilization in the duration of CPWC in grain sorghum, where results showed that non-fertilized grain sorghum will not tolerate weed competition during any time of the growing season (Okafor and Zitta, 1991). These studies, however, had mixed weed populations of broadleaf and grass species. Studies regarding the effect of grass species-only are necessary since they can be the most difficult component of weed control in grain sorghum due to limited selective control options.

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CHAPTER II

Critical period of Italian ryegrass (*Lolium multiflorum*) control in wheat (*Triticum aestivum*)

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Abstract

Field studies were conducted in North Carolina to determine the critical period of weed control (CPWC) for Italian ryegrass in wheat with an acceptable yield loss of 5%. Wheat was planted in late fall in 2017 and 2018 in zero-till fields and in 2018 in a conservation-tilled field. Treatments consisted of allowing weeds to grow from crop emergence for different intervals until removal (“weedy”), and to maintain “weed-free” conditions from crop emergence for the same intervals, and then let the weeds emerge and compete with the crop. In 2017, weed control or removal as done in two-week intervals up to 18 weeks after crop emergence (WAE) and three-week intervals up to 18 WAE in 2018. Treatments were compared through a regression analysis where timing of weed removal was related to yield loss. Additional biological measurements including Italian ryegrass density, and height were collected at 6, 12, and 18 WAE to understand the effect of crop-weed interactions on the CPWC and weed populations. The CPWC for Italian ryegrass in 2017 zero-till planted wheat was estimated from 10.7 – 18.5 WAE. The CPWC in 2018 zero-till planted wheat was from 11.6 – 17.6 WAE. The CPWC for Italian ryegrass in conservation till planted wheat in 2018 was from 12.6 to 15 WAE. Results demonstrated that the CPWC in zero-till planted wheat was not different between years, however conservation till planted wheat had a shorter CPWC.

Key words: weed removal, weed free period, critical timing, wheat, Italian ryegrass, pinoxaden, weed density, weed biomass.

Wheat (*Triticum aestivum* L.) is one of the most important food sources worldwide occupying 17% of crop acreage, and feeding about 40% of the world population while providing 20% of total food calories and protein in human nutrition worldwide (Gupta et al. 2008). Nonetheless, wheat is often an secondary crop compared to other more widely grown grains in agronomic productions in countries such as the United States, where its production typically is part of dual-cropping systems, often rotated with cotton (*Gossypium hirsutum* L.), soybeans [*Glycine max* (L.) Merr.] or peanuts (*Arachis hypogaea* L.) (Culpepper and York, 1997). Wheat production comes with an additional challenge with weed management because the application of selective grass herbicides represents a significant proportion of total production costs. Moreover, prolonged emergence periods from species such as Italian ryegrass (*Lolium multiflorum* L.) are particularly difficult to control successfully (Scursoni et al. 2012). Italian ryegrass is a vigorous, erect winter annual that is consistently ranked as one of the most troublesome weeds in wheat (Webster and MacDonald, 2001). Severe infestations are not uncommon in North Carolina wheat fields and often result in crop abandonment (Bailey and Wilson, 2003). Failure to control Italian ryegrass results in reduced wheat yield, quality or both (Hashem et al. 1998; Justice et al. 1994; Kinfe and Peeper 1991; Liebl and Worsham 1987; Stone et al. 1998).

Italian ryegrass is a global problem, as its influence in reduced productivity of wheat is seen worldwide (Gonzalez-Andujar and Saavedra, 2003; Holm et al. 1977; Paynter and Hills, 2009; Trusler et al. 2007). *Lolium spp*. have evolved resistance to Acetyl-CoA-carboxylase (ACCase, Herbicide Group [HG] 1) inhibitors in 15 countries with 67 different biotypes of Italian ryegrass involved (Heap, 2020). Additionally, Italian ryegrass resistance to acetolactate synthase (ALS, [HG] 2) inhibitors is becoming a widespread problem, especially in the US

(Bararpour et al. 2018). Resistant populations have been confirmed in Arkansas, California, Delaware, Georgia, Idaho, Kentucky, Louisiana, Maryland, Mississippi, Missouri, North Carolina, Oklahoma, Oregon, South Carolina, Tennessee, and Washington (Heap, 2020).

There are limited options regarding selective grass herbicides in wheat. An effective option for producers in the US is pinoxaden, which is an ACCase-inhibitor labeled for post-emergence control of grass weed species including Italian ryegrass. Contrasting with commonly used selective grass herbicides such as diclofop and other ACCase-inhibitors, pinoxaden is not antagonized by broadleaf herbicides and has a wider application window (Bararpour et al. 2018). However following its rapid adoption, subsequent monitoring revealed that 25% of Italian ryegrass populations in the US are cross-resistant to diclofop and pinoxaden (Bararpour et al. 2018). In the early 2000s, herbicide weed management strategies were the only practical means of controlling Italian ryegrass, but integrating herbicide programs within a tillage system results in improved overall long-term weed control and increased crop production (Bailey and Wilson, 2003; Bararpour et al. 2018).

The evolution of herbicide-resistant populations of Italian ryegrass has resulted in reduced number of herbicide applications and adoption of no-till or conservation tillage by wheat producers (Bond et al. 2014; Carpenter and Gianessi, 1999; Cerdeira and Duke ,2006; Taylor and Coats, 1996). Conservation tillage and no-till promotes accumulation of plant residue on the upper layers of the soil contributing to: enhanced soil microbial activity leading to a greater availability of soil nutrients, a reduction in vulnerability of soil erosion (Service, 2007), and inhibition of weed seed germination due to shading or cooler temperatures at the soil surface, which result in Italian ryegrass population reduction (Bararpour et al. 2018). Nonetheless different studies have shown that reduced tillage systems may favor Italian ryegrass proliferation

(Kegode at al. 1999). This may result in a rapid increase in soil seedbank due to inconsistent weed control. Consequently, the need for intensified herbicide use may lead towards selection of resistant biotypes (Cerdeira and Duke, 2006). Tillage timing can also be a factor in reduced weed seed viability, moving seeds to different depths in the soil profile and creating an unfavorable environment during critical stages of germination and reproduction (Locke et al. 2002).

Agricultural production systems are incorporating more integrated weed management programs, which can diminish weed populations over time, using tactics that reduce their dependence on herbicides solely (Liebman et al. 2001). Management practices that increase the competitive ability of crops with weeds are important factors of these programs. Competitive ability is conferred by a combination of morphological traits that allow the crop to utilize a greater portion of limited resources than neighboring weeds (Worthington et al. 2014). Understanding emergence dynamics of weed populations and competition is essential for successful weed control and high yielding crops (Scursoni et al. 2012). Therefore, improvement of weed management strategies require a better understanding of weed-crop interactions (Scursoni et al. 2012). One useful strategy for weed management programs is the use of the critical period for weed control (CPWC).

The CPWC is defined as the period in a crop's growth cycle during which weeds must be controlled to prevent yield losses (Knezevic et al. 2002). The CPWC represents the time interval between two separately measured crop-weed competition components: the critical time for weed removal (CTWR) and the critical weed free period (CWFP). The CTWR provides an insight about the maximum amount of time that early season weed competition can be tolerated by the crop before it suffers from an irreversible yield reduction (Knezevic and Datta, 2015). This is used to determine the commencement of the CPWC. On the contrary, the CWFP describes the minimum weed-free period necessary from the time of crop emergence to prevent unacceptable yield losses (Knezevic and Datta, 2015). Therefore, the CWFP indicates the termination of the CPWC. Both components are subjected to a regression approach to generate weedy and weed-free curves that depend on the level of acceptable yield loss (AYL) used to predict the beginning and the end of the CPWC (Knezevic and Datta, 2015). Most CPWC studies set the threshold at 5% AYL. Theoretically, weed competition outside of the CPWC does not contribute to crop yield loss greater than the set threshold.

The use of herbicides with non-residual activity resulted in a renewed interest in defining suitable timing and periodicity for weed control (Knezevic et al. 2002). The beginning and duration of the CPWC may fluctuate depending on numerous factors such as: the characteristics of the crop and weeds present, environmental variables such as temperature and precipitation, and cultural practices implemented in the system (Hall et al. 1992). Studies regarding the CPWC of Italian ryegrass in wheat have not previously been performed. Moreover, the effects of tillage and its influence on the CPWC of wheat in the presence of Italian ryegrass may lead to a better understanding of the competitive ability of wheat under different environment. Thus, the objectives of this study were to determine if there is a defined CPWC of Italian ryegrass in wheat and the effect of tillage on its duration.

Materials and Methods

Field studies were established to evaluate the critical period of weed control for Italian ryegrass in wheat during the winter growing seasons of the years 2017-2018 and 2018-2019 at the NCDA&CS Piedmont Research Station in Salisbury, NC (35.691633, -80.637698). The USDA web soil survey (USDA-NCRS 2020) indicate that the soil is a Lloyd clay loam (fine, kaolinitic, thermic Rhodic Kanhapludult) with a pH of 5.7. The wheat variety used was "DynaGro Shirley", which is well adapted and high yielding at the NC Piedmont region (Weisz, 2013). It was drill-planted on a no-tilled field at a rate of 112 kg or 1.31 million seeds ha^{-1} on November 15, 2017 and October 30, 2018. Additionally, in year two, wheat was drill-planted at the same seeding rate (1.31 million seeds ha^{-1}) on a separate field with conservation tillage. Plots were 9.14 meters long and 3.04 meters wide with rows spaced at 19 centimeters. Standard management practices were followed regarding fertilization and insect control according to the NC Small Grain Production Guide (2013).

