ABSTRACT

BANSAL, MANISH KUMAR. Wheat (*Triticum aestivum*) Growth and Yield Response to Previous Summer Crop, Sorghum (*Sorghum bicolor*) Allelochemicals and Pre-Plant Nitrogen Fertilization (Under the direction of Dr. Wesley J Everman and Dr. James Burton).

Grain sorghum is the third largest grain crop grown in the United States after corn and wheat. It has recently gained renewed interest as an animal feedstock in the Southeastern region. North Carolina is one of the largest meat animals producing states in the United States. Growing demand for grain and increased shipping costs created a need to produce more feed grains in the state. In North Carolina, wheat is a grain crop that can be grown in a double crop system with soybean. An alternative to soybean, grain sorghum is a crop that can fit as a double crop with wheat to help increase overall feed grain production. But there were growers concern about including grain sorghum into double crop with wheat due to its large quantity of biomass production and allelopathic potential on wheat.

In field experiments, desiccants (Glyphosate and sodium chlorate) were applied to grain sorghum at various grain fill stages: green or 0% browning, 50% browning, 75% browning, and 100% browning of sorghum seed head. In addition, effect of sorghum varieties (DKS5367 and P83P17) and desiccation (desiccated and nontreated) on subsequent wheat yield was also recorded. Desiccants applied on green seed head of sorghum affected the sorghum biomass and yield. No effect on yield and biomass was observed when desiccants were applied to 100 percent brown seed head. When wheat follows sorghum, no effect of any sorghum treatments (variety and desiccation) was observed on wheat yield in both years.

Another field experiment investigated the effect of sorghum (P83P17 and DKS5367)/corn (DKC6067) hybrid and pre-plant nitrogen rates (17, 34, 51, and 68 Kg ha^{-1}) on following winter wheat attributes was evaluated. P83P17 produced higher quantity of residue

followed by DKS5367 and DKC6067 at most of the locations. Summer crop hybrids had effect on wheat tiller biomass. No effect of summer hybrids was observed on tiller nitrogen content, but wheat yield was different at 2 out of 5 locations. However, residue of summer hybrids had significant impact on wheat yield. With increase in summer crop residue there was decrease in wheat yield. Wheat yield was 2.93, 3.03, 2.66, and 2.56 Mg ha^{-1} at summer crop residue of 10-15, 15-20, 20-25, and 25-30 Mg ha^{-1}, respectively. At the same time, no significant difference was observed between corn and any sorghum hybrids on wheat yield.

A laboratory experiment to determine the sorgoleone activity on different weed and wheat varieties was evaluated. Sorgoleone activity was more visible on grass weeds than on broadleaf weeds. Italian ryegrass was most susceptible weed with highest growth reduction of 77% at 3 g L^{-1} of sorgoleone. At same dose, large crabgrass was second most susceptible weed showing maximum reduction of 32% followed by velvetleaf, and sicklepod with 25 % and 24% reduction in shoot length, respectively. No effect on any of wheat variety was observed. In wheat group study, only higher sorgoleone doses of 0.2 g L^{-1} and 0.3 g L^{-1} decreased the shoot length by almost 4% and 6%, respectively across all the groups. In between groups, hard red was the one most significantly affected compared to others. At highest dose (0.3 g L^{-1}), hard red had shoot length reduction of almost 13% compared to 5% and 8% in soft red and hard white. Soft white did not exhibit any effect of different sorgoleone dose on shoot length.

Wheat (*Triticum aestivum*) Growth and Yield Response to Previous Summer Crop, Sorghum (*Sorghum bicolor*) Allelochemicals and Pre-Plant Nitrogen Fertilization

by
Manish Kumar Bansal

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APPROVED BY:

Dr. Wesley J. Everman Committee Co-Chair	Dr. James D. Burton Committee Co-Chair
Dr. Ronnie W. Heiniger	Dr. David L. Jordan

DEDICATION

I would love to dedicate this work to my parents, Sadhu Ram, and Raj Rani, for their love, support and providing me the best education. My younger Sister (Nitu) who takes care of our parents. Dedicate this dissertation to my wife, Nuong Cao, for her support and love. Also, dedicate it to my little niece, Gunika, for bringing a smile on my face whenever I felt sad. At last, thanks to all my friends, for their help and encouragement at some point in my life.

BIOGRAPHY

Manish Kumar Bansal was born in small town of Rampura Phul, Punjab, India. He finished his high school in 2002 and got admitted to Punjab Agricultural University, Ludhiana, Punjab, India in 2004. After finishing his B.Sc. in 2008, he started working as loan officer in State Bank of India. Manish was accepted to University of Georgia, Athens in 2010 to conduct a research on postharvest storage of Vidalia Onions under the guidance of Dr. Dan McLean. After completing his M.S. degree in December 2012, he joined the Department of Crop Science at North Carolina State University in the summer of 2013. His doctoral research focused on allelopathic effects of Grain Sorghum on following winter wheat under the guidance of Dr. Randy Weisz. After Dr. Weisz's retirement he joined the lab of Dr. Wesley Everman and continued his research under him.

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CHAPTER 1

Literature Review

M. K. Bansal[1], R. W. Heiniger[1], J. D. Burton[2], D. L. Jordan[1], R. Weisz[1], and W. J. Everman[1]

Graduate Research Assistant[1], Professor[1], Professor Emeritus[2], Professor[1], Professor Emeritus[1], and Associate Professor[1]

[1]Department of Crop Science, North Carolina State University

Raleigh, NC 27695-7620

[2]Department of Horticultural Science, North Carolina State University

Raleigh, NC 27695-7620

Importance of Wheat (*Triticum aestivum* L.)

Wheat is one of the most widely grown cereals in the world, planted on over 17% of the total crop acreage (Gupta et al. 2008). A majority (>65%) of the world population, especially in the developing countries, is dependent on wheat for nutrition needs (Braun et al. 2010). 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). Wheat production is growing annually but is still not keeping up the pace with world population growth (Dixon et al. 2009). In 2014, the world wheat production was 725 million tons (USDA-ERS, 2019) and wheat production will need to be about 900 million tons to meet global demand by 2050.

The United States ranks third in wheat production worldwide after China and India. In 2014, the US harvested 61 million tons of wheat, which is approximately 8% of world wheat production (USDA-NASS 2020). The USDA classifies wheat into five classes which are hard red winter, hard red spring, soft red winter, white, and durum (USDA-ERS, 2020). Out of total national production in 2014, the shares of hard red winter, hard red spring, soft red winter, white, and durum wheat market classes were 36%, 27%, 23%, 11%, and 3%, respectively (USDA-ERS, 2019). North Carolina (NC) produces primarily soft red winter wheat and contributes about 2% (1.34 million tons) to the total national wheat production and about 10% to national soft red winter wheat production in 2014 (USDA-NASS, 2020). Winter wheat is typically planted in November and harvested around June in NC. The wheat acreage and production in NC had been increasing till 2014, owing to comparatively higher prices of wheat. The price of soft red winter wheat has been around $5 per bushel after 2008, as compared to pre-2008 when it was $3 per bushel or lower (USDA-ERS, 2020).

Importance of Grain Sorghum (*Sorghum bicolor* (L.) *Moench*)

Sorghum originated in Africa nearly 7,000 years ago and was introduced to the United States during the 18th century (Dahlberg, 2000). Because of its origin in a tropical region, sorghum is more heat and drought tolerant than C3 crops, like wheat, which originated in more temperate regions (Machado and Paulsen 2001). Sorghum is among the most efficient crops in conversion of solar energy and use of water and considered as a high-energy, drought tolerant crop (Ghani et al. 2015). Sorghum uses C4 photosynthetic mechanisms that promote more efficient utilization of water and nutrients compared to C3 crops (Prasad et al. 2006). C4 photosynthetic adaptation allows for more efficient carbon utilization, especially during suboptimal growing conditions when leaf water potential is low. This adaptation is especially important for maintaining sorghum nutrient uptake and utilization during physiological and grain developmental stages (Machado and Paulsen 2001).

Sorghum is a unique crop because it can be used for its starch, sugar, or cellulose for different purposes (Rooney et al., 2007). Its principle use is, as fodder, in the beef and cattle industry. Sorghum can serve as a productive, low input crop compared to corn. Sorghum produces high quality grains for feed. This is important as feed value of the sorghum grain is relatively comparable to corn in terms of crude protein, total digestible nutrients, and net energy for gain (Gaylean et al., 2010). 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 and can serve as good feed for poultry and hog industry (Ghani et al. 2015, Browning 1966; Myer et al. 2013). Continued focus on water use in the face of dynamic climatic conditions will place a stronger emphasis on the use of grain sorghum as an alternative crop energy source to corn for livestock production (Warren et al., 2017).