The experimental design was a randomized complete block replicated four times. The first year treatments consisted of weed interference periods up to the 18th week after crop emergence (WAE), resulting in nine "weedy" and "weed-free" treatments (2, 4, 6, 8, 10, 12, 14, 16, 18, WAE). The second year weed interference periods were increased from two to three weeks as first year field observations noted very slow plant growth in two-week intervals. Therefore, treatments consisted of weed interference periods up to the 18th WAE, resulting in six "weedy" and "weed-free" treatments (3, 6, 9, 12, 15, and 18 WAE). In weedy treatments, Italian ryegrass was allowed to grow in the plots up to the corresponding WAE, and then it was controlled for the rest of the season. In weed-free treatments, Italian ryegrass was not allowed to grow in the plots up to its corresponding WAE, after which it was allowed to grow for the rest of the season. Furthermore, both years had two control treatments consisting of weedy and weed-free all season, where Italian ryegrass was either allowed to grow in the plots or controlled throughout the entire season. Italian ryegrass was controlled with pinoxaden at a rate of 60 g ha^{-1} using a CO_2 pressurized backpack sprayer calibrated for an output of 140 L ha^{-1} at 207 kPa with TeeJet flat fan XR11002 nozzles. Broadleaf weeds were controlled early during the season as they emerged with a premix of thifensulfuron methyl + tribenuron methyl at 31.5 g ha^{-1} using the previously described output.

Three different environments were assumed for data analysis purposes. Wheat planted on 2017 no till will be referred as *environment 1*. No till planted wheat on 2018 is referred as *environment 2*, and conservation till planted wheat in 2018 is referred as *environment 3*. Crop and weed heights were recorded at the time of weed removal. Heights were measured from the soil surface up to the growing point of the plant. Similarly, Italian ryegrass plant counts were documented using a 0.5 m^2 square, where each individual plant was accounted for by isolating the crown. Italian ryegrass biomass was collected in a 0.5 m^2 square by cutting all the plants inside at soil surface and then put into paper bags which were dried in an oven at 60º C for 72 hours. Due to different treatments of timing of weed removal on the two years, the data were compared on similar removal periods, which were the 6^{th}, 12^{th} and 18^{th} WAE. Wheat was harvested using a small plot combine at the end of the season and adjusted to a 12.5% moisture content to obtain total yields. These were then standardized based on percentage, with the weed-free all season treatment set as 100% yield.

The statistical analysis of the CPWC was performed with R software (R Core Team, 2019) using statistical package *drc* (dose-response curve) (Ritz and Streibig, 2005) following a procedure described by Knezevic and Datta (2015). Weed interference treatment comparisons were based on a non-linear regression analysis where timing of weed removal and weed-free periods were associated to relative yield. The curves associated with weed interference periods were fit to a four-parameter log-logistic model after which parameter estimates were combined and tested for significance, where differences between any one of the curves estimates would indicate differences in the CPWC curve. The log logistic function used to describe this is given in Equation 1:

$$Y = [C + (D - C)]/\{1 + \exp[B(logX - logE)]\}$$

Y indicates relative yield as a percentage, *C* is the lower limit, *D* is the upper limit, *X* is the time expressed as WAE and *E* is the WAE giving a 50% response between upper and lower limits, also known as the inflection point or ED_{50} (Knezevic and Datta, 2015). The CTWR and CWFP curves were graphically represented using a four-parameter logistic regression model and a four-parameter Gompertz model in Sigmaplot version 14.0 (Systat Software, San Jose, CA), both appropriate for graphical representation of weedy and weed-free curves (Knezevic et al. 2002). Biological measurements data (crop and weed heights and weed density) was subjected to ANOVA using PROC GLM in SAS 9.4 (SAS Institute, Cary, NC 27513).

Results and Discussion

Wheat yield decreased on the three environments tested as the duration of the Italian ryegrass interference increased (Figure 1), which was previously documented (Liebl and Worsham, 1987). The three environments had dissimilar curves (Table 1) for their CTWR and CWFP, as a significant difference in at least one parameter estimate describes a statistically different curve. The CTWR to avoid yield loss of 5% or greater (Table 2) was 10.7 WAE in the environment 1, 11.6 WAE environment 2 and 12.6 WAE environment 3 (Figure 1). Even though the curves were statistically different, the CTWR or beginning of the CPWC was similar among the three environments ($p<0.05$). As with the CTWR, the CWFP curves were statistically different in each environment (Table 1) but contrary to the CTWR, the CWFP or the end of the CPWC was statically different for each environment ($p<0.05$).

The CTWR and CWFP components indicate that the CPWC for Italian ryegrass in wheat environment 1 was from 10.7 to 18.5 WAE, environment 2 was from 11.6 to 17.6 WAE, and environment 3 ranged from 12.6 to 15 WAE. Under no till conditions on both years, the CPWC was different for approximately one WAE on both ends of the curve. This variability could have been a result of planting wheat two weeks earlier on the second year compared to the first. The competitive ability of Italian ryegrass with wheat is related to its ability to reduce wheat tillering by competing for soil moisture, nitrogen, and phosphorus resources intended for wheat (Appleby et al. 1976; Ketchersid and Bridges 1987; Liebl and Worsham 1987; Perez-Fernandez and Coble 1998). The earlier planting during the second year could have enhanced the ability of the wheat to access these resources.

The CPWC of environment 3 was significantly shorter than the two no-till environments. Italian ryegrass density and height were not significantly different between environments (Figures 2 and 3), therefore weed behavior did not change regarding tillage method. This may provide evidence that weed behavior did not have an effect on the shorter CPWC in the tilled environment, but it was rather an effect that tillage had on the crop.

Italian ryegrass POST control is usually timed for its 2-3 tiller stage, when plant height is around 8 - 10 cm (Grey et al. 2003). This coincides with the CTWR starting close to the 12th WAE, as the measurement of Italian ryegrass height at 12 WAE had a mean of 6.4 cm across the three environments (Figure 2), suggesting a similar plant growth stage (2-3 tiller) to that when Italian ryegrass has been traditionally controlled. POST applications of various herbicides at the 2-3 tiller stage provided at least 88% control of Italian ryegrass in Georgia (Grey et al. 2003).

Similarly, Italian ryegrass subjected to various POST herbicides between de 1 – 3 tiller stage was controlled between 83-99% in Illinois (Hoskins et al. 2005). These studies exemplify the need of well-timed and effective weed control, which concurs with the CTWR obtained.

Italian ryegrass density was not different between the three environments when compared at the same WAE, suggesting a similar emergence behavior among years and tillage type (Figure 2). Furthermore, 6 and 12 WAE were not different, but plant density had a significant increase as it almost doubled across the three environments at 18 WAE. This agrees with recorded evidence that Italian ryegrass has prolonged emergence periods during wheat's growing season (Scursoni et al. 2012). Traditional plant emergence models were not utilized as it was not the focal point of the study, nonetheless these results give way to a possible assumptions on Italian ryegrass emergence patterns. The initial flush of weed emergence was sustained during the first 12 WAE, after which there is a second and significant flush between the 12th and the 18th WAE. Even though wheat is prominently developed by then, the increased weed density might affect wheat's reproductive development reducing total yield production. Previous Italian ryegrass density studies in wheat have shown that 50 plants per m^2 can reduce yields as much as 50% (Stone et al. 1999). Another study reported that wheat yield was reduced by 4.3% for every 10 Italian ryegrass plants per m^2 (Liebel and Worsham, 1987). The same levels of yield reductions are not observed on this study as the previously mentioned weed densities were maintained throughout the whole growing season. On a further note, weed control this late wheat's development becomes a problem as grass herbicides have to be applied at specific wheat growth stages, most of them before flag leaf development (Scursoni et al. 2012).

Italian ryegrass heights had no differences across years or environment, but overall means were different in between weeks (Figure 3), with heights of 4.6 cm at 6 WAE, 6.4 cm at

12 WAE, and 17.2 cm at 18 WAE. Italian ryegrass had almost a 3-fold increase in height between weeks 12 to 18, which fit inside the CPWC of all environments. This would suggest the rapid development of Italian ryegrass during this period could enhance its competitive ability with wheat and reduce wheat yields. Wheat heights were recorded on weedy and weed free treatments at similar WAE to understand the effect of competition in height. All environments were alike at 6 and 12 WAE, but during the second year there were differences at the 18th WAE on both tillage methods (Table 3). Environment 2 had taller wheat when Italian ryegrass was not controlled (29.1 cm) compared to controlling it all season (25.1 cm). The same behavior was observed in environment 3, as wheat was taller when Italian ryegrass was present (30.2 cm) compared to when it was controlled (25.9 cm). These results contrast with those of a previous study which stated that Italian ryegrass presence reduced wheat height (Hashem et al. 1998).

The CPWC obtained provides a guideline of the timeframe where Italian ryegrass should be controlled in wheat to reduce yield losses. The beginning of the CPWC is at around 12 WAE, but its end has slight variations, closing in around the 18th WAE at a no-till environment. Further studies could provide more information on the variation of the CPWC according to tillage type. While conservation tillage had a significantly shorter CPWC compared to no till, it should be repeated for a better understating of the effect of tillage on the CPWC of wheat.

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Table 1. Parameter estimates for Italian ryegrass weedy and weed free curves during the interference periods in wheat for the logistic equation Y=[C + (D – C)]/{1 + exp[B (logX – logE)]} with corresponding standard error on three different wheat environments.

	Weedy Curve				Weed Free Curve			
	B (± SE[a])	C (± SE)	D (± SE)	E (±)	B (± SE)	C (± SE)	D (± SE)	E (±)
No-till 2017	3.82 (4.75)	60.25 (39.09)	104.53* (6.67)	15.23 (8.81)	-12.5 (10.86)	61.40* (3.22)	98.51* (6.99)	15.30* (1.07)
No-till 2018	19.36 (28.69)	47.11 (9.18)	103.35* (6.35)	12.81* (1.46)	-4.19 (2.53)	49.62* (5.48)	103.43* (11.32)	11.62* (1.88)
Till 2018	5.25 (4.28)	34.75* (37.5)	107.34* (6.78)	17.20* (4.66)	-0.98 (0.86)	98.51* (8.13)	190.13 (264.97)	29.31 (99.60)

[a]Abbreviation: SE, Standard Error

[b]An asterisk denotes significance at the α=0.05 level within columns.