Grain sorghum is the sixth most planted grain crop in the world behind wheat, corn (*Zea mays* L.), rice (*Oryza sativa* L.), soybean (*Glycine max* L.), and barley (*Hordeum vulgare* L.). In 2012-13, 41.1 million hectares of grain sorghum was harvested worldwide which accounts for 5.5% of world feed grain area ((FAO STAT 2013). In 2014, grain sorghum was planted on 2.9 million hectares for a value of $1.7 billion and making it the third largest grain crop grown in the US. Grain sorghum planted acreage in the United States is concentrated in Kansas followed by Texas and Oklahoma (USDA-NASS 2020).

Every year North Carolina has been importing millions of bushels of corn annually to feed the state's animal industry. In North Carolina, peak grain sorghum production occurred during the 1970-80's when 30,000-49,000 hectares were planted. Grain sorghum production declined afterwards due to the introduction of more profitable crops like corn and soybean. To increase production, in the Southeastern United States, Smithfield Hog Production Division introduced programs that incentivized growers to grow sorghum by paying 95% price of corn for the grain sorghum in order to meet the demand of animal feedstocks for the local poultry and hog industry (Balota et al. 2018). As a result, in 2012, 20,000 hectares of grain sorghum were grown in North Carolina, an estimated 10-fold increase over 2011 (USDA-NASS, 2020). To increase the acreage further grain sorghum needs to be introduced in a double-cropping system with wheat.

Crop residue impact on nitrogen

In the Eastern Great Plains, winter wheat is typically planted in a double cropping system in rotation with summer crops such as soybean, corn, or grain sorghum. Crop residue from the previous crop is generally incorporated into the soil before wheat planting. This crop residue left near the surface or incorporated can affect the nitrogen requirement in both reduced tillage and no tillage cropping system (Kelley and Sweeney, 2005). Soil microorganisms have a C:N ratio near 8:1 and need a C:N ratio near 24:1 as their diet. Soil microorganisms require more nitrogen to decompose crop residue with C:N ratio higher than 24:1 (USDA NRCS, 2011), and they can immobilize significant amounts of nitrogen applied to the soil which results in less nitrogen available for following crop (Staggenborg et al., 2003, Sanford and Hairston, 1984). Grain sorghum has a C:N ratio near 60:1 and it produces large quantities of biomass. Chad et al., 2000, compared wheat grown under different tillage conditions after sorghum. They found that when wheat was planted in tilled conditions it affected the stand establishment but did not affect the yield. On the contrary, development of wheat was little affected, yield was reduced when wheat was grown in no-till conditions following sorghum. Knowles et al., 1993 reported nitrogen deficiency in wheat when it was planted as a double crop in rotation with sorghum compared to a continuous wheat system. Sanford and colleagues, 1973, observed almost 20 percent less grain yield in wheat when it followed sorghum compared to when it was planted after soybean. They also reported wheat growth was inhibited as much as 15 percent when planted after sorghum compared to soybean. Nitrogen needs to be added to soil to enhance the residue decomposition with higher C:N and growth of the following crop (USDA NRCS, 2011). N rate applied to wheat to obtain optimum yield varies, depending on the previous crop (Wary et al., 1994; Staggenborg et al., 2003). Lowest wheat yield was observed, in sorghum-wheat rotation when compared to rotations with corn, soybean, and wheat, when N was applied either pre-plant only or 70 pounds per acre to wheat. Wheat yield gets optimized at higher rates of N (160 pounds per acre) following either corn, sorghum, or soybean (Wary et al., 1994). At low rates of N applied to wheat following sorghum, wheat had more deficits in N under the wheat-sorghum compared with wheat-wheat cropping system; however, there was no significant difference in yield and N-uptake by wheat at higher rates of N applied to wheat (Knowles et al., 1993).

Allelopathy

The idea of plants releasing chemicals in the environment and affecting the plants in the neighborhood has been known since c. 370 BC. This knowledge has been used by Greeks and Romans in their agriculture practices as early as 64 AD. Detrimental effects of walnut trees to nearby crops have been well known (Malik 2008). Even though this plant-plant interference has been known for a long time, the name 'Allelopathy' was coined in 1937 by Hans Molisch for this phenomenon. Allelopathy, which means the detrimental effect of one on the other, is derived from two Greek words 'allelon' (of each other) and 'pathos' (to suffer) (Rizvi et al., 1992). Allelopathy is the phenomenon of producing certain chemicals by plant species which affects the growth of other species in vicinity. Plants can produce these chemicals either by roots when they are still alive or by dead decaying matter (Putnam and Duke, 1974; Putnam and Defrank, 1983). An allelopathic effect of crop residues to control weeds was first suggested by Putnam and Duke in 1974.