Table 2. Critical timing of weed removal (CTWR) and critical weed free period (CWFP) for Italian ryegrass in wheat expressed in weeks after crop emergence in three different environments for a 5% allowable yield loss threshold.

	CTWR[a,b]	CWFP
No-till 2017	10.7	18.5
No-till 2018	11.6	17.6
Till 2018	12.6	15

[a]Abbreviation: CTWR, critical timing of weed removal; CWFP, critical weed free period.

[b]Expressed in weeks after crop emergence.

Table 3. Wheat heights in centimeters when competing with Italian ryegrass or in a weed free situation across 6, 12 and 18 weeks after crop emergence.

	Weedy wheat height[b]			Weed free wheat height[b]		
WAE[a]	Env[a]. 1 (±SE)	Env. 2 (±SE)	Env. 3 (±SE)	Env. 1 (±SE)	Env. 2 (±SE)	Env. 3 (±SE)
6	8.3 (0.3)	8.5 (0.5)	9.1 (0.2)	8.6 (0.2)	8.6 (0.5)	9.0 (0.4)
12	9.1 (0.6)	8.3 (0.1)	9.6 (0.3)	9.3 (0.2)	9.2 (0.6)	8.8 (0.7)
18	29.1 (1.6)	30.2 (2.0)	31.4 (1.7)	32.2 (1.8)	25.1 (1.3)	26.0 (1.1)

[a]Abbreviations: WAE, weeks after emergence; ENV, environment

[b]Heights are expressed in cm

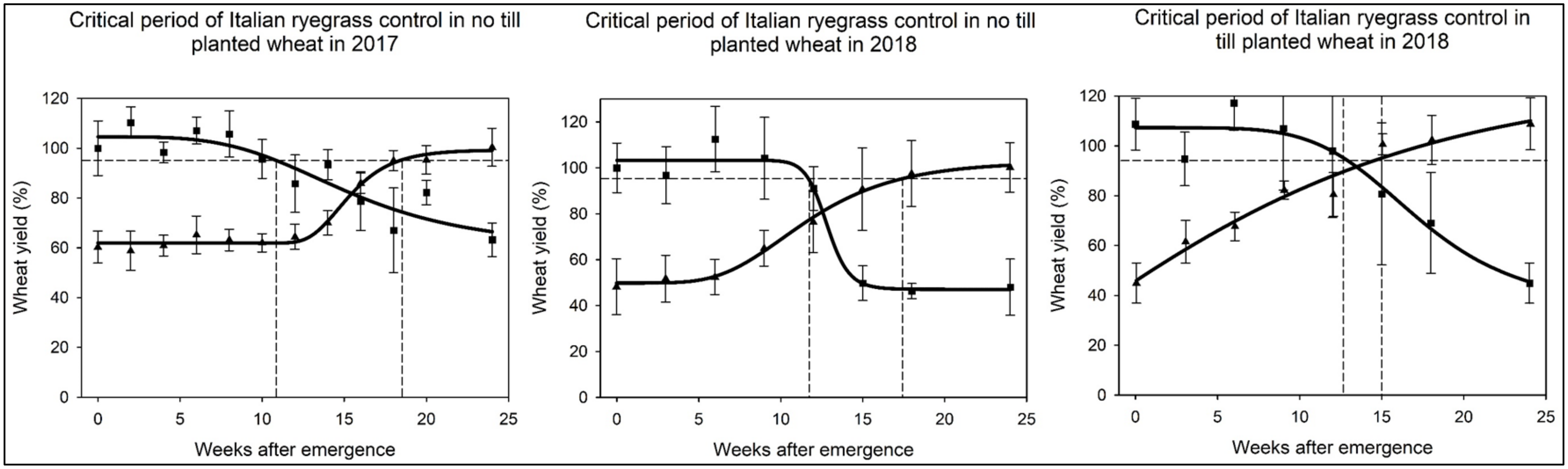

Figure 1. Critical period of Italian ryegrass control in wheat planted in 2017 no-till, 2018 no-till and 2018 conservation till with yield expressed as a percentage of weed-free wheat yield using the Logistic model (Knezevic et al. 2002) to determine the Critical of Time Weed Removal (CTWR) and the Gompertz model (Knezevic et al. 2002) to determine the Critical Weed-Free Period (CWFP).

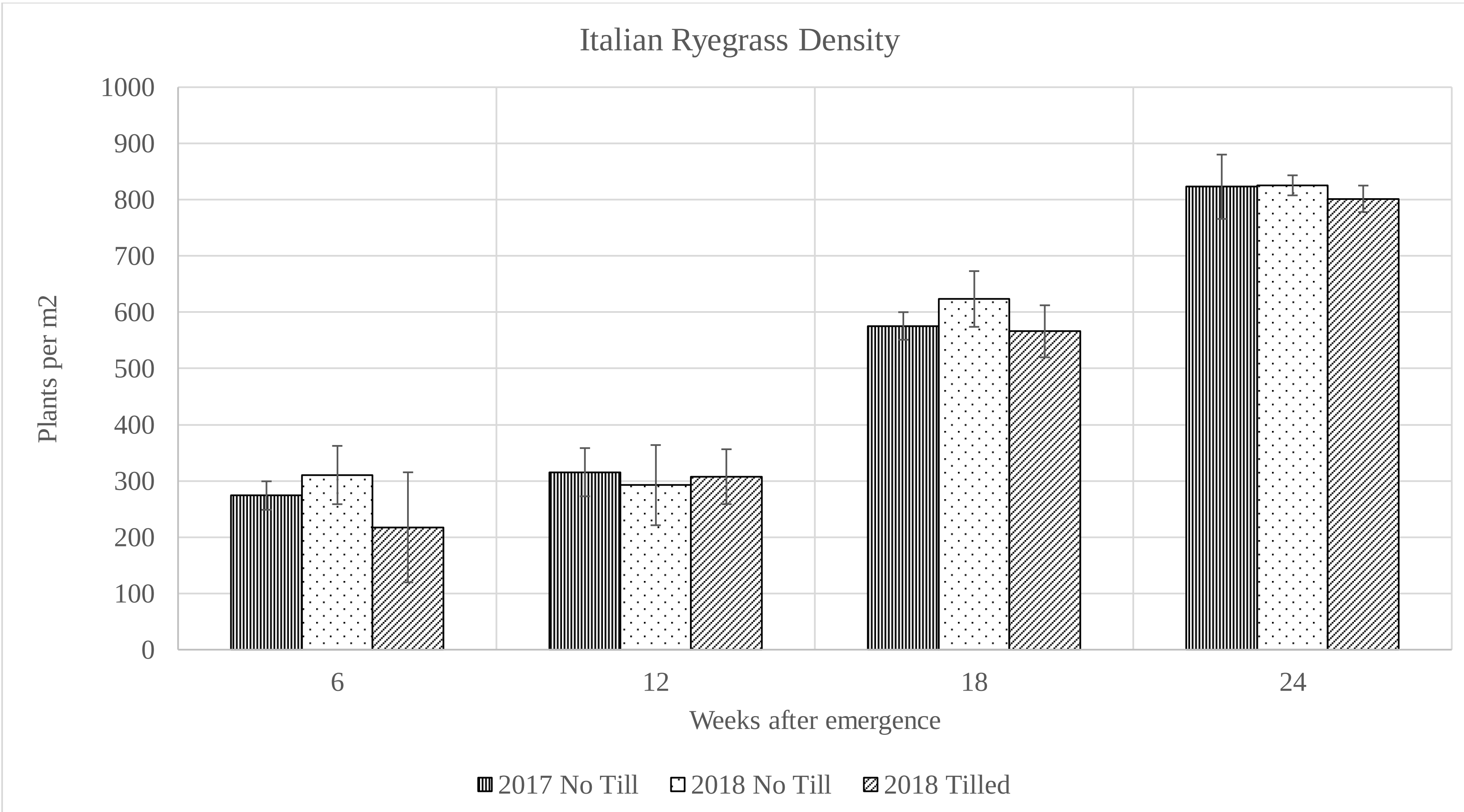

Figure 2. Italian ryegrass density in plants per 0.5 meters^2 at the critical timing of weed removal treatments across 6, 12, 18 and 24 weeks after wheat emergence.