Plants from different genera are known to release allelopathic chemicals (Putnam and Duke, 1974). These allelocemicals are highly water soluble and could be released after rain through leaching by plant production through roots and decomposing residue. Production of these allelochemicals has been influenced by various factors such as age, genetics, location or environment, and the cropping system that sorghum is grown under (Weston and Czarnota., 2001). These allelochemicals are selective and effects of these depend on species, concentration, and different soil processes like persistence and movement.

Allelopathic potential of Grain sorghum

Grain Sorghum is one of the crops known to produce a number of different chemicals that can have allelopathic effects (Putnam and Defrank, 1983). Grain sorghum is known to cause 'soil sickness' and have a negative impact on the crop grown in rotational systems (Putnam and Defrank, 1983). Different hypotheses have been proposed for the detrimental effect of sorghum on the following crop (Putnam and Defrank, 1983). According to one hypothesis it could be due to the natural chemical released by living plants and their decaying organic matter (Putnam and Duke, 1974; Putnam and Defrank, 1983). Another hypothesis suggested that living sorghum plants and microbes which are stimulated by oxidizing organic matter might deplete the nutrient resources which lead to the negative impact on the following crop. Earlier studies conducted in the 1980s and 90s have shown the phytotoxicity of sorghum in the field either by presence of living or decomposing sorghum roots. Phytotoxin accumulation in soil by decomposing root residues of sorghum can have adverse effects if sorghum is grown continuously over the years in the same field (Weston et al 2013). Sorghum releases large quantities of phytotoxins during early stages of residue decomposition (Alsaadawi et al., 2007). However, phytotoxic studies conducted on decaying residue had shown that the toxicity of decaying residue reduces with decomposition time (Putnam and Defrank, 1983). Guenzi et al. (1967) observed that growth of winter wheat double cropped after sorghum in the Great Plains was strongly inhibited after sorghum. However, the allelopathic potential of decomposing sorghum residue decreased with time and had no effect on wheat seedlings after 28 weeks. Additional experiments on sterile water extracts of sorghum roots inoculated with *Trichoderma viride* or *Aspergillus sp.* resulted in toxicity disappearing in a short time. Conversely, several weeks were required to detoxify the soil after addition of root residues of sorghum with a non-sterile and non-inoculated field soil.

Germination, shoot, and root growth of radish (*Raphnus sativus* L.), wheat, rice, and corn was significantly reduced by water extract of sorghum residue (Kim et al., 1993). Seed germination of alfalfa was inhibited by up to 80% when seeds were exposed to sorghum extracts (Chung and Miller 1995).

The allelopathic influence of living sorghum and its residues has been observed both in monoculture and multiple cropping systems (Weston et al., 2013). In field study, Sene et al. (2000) found that establishment of peanut seedlings was better in between rows than within rows of previous sorghum crop. Sorghum has been suspected to be allelopathic to winter wheat (Guenzi et al., 1967). Studies have been done in the past which shows the reduction in the yield of crops like wheat and oat when it follows sorghum. Several factors influence sorghum allelopathy including nitrogen and plant part (Staggenborg et al., 2003). Soil fertility might play an important role in production of sorghum allelopathic compounds. Nitrogen deficiency can affect the growth of plant more than photosynthesis thus allowing more carbohydrates available for synthesis of phenolic compounds. (Koricheva 1999). However, attempts to overcome the allelopathy by adding fertilizers had mixed results. Bhowmik and Doll (1984) reported that adding supplements of nitrogen and phosphorus to various allelopathic residues did not alleviate the negative effects of the residues on crop growth. Sène et al. (2001) reported improving nitrogen nutrition also increased the concentration of both phenols and the total phenol pool size. They concluded that environmental factors that promote growth and grain yield also enhance the total phenol synthesis in sorghum vegetative parts. Allelopathic effects of sorghum on the following wheat crop also depend on part of the plant incorporated into soil. Grain yield of wheat was decreased by 7 percent when the whole sorghum plant was incorporated into soil and yield was decreased by 10 percent when only sorghum roots were incorporated into soil compared to non-treated (Cheema et al., 2008). Incorporation of sorghum roots into soil also reduces dry weight of numbers of certain weeds in wheat, while it increases the wheat grain yield by 16-17 percent over the control. Ben-Hammouda et al. (1995) found that water extract from different sorghum parts: seeds, glumes, leaves, stems, and roots differs in their ability to suppress wheat seedling growth with stem being the most allelopathic reducing radicle elongation of wheat by up to 75 percent compared to non-treated. They also found that sorghum cultivar differs among themselves in production of phenolic and their ability to suppress wheat seedling growth.

Sorghum can also compete with weeds and can inhibit the growth of weeds. Studies have been done in the past to see the negative impact of residue or water extracts of sorghum on different weeds (Putnam and Defrank, 1983; Cheema et al., 2004). Different ways of suppressing weeds by crops having allelopathic effects are: rotation with desired crop, incorporation into soil, surface mulch, spraying aqueous extracts, or intercropping (Cheema et al., 2009). Different plant cultivars differ in their ability to compete with different weed species due to the rapid growth and competition for growth requisites including water, light, and nutrients (Putnam and Duke, 1974). Different sorghum cultivar produces different concentrations of phenolics and concentration decreased with the plant maturity (Woodhead, 1981). Weed seed germination and seedling growth can be greatly reduced during earlier stages of residue decomposition but the growth and development may improve during later stages of residue decomposition (Weston et al., 2013). Sorghum allelochemical effects on root development of other weed species decreases with time. When soil was applied with sorghum allelochemical and weeds were grown, after 3 weeks there was little effect on root development of weeds while shoot growth was affected (Weston and Czarnota, 2001). Allelopathic potential of 'Sorgaab'(water extract of mature sorghum plants after being soaked in water for 24 h) has been studied intensively in Pakistan. Sorgaab when sprayed as an herbicide reduced weed dry weight. The effect of Sorgaab has been evaluated to control weeds in various crops like wheat, maize [*Zea mays* L.], cotton [*Gossypium hirsutum* L.], mungbean [*Vigna radiata* L.]. Studies demonstrates that weed density of various weed species such as white goosefoot (*Chenopodium album)*, littleseed canarygrass (*Phalaris minor)*, wild oat (*Avena fatua)*, field bidweed (*Convolvulus arvensis)*, and toothed dock (*Rumex dentatus)*, has been reduced when sorgaab is applied as foliar application (Bhatti et al., 2000; Cheema and Khaliq, 2000; Cheema et al., 2004). In field study, Putnam and DeFrank (1983) found that sorghum residue reduces the number and biomass of smooth crabgrass and common purslane by 98 and 70 percent respectively. Cheema and Khaliq (2000) used sorgaab as herbicide in wheat to control weeds. They also observed the reduction in weed biomass when sorghum stalks were incorporated in soil. When sorghum was incorporated in soil as green manure it significantly suppresses the weed population in subsequent alfalfa (Medicage sativa L.) crop (Forney et al., 1985). Toxicity of sorghum extracts on weeds also depends on size with small-seeded weeds being affected more compared to large-seeded weeds under different field or greenhouse conditions (Einhellig and Souza 1992; Netzly and Butler 1986; Uddin et al. 2012; Weston 1996). A lab study, done by Guenzi et al (1967), found that root and shoot growth of wheat was inhibited when seeds were soaked in water extracted from roots and stalks of sorghum for 6 hours and allowed to grow in petri dishes. Uddin et al., 2009, showed broadleaf weed species were more susceptible than grass weed species when treated with sorghum exudate. Shoot growth reduction of 70-80% was noticed in broadleaf weeds compared to grass weeds. They reported that false cleavers (*Galium spurium* L.), redroot pigweed, curly dock (*Rumex crispus* L.), and common lambsquarters (*Chenopodium album*) were the most susceptible among all weed species.