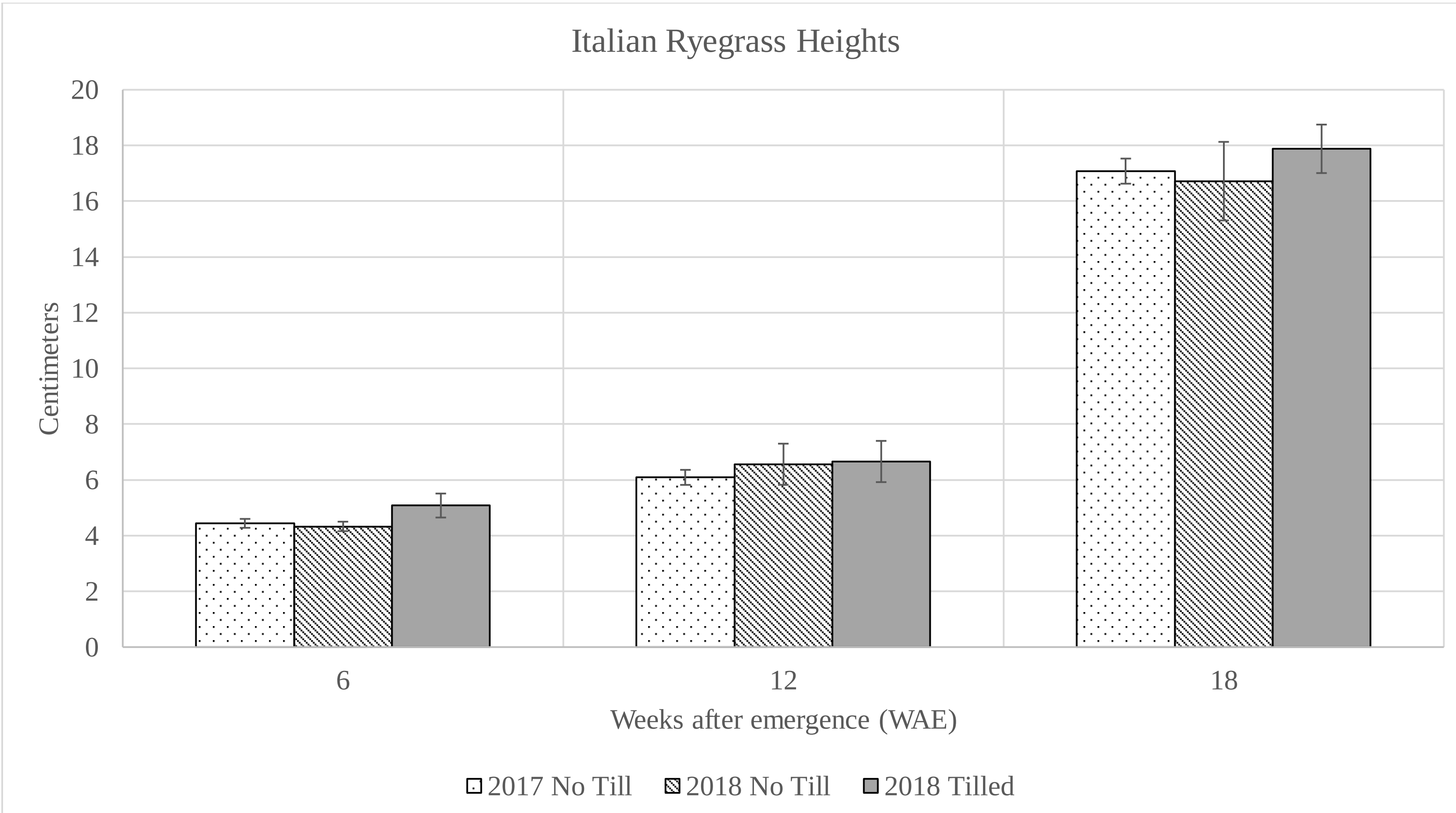

Figure 3. Italian ryegrass heights in centimeters in wheat across 6, 12 and 18 weeks after crop emergence.

CHAPTER III

Critical period of grass weed control in grain sorghum (*Sorghum bicolor*)

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Abstract

Field experiments were conducted in two locations (Clayton and Rocky Mount) in North Carolina to determine the CPWC of grass weeds in grain sorghum with an acceptable yield loss of 5%. Sorghum was planted in May and June, with 38 and 91 cm row spacing arrangements using an Inzen Z sorghum variety. Treatments consisted of “weedy” and “weed-free” plots up to 2, 3, 5, and 7 weeks after crop emergence (WAE) and two controls of weedy and weed-free all season. Treatments were compared through a regression analysis where timing of weed removal was related to yield loss. Additional biological measurements including weed density, biomass and height were collected to understand the effect of crop-weed interactions on the CPWC and weed populations. At Clayton the CPWC for May-planted sorghum in 38 cm and 91 cm rows was 2.58 - 8.76 WAE and 2.38 - 6.41 WAE, respectively. The CPWC for June-planted sorghum in 38 cm and 91 cm rows was 2.62 - 5.85 WAE and 2.22 - 6.21 WAE, respectively. At Rocky Mount the CPWCs for May-planted sorghum in 38 cm and 91 cm rows were 2.51 - 5.43 WAE and 3.39 – 5.36 WAE. The CPWCs for June-planted sorghum was 2.16 – 5.96 WAE and 2.95 – 6.10 WAE. Results suggest that planting arrangements such as planting date and row width may not have a strong influence on the duration CPWC.

Key words: Weed removal, weed free, grasses, grain sorghum, milo, nicosulfuron, inzen

Grain sorghum (*Sorghum bicolor* (L) Moench.) is a cereal crop grown in the United States as a summer crop primarily in semi-arid regions. In these areas, grain sorghum is superior to corn due to its ability to tolerate extremely harsh environmental conditions of abiotic stress such as drought and heat (Ghani et al. 2015; Ottman and Olser, 2009; Stahlman and Wicks, 2000). Sorghum grains can contain 10-13% protein, 2-3% fat and 70-80% carbohydrate content, demonstrating a promising future towards replacement of other grains used in livestock and poultry feeding programs. In an effort to increase its production in the Mid-Atlantic, in 2012 Smithfield Hog Production Division introduced programs that incentivized growers to produce grain sorghum. Four years later, total acreage of grain sorghum in Virginia and North Carolina had tripled (Balota et al. 2018).

Despite its potential, grain sorghum is underutilized given few weed management options available. In addition to other biotic and abiotic factors, weeds are considered to be a major constraint, causing between 15-97% yield losses (Peerzada et al. 2017). In fact, most of the increased production costs of grain sorghum come from weed control as it reduces productivity and quality (Geier et al. 2009). In the US sorghum producers spend about $103 million dollars per year in weed control (Bridges 1992; Walker et al. 2005). Previous studies have stated that despite grain sorghum's potential of feed value and crop hardiness, the total worldwide area under grain sorghum production has declined due to limited weed management options available, especially in the US (Kumar et al. 2012; USDA-NASS, 2016).

Weeds compete with grain sorghum for light, soil nutrients and moisture which may result on yield loss or deteriorated grain quality (Stalhman and Wicks, 2000). Grain sorghum is a poor competitor against weeds due to slow growth and poor early vigor for the first 20-25 days (Rizzardi et al. 2004). In addition, the limited availability of soil moisture in dry environments where grain sorghum is usually grown can restrict the activation and reduce the efficacy of pre-emergence herbicides (Henning et al. 2010), obliging growers to depend on post-emergence weed control. Most of the postemergence herbicides registered for sorghum are effective against broadleaf species but have limited activity on grassy weeds (Werle et al. 2016).

Many species in Poaceae are considered to be the most common and troublesome weeds in grain sorghum in the United States, particularly those species from the genus *Echinochloa*, *Panicum*, *Digitaria* and *Sorghum* (Dennis, 1988). Even a low level of weed infestation in the early stages could be detrimental to sorghum yield, where heavy infestation with grassy weeds two weeks after sorghum emergence can reduce the yield by up to 20% (Smith and Scott, 2010). Another study argues that merely one barnyardgrass (*Echinochloa crus-galli L.*) plant per meter of crop row reduced sorghum yield by nearly 10%, whereas 174 plants per square meter reduced yield by 52% (Norris 1980). Smith et al (1990) reported that barnyardgrass, large crabgrass, and Texas panicum reduced grain sorghum yield 2.6% for each week of weed interference regardless of grass species.

Herbicides that control grasses in grain sorghum are limited as selective chemical control alternatives are not readily or sparsely available for producers. Other factors that add to this issue are the high cost of herbicides labeled for grain sorghum, likelihood of herbicidal resistance development and lack of an adequate knowledge of appropriate timing of weed control (Gholami et al. 2013; Mishra et al. 2015). Research on reduced herbicide use and integration of mechanical and chemical approaches with cultural weed control strategies could partially help in solving these problems (Hozayn et al. 2012). Previous studies have shown that the use of multiple crop management options had weed suppressive characteristics and their integration aid in the development of effective weed management strategies in sorghum (Mishra et al. 2015).

Selection of a competitive grain sorghum cultivar should be the first step of an integrated weed management plan. Doing so is one way to potentially suppress weed growth without sacrificing crop yield (Frick, 2000). Another step of an integrated weed management plan includes choosing an appropriate plant density. Studies have shown that increased plant densities negatively affect light interception by weeds (Gholami et al. 2013; Besançon et al. 2017). Furthermore, decreased weed growth was observed at 207,000 plants ha^{-1} compared to 120,000 plants (Burnside, 1977). An additional step of integrated weed management is the selection of appropriate row width. In grain sorghum row spacing may range from 15 cm to 100 cm, with 76 cm being the most common, and it is planted with a variety of configuration, generally planted on beds or flats (Besançon et al. 2017; Hewitt, 2015; Ottman and Olsen, 2009; Vanderlip et al. 1998). The traditional method of sorghum cultivation in 76 cm wide rows may facilitate mechanical weed control but it limits the crop yield (Schatz et al. 1990). The effect and influence of row spacing on sorghum's canopy architecture, light interception, weed suppression and total grain yield has gained attention for a while (Staggenborg et al. 1999). Studies have shown that reduced row spacing can increase sorghum's ability to compete for incoming light more efficiently, increase crop productivity and reduce weed emergence (Grichar et al. 2004; Holt 1995). Moreover, decreased weed biomass and seed production can also be observed as a result of high crop leaf area index and increased shading of weeds (Traore et al. 2003). Row spacing arrangements of 45 cm can result in improved grain sorghum yields and reduced weed population (25-54%) as compared to 60-90 cm row spacing (Bishnoi et al. 1990). Rows that are narrower than 45 cm have not consistently yielded better, however they can improve weed control (Vanderlip et al. 1998). In heavily weed infested fields, narrow row spacing suppressed weed biomass and increased yield by 72% and 45% (Marin and Weiner, 2014). Quicker canopy coverage can be observed in high density sorghum, therefore combining narrow row spacing with higher seeding rates may increase overall yields (Smith et al. 1990). In semi-arid tropical regions, hand weeding and mechanical cultivation are the most common method for weed control in grain sorghum (Mishra et al. 2015). Unfortunately, labor scarcity and elevated mechanical equipment restricts these strategies on a larger scale (Peerzada et al. 2017).

An integrated weed management plan includes cultural practices as well as herbicides. Growers typically depend on different chemical and non-chemical approaches for controlling weeds, but they predominantly focus on herbicides (Hozayn et al. 2012). Grass control in grain sorghum can be difficult due to limited options for selective control. Quinclorac was rebranded as Facet L and introduced for weed control in sorghum in 2013. For some grass weed species it can be an effective herbicide when timely applications are done (at or before weeds reach 5 cm), as delayed applications may present inconsistent control (Vincent, 2015). Susceptible grass species include large crabgrass (*Digitaria sanguinalis* (L.) Scop.), broadleaf signalgrass (*Urochloa platyphylla* (Nash) R.D. Webster) and fall panicum (*Panicum dichotomiflorum* Michx.). Texas millet (*Urochloa texana* Buckl.), goosegrass (*Eleusine indica* (L.) Gaertn.) and crowfoot grass (*Dactyloctenium aegyptium* (L.) Willd.) are not affected by quinclorac (Vincent 2015). Acetolactate synthase (ALS) herbicides used for grass control are not used in conventional sorghum due to its susceptibility to them, however a wild sorghum accession with tolerance to ALS herbicides was identified in Kansas in 2004 (Tuinstra and Al-Khatib, 2007). This trait was introgressed from wild sorghum to develop ALS-tolerant grain sorghum hybrids adapted for use in sorghum-producing areas (Tuinstra and Al-Khatib, 2007; Tuinstra et al. 2009). DuPont® acquired the rights for this trait and labeled the technology as “Inzen” (Werle et al. 2017). Inzen sorghum varieties contain a double mutation in the ALS gene, Val560Ile and

Trp574Leu (Tuinstra and Al-Khatib, 2007). The aforementioned confer tolerance to the sulfonylurea and imidazolinone families (Werle et al. 2016). The ALS herbicide active ingredients in this case were nicosulfuron and rimsulfuron. Studies have shown that both herbicides provide excellent control of grass weeds, and grain sorghum hybrids with tolerance to them have provided growers with an option of selective postemergence grass control (Henning et al. 2010).

During the first two weeks after crop emergence, weed competition usually does not reduce grain sorghum yields, regardless of weed species (Burnside and Wicks, 1964; Feltner et al. 1969; Smith et al. 1990). Weed competition beyond two weeks after crop emergence may reduce yields depending on species and environmental conditions (Burnside and Wicks, 1964; Feltner et al. 1969; Smith et al. 1990). It is important for grain sorghum growers to understand the periods where grass weed control is vital. The critical period of weed control (CPWC) explores the period in a crop's growth in which weeds must be controlled to prevent considerable yield losses (Knezevic et al. 2002). The CPWC represents the time interval between two separately measured crop-weed competition components: the critical time for weed removal (CTWR) and the critical weed free period (CWFP). The CTWR conditions the maximum amount of time that early season weed competition can be tolerated by the crop before it suffers from an irreversible yield reduction (Knezevic and Datta, 2015). This is used to determine the beginning of the CPWC. On the other hand, the CWFP describes the minimum weed-free period required from the time of crop emergence to avoid unacceptable yield losses (Knezevic and Datta, 2015). Thus, the CWFP indicates the end of the CPWC. Both components are subjected to a regression approach to generate weedy and weed-free curves that depend on the level of acceptable yield loss (AYL) used to predict the beginning and the end of the CPWC (Knezevic and Datta, 2015).

The majority of CPWC studies set the threshold at 5% AYL. Theoretically, weed competition outside of the CPWC does not contribute to crop relative yield loss greater than the set threshold.

The CPWC within a crop is subject to biological factors such as characteristics of the crop itself, weed species and weed density as well as abiotic factors such as temperature, precipitation and cultural practices implemented (Hall et al. 1992). Studies about the CPWC in grain sorghum have not been published previously, and there should be an emphasis on grassy weeds as they are traditionally more challenging to control. Additionally, understanding the effect of cultural practices such as planting date, row spacing, and herbicide tolerant varieties may lead to a better understanding of the CPWC and could provide guidelines for integrated weed management programs in grain sorghum. Therefore, this study was designed with the objective to determine the CPWC of grass weeds in ALS-tolerant grain sorghum as influenced by planting date and row spacing.

Materials and Methods

Field studies were established to evaluate the critical period of weed control for grasses in grain sorghum during the summer of 2019 at the Central Crops Research Station at Clayton, NC (35.675094, -78.510803) and at the Upper Coastal Plains Research Station in Rocky Mount, NC (35.896962, -77.672884). The USDA web soil survey (USDA-NCRS 2020) designated the Clayton soil as a Dothan loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudult) and had a pH of 6.2 (USDA-NCRS 2020). The Rocky Mount soil was a Rains fine sandy loam (fine-loamy, siliceous, semiactive, thermic Typic Paleaquult) with a pH of 6.1. The sorghum variety used was ADV G2250ALS (Advanta Seeds, Irving TX), which contained the Inzen sorghum trait. Sorghum was planted at a rate of 270,000 seed ha^{-1} using two separate row spacing arrangements; 38 and 91 cm between rows. The experiment had two planting dates per site, the first planting date being May 15, 2019 at Rocky Mount and May 16, 2019 at Clayton. The second planting date was June 14, 2019 at Rocky Mount and June 15, 2019 at Clayton. These planting dates are henceforth referred to as May-planted and June-planted grain sorghum, respectively. Plots were 3.65 meters wide by 9.14 meters long. Standard management practices were followed regarding fertilization and insect control following guidelines by the Grain Sorghum Best Management Practices for Mid-Atlantic Production (2016).

The experimental design consisted of a randomized complete block with two factors (row spacing and planting date) replicated four times. Treatments were comprised of weed interference periods of 2, 3, 5 and 7 weeks after crop emergence (WAE), resulting in eight "weedy" and "weed-free" treatments. In the weedy treatments, grasses were allowed to grow in the plot up to the corresponding treatment WAE, from then it was controlled for the rest of the growing season. In weed-free treatments, grasses were not allowed to grow in the plots up to the corresponding treatment WAE, after which they were permitted to grow for the rest of the season. Additionally, there were two control treatments for each factor consisting of weedy and weed-free all-season plots, where grasses were either allowed to grow in the plots or controlled during the entire season. Grasses were controlled with nicosulfuron at a rate of 69 g of a.i. ha^{-1} using a CO2 pressurized backpack sprayed calibrated for an output of 140 L ha^{-1} at 207 kPa with TeeJet flat fan XR11002 nozzles when treatment applications required. Grass weed selection was done controlling broadleaf weed species with a premix of bromoxynil plus pyrasulfutole at a rate of 264 g a.i. ha^{-1} when weeds were less than 5 cm tall.

Crop and weed heights were recorded at the time of weed removal, where heights were measured from the soil surface up to the growing point of the plant. Overall grass weed plant counts were documented using a 0.5 m^2 square, where each individual plant was accounted for. Grass weed biomass was collected in the same 0.5 m^2 by cutting all the plants inside at soil surface and then put into paper bags which were set to dry in an oven at 60º C for 72 hours. Grain sorghum was harvested using a small plot combine at the end of the season and adjusted to a 12.5% moisture content to obtain total yields. These yields were then standardized based on percentage to obtain relative yield, with the weed-free all season treatment indicating 100% yield.

The statistical analysis of the CPWC was performed with R software (R Core Team, 2019) using statistical package *drc* (dose-response curve) (Ritz and Streibig, 2005). Treatment comparison was based on a non-linear regression analysis in which timing of weed removal and weed-free periods were associated to relative yield. Curves were fit to a four-parameter log-logistic model after which parameter estimates were combined and tested for significance, where differences between curve estimates would indicate differences in the CPWC. The log logistic function used is given in Equation 1:

$$Y = [C + (D - C)]/\{1 + exp\ [B(logX - logE)]\}$$

Y indicates relative yield as a percentage, *C* is the lower limit, *D* is the upper limit, *X* is the time expressed as WAE and *E* is the WAE giving a 50% response between upper and lower limits, also known as the inflection point or ED50 (Knezevic and Datta, 2015). The CTWR and CWFP curves were graphically represented using a four-parameter logistic regression model and a four-parameter Gompertz model in Sigmaplot version 14.0 (Systat Software, San Jose, CA), both appropriate for graphical representation of weedy and weed-free curves (Knezevic et al. 2002). Biological measurements data (crop and weed heights, weed density and weed biomass) were subjected to ANOVA using PROC GLM in SAS 9.4 (SAS Institute, Cary, NC 27513)

Results and Discussion

Weed density. Location and row spacing were not significant factors ($p<0.05$) therefore results were pooled. Previous studies have observed reduced weed populations (grasses and broadleaves mixed) while using narrower rows (Holt, 1995; Bishnoi et al. 1990; Bishnoi and Mays, 2002, Besaçon et al. 2017). In this study locations had different grass species compositions (Table 1) yet total grass weed density was not reduced by narrow rows (Table 2). WAE was significant for grass weed density as totals increased throughout these weeks (Table 2). Additionally, the interaction between planting date and WAE was significant, however significant differences occurred only at the 3rd WAE, where grain sorghum planted in May (231 plants per m^2) had almost three times as many grass weeds compared to that planted in June (84 plants per m^2) (Table 2). Values at 2, 5 and 7 WAE were not significantly different between planting dates for plant density. At 5 WAE May-planted grain sorghum plots had a slight reduction in grass weed density while June-planted grain sorghum plots followed a trend of increasing grass density as WAE increased through the season. The decrease in plant density at the 5 WAE for the May planted sorghum could have been a result of higher temperatures and limited precipitation between the 3rd and 5th WAE (Figure 1). The maximum temperatures during this two week span were often over 32 ºC and precipitation was nonexistent. After this two week span, there are two precipitation events in the following two weeks which could have increase grass germination and influenced overall population.

Grass Weed Heights. No single factor or interaction other than WAE was significant for weed height, therefore data was pooled over location, planting date, and row spacing. As WAE increased, a significant increase in grass weed heights was observed (Table 2).

Weed biomass. The interaction of location by WAE was statistically significant for weed biomass. Clayton and Rocky Mount had similar grass weed dry matter at 2 and 3 WAE but there were significant differences at the 5^{th} and 7^{th} WAE. Clayton (226 g and 371 g per m^2) had more weed biomass during these weeks than Rocky Mount (129 g and 233 g per m^2), respectively (Table 2). Weed densities were not different between locations, suggesting that the weed species composition could have affected total weed biomass. Grass weeds that were found at Clayton could favor more biomass due to growth habit which favors larger leaves and upright growth, therefore producing more plant matter than those found only at Rocky Mount which have generally smaller leaves and prostrate growth (Table 3). As opposed to studies indicating that narrow rows suppress weed biomass (Smith et al. 1990; Traore et al. 2003), in this experiment row spacing did not reduce weed biomass compared to wider rows.

Grain sorghum height under weed interference. Grain sorghum height was measured in cm from the base of the plant at soil level up to tallest leaf. A significant location by planting date effect was observed, therefore results were averaged over WAE and row spacing (Table 4). Grass weed competition with grain sorghum does not have a clearly defined effect on plant height as plant height measurements were not consistent across weeks of weed interference. At Clayton, May-planted grain sorghum was taller than June-planted at the 2^{nd}, 5^{th} and 7^{th} WAE. At Rocky Mount, May-planted grain sorghum was shorter than June-planted at the 3^{rd} and 7^{th} WAE. Clayton had taller May-planted sorghum but June-planted was shorter when compared to Rocky Mount, except at the 5^{th} WAE.

Grain sorghum height under weed free conditions. Weed free sorghum height was measured to look for differences that the experiment factors could have in grain sorghum while growing on a weed-free environment. Similar to grain sorghum growing under weedy conditions, row spacing was not significant for sorghum height. The three-way interaction of location by planting date by WAE was highly significant, therefore results are analyzed and averaged over row spacing (Table 4). At Clayton the 2nd and 3rd WAE had similar plant heights at both planting dates, however at 5 and 7 WAE May-planted sorghum is taller than June-planted. At Rocky Mount, May-planted sorghum is shorter on all WAE except at the 5th WAE compared to June-planted sorghum. May-planted sorghum heights were similar between locations, except for 5 WAE were it was taller at Clayton. Results were more varied between locations for June-planted sorghum, with heights at Rocky Mount being greater at the 3rd and 7th WAE, but shorter at the 5th WAE.

Grain sorghum yield loss due to weed interference and CPWC. Grain sorghum yield was expressed as relative yield in terms of 100%, where yield from plots kept weed-free throughout the whole growing season express 100% relative yield. Both locations had grain sorghum yield reductions with continued duration of grass weed interference with the crop. Grass weed competition with grain sorghum has been previously documented to reduce up to 2.6% of grain sorghum yield for each week allowed to compete (Smith et al. 1990). Another study presented results where uncontrolled weed growth had yield losses of up to 60% (Magani, 2008). In the experiment conducted at Clayton, total yield losses for uncontrolled grass weed growth neared 100% independent of planting date or row spacing (Figure 2). At Rocky Mount, grain sorghum yield loss due to uncontrolled grass weed growth all season ranged between 60 - 90% (Figure 3). Total grass weed density was similar between locations, whereas grass weed biomass at Clayton was greater than Rocky Mount (Table 2), presumptively due to different weed species composition and a higher moisture retention tendency from soils at the Clayton which resulted in greater weed biomass. This could have had an impact on yield loss, significantly amplifying the probability of total crop loss. Both locations had a significant difference in their CPWC among planting factors as planting date and row spacing. A significant difference in at least one of the parameter estimates indicates dissimilar curves (Table 5).

CTWR. At Clayton, the CTWR curve indicated that to prevent yield losses of 5 % or greater in May-planted grain sorghum, grass weeds had to be controlled at 2.58 WAE in 38 cm row spacing, and 2.38 WAE in 91 cm row spacing (Figure 2, Table 6). In June-planted grain sorghum, the CTWR indicated grasses had to be controlled at 2.62 WAE in 38 cm row spacing and 2.22 WAE in 91 cm (Figure 2, Table 6). Although the curves were not similar (Table 5), these specific four values of the CTWR were not statistically different from each other, indicating on average a CTWR of 2.45 WAE among factors (Table 6). In other words this indicates that at Clayton grass weed competition before the first 2.45 WAE does not cause yield losses of 5 % or greater. These results are similar to those of previous studies that state that weed competition on the first two weeks after crop emergence does not reduce gain sorghum yields regardless of the weeds that were present (Burnside et al. 1964; Feltner et al. 1969; Smith et al. 1990). Yield losses over the 5% level observed at Clayton after the first 2.45 WAE. This supports results of previous studies reporting weed growth beyond two weeks after crop emergence reduced grain sorghum yield (Burnside et al. 1964; Feltner et al. 1969; Smith et al. 1990; Smith and Scott, 2010). Another study observed grain sorghum's poor competitive ability during the first 20-25 days comes as a result of slow growth and poor early vigor, although it eventually establishes a dense canopy (Rizzardi et al. 2004).

At Rocky Mount the CTWR to prevent yield losses of 5% or more in May-planted grain sorghum was 2.51 WAE for 38 cm row spacing and 3.39 WAE for 91 cm row spacing (Figure 3, Table 6). These results were not significantly different between each other indicating on average for May-planted grain sorghum the CTWR was 2.9 WAE, coinciding with previous research which reported weed competition before 2 WAE does not reduce yields (Burnside et al. 1964, 1964; Feltner et al. 1969; Smith et al. 1990). The CTWR for June-planted sorghum was not different among row spacing (Table 6). The four CTWR values are similar except May-planted sorghum at 91 cm rows with June planted sorghum at 38 cm rows, where the May-planted sorghum had a later CTWR (3.39 compared to 2.16 WAE). Other studies have found narrow rows compared to wider rows result in a higher yielding crop, but narrow rows do not affect the CTWR (Atkins et al. 1968; Burnside et al. 1964; Holt, 1995; Hozayn et al. 2012; Scott et al. 2013; Staggenborg et al. 1999), however it is supported by these studies observing narrow rows yield greater (3487 kg ha^{-1}) than wide rows (2409 kg ha^{-1}) when kept under weed-free conditions despite having an earlier CTWR (Table 7).

CWFP. At Clayton, the CWFP or the time up to when the crop is kept weed free before allowing weeds to compete before reducing yields by 5% or more resulted in greater variability than the CTWR. May-planted grain sorghum had a CWFP of 8.76 WAE for 38 cm row spacing and 5.85 WAE for 91 cm row spacing (Figure 2, Table 6). Results at Clayton do not align with previous research, as the narrow row spacing required a longer weed-free period to avoid yield losses of 5% or more. The 38 cm row spacing kept under weed free conditions for the whole season produced 721 kg ha^{-1} compared to 360 kg ha^{-1} of the 91 cm row spacing (Table 7). Since narrow rows yielded more, it is plausible there was a greater proportion of yield to compete for, which could in turn could have extended the CWFP. The greater yield potential of the narrow row spacing could also have had an effect on yield variability, therefore affecting the curve of the CWFP. Visual observations of the CWFP curve and its corresponding means show that even though at 7th WAE the relative yield is already over 95%, the lower yields at the 3rd and 5th WAE "push" down the CWFP curve, thus extending its duration up to 8.76 WAE (Figure 2). The June-planted grain sorghum at Clayton had similar CWFP (Table 6). Row spacing did not influence the CWFP however narrow rows (364 kg ha^{1}) yielded more than wider rows (97 kg ha^{-1}) (Table 7).

The CWFP values for Rocky Mount were not different among planting factors (Table 6). Row spacing did not have an influence on the CWFP but did affect potential yield. May-planted sorghum yielded more in narrow rows (3640 kg ha^{-1}) compared to wider rows (2409 kg ha^{-1}). Likewise June-planted sorghum yielded more in narrow rows (3487 kg ha^{-1}) compared to wider rows (1148.2 kg ha^{-1}) (Table 7).

CPWC. The CTWR and CWFP components are combined to obtain the CPWC, where the CTWR is defined as the start and the CWFP is the end of the CPWC (Knezevic and Datta, 2015). The CPWC for Clayton indicate that grain sorghum has to be kept weed free at least since 2.22 WAE and can extend all the way to 8.76 WAE, depending on planting date and row width arrangement (Table 7). The CPWC for Rocky Mount starts at least at 2.16 WAE and can extend up to 6.1 WAE depending on planting arrangements (Table 7). Statistically the CPWC at Rocky Mount was similar to Clayton however yield potential under weed-free conditions was almost ten times as much in certain cases. These results validate the statement that the CPWC of a crop may depend on location (Knezevic et al. 2002), and growers should consider these factors into their crop selection as well as their integrated weed management plan.

The CPWC for grain sorghum was clearly defined with some variation according to location and cultural practices such as planting date and row spacing. It is essential for grain sorghum growers to understand the importance of grass weed control, as the results provided significant evidence on the effect of grasses on yield reductions, which could be up to 100%. The different planting arrangements in this experiment were not only implemented as a basis of comparison in between them, but also as an aid for potential equipment or timing limitations for grain sorghum growers. The data provided delivers a guideline for weed control timings that help the grower protect their yields regardless of the planting conditions.

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Table 1. Grass weed species percentage composition at Clayton and Rocky Mount over weeks. Yellow foxtail compositions had a significant difference between planting dates therefore these results are presented separately.

Location	WAE[a]	Grass Weed Species[bc]							
		Fall panicum	Texas millet	Johnsongrass	Broadleaf signalgrass	Goosegrass	Large crabgrass	Yellow foxtail	
								Planting Date[d]	
								May	June
Clayton								-	-
	2	0 c	0 d	3.41 d	-	49.47 a	49.19 b		
	3	16.37 a	2.08 c	12.61 b	-	26.97 bc	41.95 b		
	5	10.19 b	6.35 a	8.63 c	-	36.57 b	38.23 b		
	7	7.70 b	4.21 b	23.96 a	-	23.09 cd	41.01 b		
Rocky Mount		-	-	-					
	2				0 c	22.47 cd	55.65 a	0 d	6.16 a
	3				13.24 a	16.66 cd	50.54 a	0 d	4.73 ba
	5				10.67 ba	16.09 d	55.76 a	2.50 cd	6.29 a
	7				7.07 b	15.26 d	54.93 a	3.06 bc	5.39 ba

[a]Abbreviation: WAE, weeks after emergence.

[b]Expressed in terms of grass density composition percentage.

[c]Values with similar letters within columns are not different at the $\alpha=0.05$ level.

[d]Values with different letters at the planting date are factor are different at the $\alpha=0.05$ level.

Table 2. Plant density, height and biomass of grass weed species at the corresponding weeks after grain sorghum emergence at the critical timing of weed removal treatments.

	Grass Weed Density[ad]		Grass Weed Height[bd]	Weed Biomass[cd]	
Weeks after crop emergence	May-planted	June-planted		Clayton	Rocky Mount
2	204 bc	84 d	7 d	73 cd	44 d
3	231 bc	85 d	25 c	104 c	84 cd
5	143 cd	240 b	51 b	226 b	129 c
7	284 ab	350 a	79 a	371 a	233 b

[a]Grass weed plant density expressed as plants per m^2.

[b]Grass weed height expressed in cm.

[c]Weed biomass expressed in grams of dry matter per m^2.

[d]Values in the same column followed by the same letter are not considered statistically different at the $p<0.05$ level.

Table 3. Grass weed species composition at Clayton and Rocky Mount and their leaf dimensions[a] (Bryson and DeFelice, 2009).

Scientific Name	Common Name	Clayton	Rocky Mount	Leaf Length	Leaf Width
Panicum dichotomiflorum	Fall Panicum	X		10 - 50	8 - 20
Urochloa texana	Texas Millet	X		8 - 27	0.7 - 2
Sorghum halepense	Johnsongrass	X		20 - 60	1 - 3
Digitaria sanguinalis	Large Crabgrass	X	X	3 - 20	0.3 - 1
Eleusine indica	Goosegrass	X	X	5 - 35	0.3 - 0.8
Setaria pumila	Yellow Foxtail		X	5 - 30	0.4 - 1
Urochloa platyphylla	Broadleaf Signalgrass		X	4 - 15	0.6 - 15
Echinochloa crus-galli	Barnyardgrass		X	10 - 50	0.5 - 3

[a]Leaf dimension expressed in cm.

Table 4. Grain sorghum height at the corresponding weeks after crop emergence in weedy and weed-free environment.

	Grain sorghum height with grass weed interference[ab]				Grain sorghum height without grass weed interference[ac]			
	Clayton		Rocky Mount		Clayton		Rocky Mount	
Weeks after crop emergence	May-planted	June-planted	May-planted	June-planted	May-planted	June-planted	May-planted	June-planted
2	22 hi	12 j	13 j	18 ji	16 ih	14 ih	11 i	18 h
3	35 fg	29 hg	27 h	43 e	30 g	26 g	25 g	39 f
5	71 b	63 c	46 e	42 fe	71 c	64 d	45 e	46 e
7	73 b	63 c	55 d	86 a	81 ba	75 d	77 bc	86 a

[a]Grain sorghum heights expressed in cm.

[b]Values with similar letters within a grass weed environment are not considered statistically different at the p<0.05 level.

[c]Values with similar letters within a weed-free environment are not considered statistically different at the p<0.05 level.

Table 5. Parameter estimates for the CPWC and CTWR Curves. A significant value in at least one of the parameters indicates different curves. The letter (*A*, *B*, *C*, *D*) indicates a parameter estimate and the number (1-4) indicate the curve of the 4-parameter logistic equation.

	Critical timing of weed removal[a]				Critical weed free period[a]			
	Estimate	Std. Error	t-value	p-value	Estimate	Std. Error	t-value	p-value
B:1	8.70152	2.68283	3.2434	0.001724 **	-1.18883	0.50521	-2.3532	0.021071 *
B:2	7.73518	2.33323	3.3152	0.001378 **	-3.03777	1.00889	-3.0110	0.003484 **
B:3	11.85110	7.56025	1.5676	0.120932	-3.94961	1.24053	-3.1838	0.002071 **
B:4	6.25057	1.32946	4.7016	1.061e-05 ***	-2.38704	0.72521	-3.2915	0.001484 **
C:1	0.85481	3.90820	0.2187	0.827424	1.66140	6.88532	0.2413	0.809943
C:2	0.57022	3.93739	0.1448	0.885216	1.41522	6.72831	0.2103	0.833939
C:3	3.13994	3.70227	0.8481	0.398906	5.73793	6.65292	0.8625	0.391008
C:4	-0.16988	4.20670	-0.0404	0.967888	0.58484	6.85056	0.0854	0.932180
D:1	100.53900	3.85063	26.1098	< 2.2e-16 ***	123.10188	26.50977	4.6436	1.324e-05 ***
D:2	99.43471	3.97129	25.0384	< 2.2e-16 ***	99.65904	6.85445	14.5393	< 2.2e-16 ***
D:3	98.19239	3.75188	26.1715	< 2.2e-16 ***	99.32622	5.65855	17.5533	< 2.2e-16 ***
D:4	99.13477	4.13514	23.9737	< 2.2e-16 ***	103.65848	7.29177	14.2158	< 2.2e-16 ***
E:1	3.59094	0.22966	15.6360	< 2.2e-16 ***	3.42769	1.42485	2.4056	0.018451 *
E:2	3.51144	0.19883	17.6608	< 2.2e-16 ***	2.58828	0.26612	9.7261	3.321e-15 ***
E:3	3.55468	0.40158	8.8518	1.718e-13 ***	2.82614	0.24244	11.6571	< 2.2e-16 ***
E:4	3.70668	0.20421	18.1511	< 2.2e-16 ***	2.41058	0.28766	8.3800	1.453e-12 ***

[a]Asterisks denote significance where *= p<0.05, **= p,0.01, ***= p<0.001.

Table 6. Critical timing of weed removal (CTWR), critical weed free period (CWFP) and critical period of grass weed control (CPWC) in grain sorghum to prevent yield losses over 5% at two locations.

		Clayton					Rocky Mount				
		CTWR[a]		CWFP[a]			CTWR[a]		CWFP[a]		
Planting Date	Row Spacing[b]	Estimate	Std. Err	Estimate	Std. Err	CPWC	Estimate	Std. Err	Estimate	Std. Err	CPWC
May	38	2.58	0.20	8.76	1.13	2.58 - 8.76	2.51	1.08	5.43	1.62	2.51 - 5.43
	91	2.38	0.22	6.41	2.12	2.38 - 6.41	3.39	1.82	5.36	2.01	3.39 - 5.36
June	38	2.62	0.21	5.85	1.57	2.62 - 5.85	2.16	0.62	5.96	1.01	2.16 - 5.96
	91	2.22	0.24	6.21	1.33	2.22 - 6.21	2.95	1.79	6.10	1.41	2.95 - 6.10

[a]Weeks after crop emergence.

[b]Row spacing dimensions in centimeters.

Table 7. Potential grain sorghum yield under different planting arrangements if kept weed free throughout the whole season.

	Clayton				Rocky Mount			
	May		June		May		June	
	Row Spacing[a]							
	38	91	38	91	38	91	38	91
Potential Yield[b]	721	374	360	97	3640	2409	3487	1148

[a]Row spacing dimensions in cm.

[b]Grain sorghum yield expressed in kg per ha^{-1}.

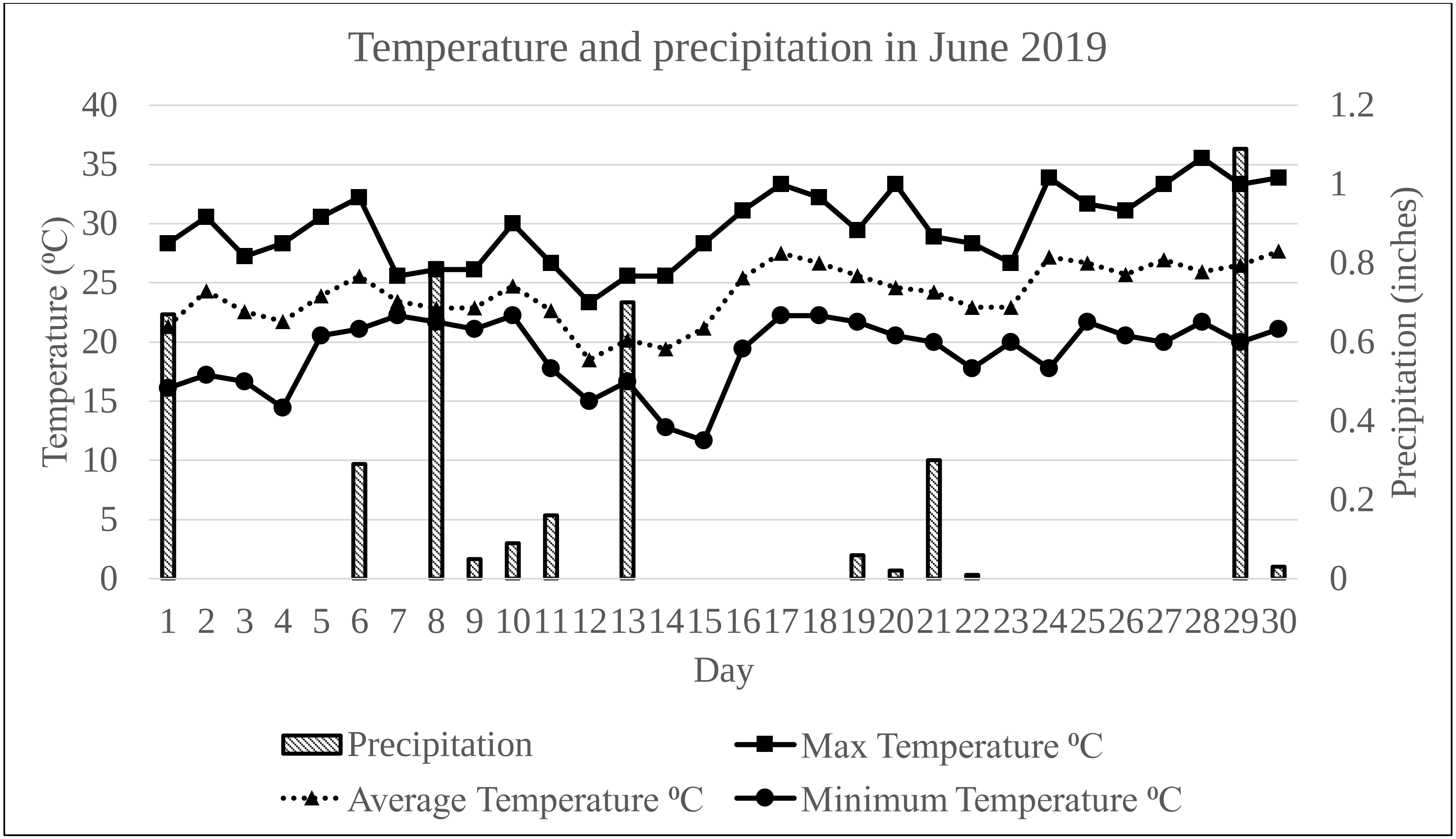

Figure 1. Temperature and precipitation in North Carolina's Central and Coastal Plains area for June 2019.

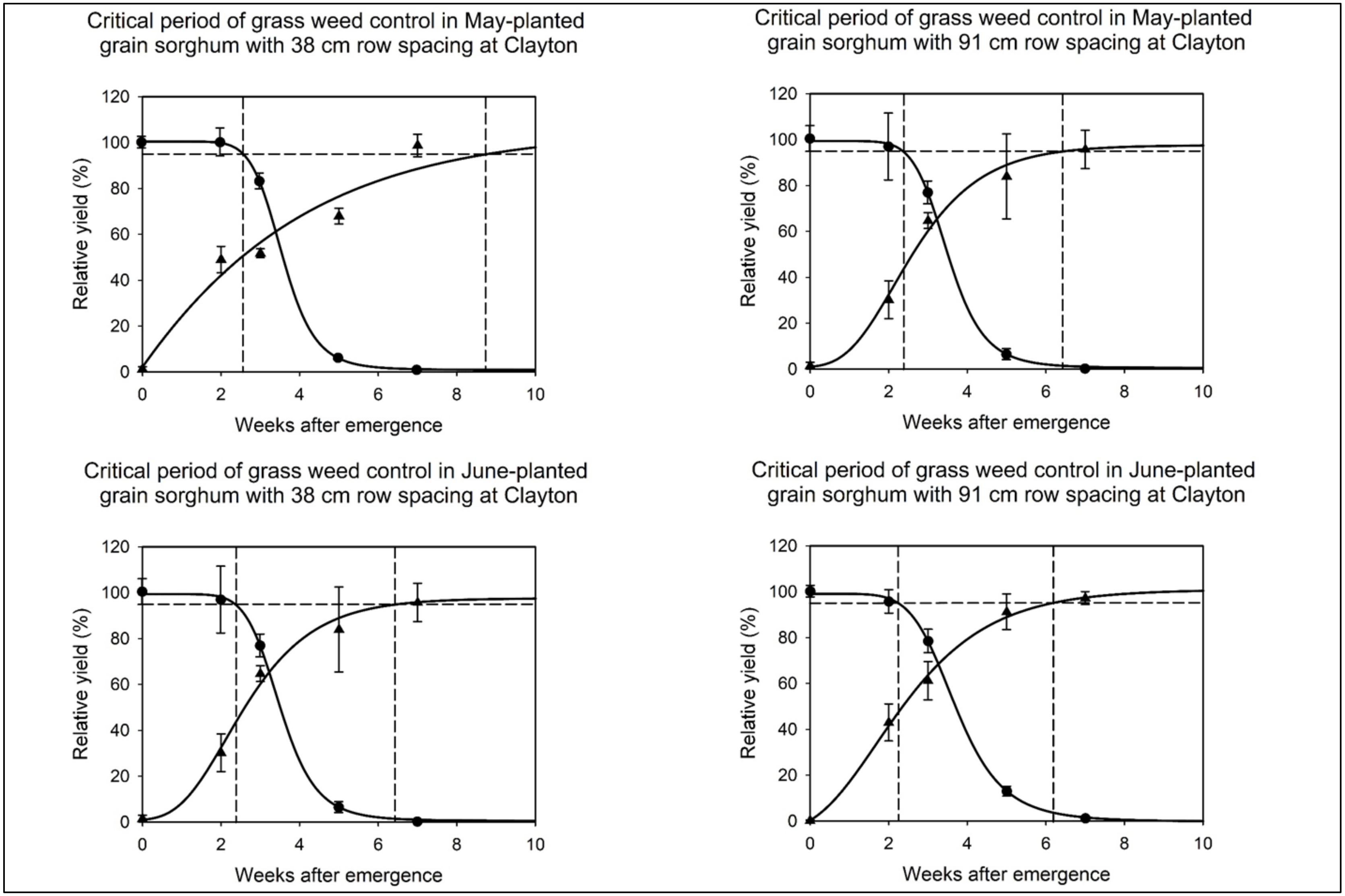

Figure 2. Critical period of weed control curves at Clayton on multiple planting arrangements according to planting date and row spacing.

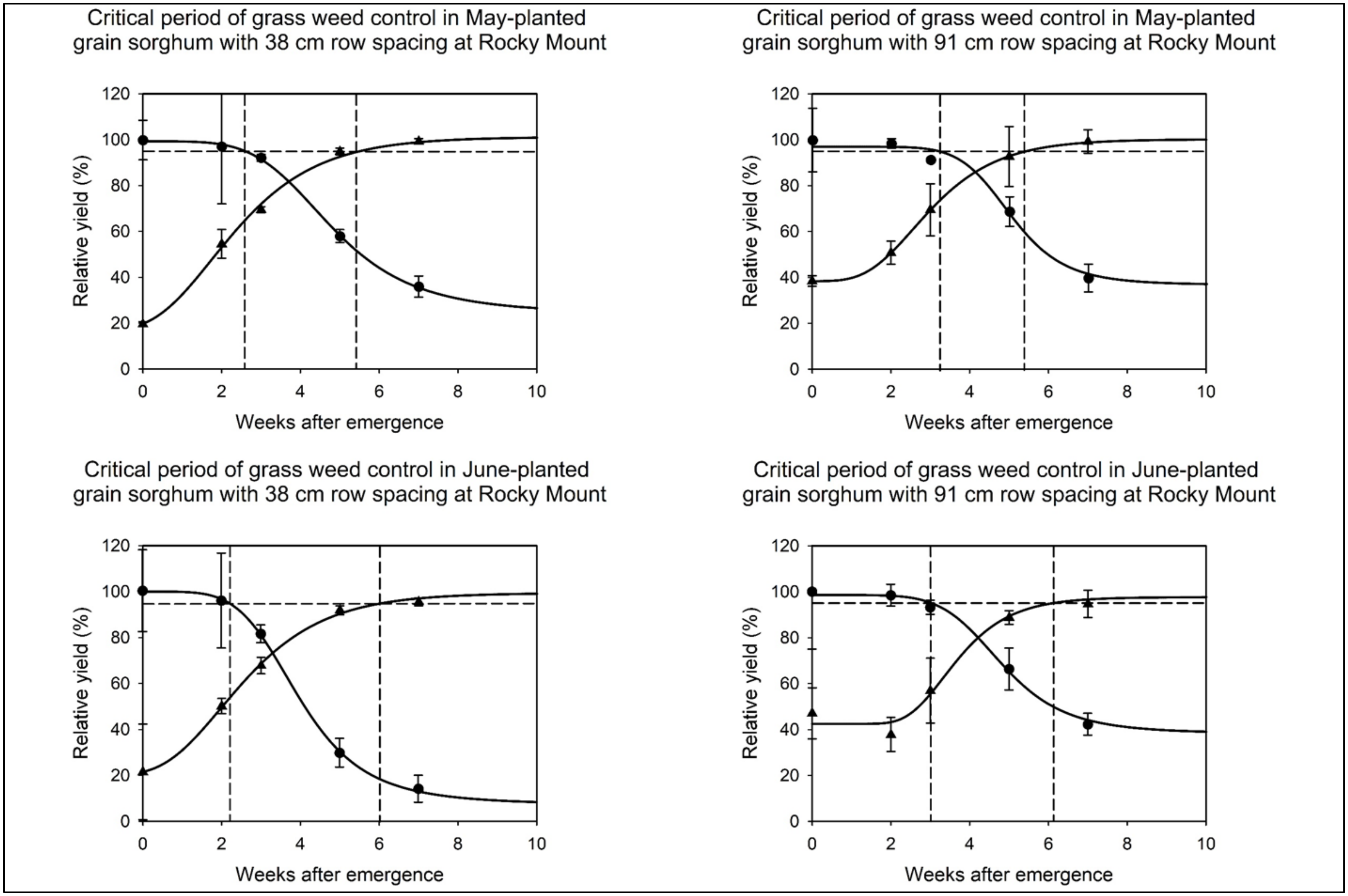

Figure 3. Critical period of weed control curves at Rocky Mount on multiple planting arrangements according to planting date and row spacing.