Sorgoleone

During the past few decades, a considerable amount of research has been done on allelopathic potential of sorghum exudates. Netzly and Butler in 1986 found a unique hydroquinone from sorghum root exudates which was later called sorgoleone. Sorgoleone is a lipophilic compound (Czarnota et al., 2003a) and the major chemical constituent of sorghum root exudates (Czarnota et al., 2003b). Sorgoleone along with its resorcinol analogue is present in 1:1 ratio in root exudates (Dayan et al., 2009) but sorgoleone concentration could be as much as 90% of the total composition (Czarnota et al., 2003b). Sorgoleone is produced only by root hairs and proportional to root biomass; and cannot be produced if root hairs are absent. Sorghum starts producing sorgoleone through root hairs shortly after the radicle emergence (Czarnota et al., 2003a). Sorgoleone is exuded as an oily droplet at the tip of the root hair (Netzly and Butler, 1986; Czarnota et al., 2003a). Sorgoleone production is a continuous process if root hairs are functional and exudates don’t accumulate on root tip and removed constantly (Dayan et al., 2009). Production of sorgoleone and root hair formation is influenced by temperature and environment (Dayan, 2006; Yang et al., 2004). Production of root hairs was maximized under standard growth temperature of 25 to 35ºC. Humidity and oxygen are an important factor in production of functional root hairs and thus sorgoleone. Environment with high humidity and low oxygen resulted in limited root hair formation and thus sorgoleone production (Yang et al., 2004).

Sorgoleone production varied considerably among types of different sorghum cultivars (Uddin et al. 2009). Based on quantitative analysis of sorghum accessions, done by Rimando et al. 2005, sorgoleone concentration ranges from about 40 to 800 $\mu g\ mg^{-1}$ of root extract. Nimbal et al. (1996) reported that production of sorgoleone ranged between 0.67 and 17.8 $mg\ g^{-1}$ of root fresh weight while most of the cultivars produced between 1.5 and 10 mg g^{-1} of root fresh weight. Sorghum may produce large quantities of these compounds in both root or shoot tissues, and high concentration of sorgoleone may be observed in the soil following sorghum harvest (Sene et al. 2000). However, the plant growth inhibitory activity of sorghum exudates acts only on in short-term, generally less than eight weeks (Weston and Czarnota 2001).

References

Alsaadawi, I. S., Al-Ekelle, M., & Al-Hamzawi, M. (2007). Differential allelopathic potential of grain sorghum genotypes to weeds. *Allelopathy Journal*, *19,* 153-160.

Balota, M., Thomason, W., Mehl, H., Cahoon, C., Reay-Jones, F., Taylor, S., & Everman, W. (2018). Revival of grain sorghum in the mid-atlantic. *Crops & Soils, 51*, 32-47.

Ben-Hammouda, M., Kremer, R. J., Minor, H. C., & Sarwar, M. (1995). A chemical basis for differential allelopathic potential of sorghum hybrids on wheat. *Journal of Chemical Ecology*, *21*(6), 775-786.

Bhatti, M. Q. L., Cheema, Z. A., and Mahmood, T. 2000. Efficacy of sorgaab as natural weed inhibitor in Raya. *Pakistan Journal of Biological Sciences. 3*: 1128–1130.

Braun, H. J., Atlin, G., and Payne, T. (2010). Multi-location testing as a tool to identify plant response to global climate change. In: *Climate Change and Crop Production*, 115-138.

Browning, C. B., & Lusk, J. W. (1966). Comparison of feeding value of corn and grain sorghum silages on the basis of milk production and digestibility. *Journal of Dairy Science*, *49*(12), 1511-1514.

Chad, M. R., James, P. S., & Gary, M. P. 2000. Allelopathy of sorghum on wheat under several tillage systems. *Agronomy Journal*, *92*, 855–859.

Cheema, Z., & Khaliq, A. (2000). Use of sorghum allelopathic properties to control weeds in irrigated wheat in a semi-arid region of punjab. *Agriculture, Ecosystems & Environment, 79,* 105-112.

Cheema, Z., Khaliq, A., & Farooq, M. (2008). Sorghum allelopathy for weed management in wheat. In: *Allelopathy in sustainable agriculture and forestry*, 255-270.

Cheema, Z., Khaliq, A., & Saeed, S. (2004). Weed control in maize (zea mays L.) through sorghum allelopathy. *Journal of Sustainable Agriculture, 23*, 73-86.

Cheema, Z., Mushtaq, M., Farooq, M., Hussain, A., & Shahzad, I. (2009). Purple nutsedge management with allelopathic sorghum. *Allelopathy Journal, 23.*

Chung, I., & Miller, D. A. (1995). Allelopathic influence of nine forage grass extracts on germination and seedling growth of alfalfa. *Agronomy Journal, 87*(4), 767-772.

Czarnota, M., PAUL, R., Dayan, F., NIMBAL, C., & WESTON, L. (2009). Mode of action, localization of production, chemical nature, and activity of sorgoleone: A potent PSII inhibitor in sorghum spp. root exudates. *Weed Technology, 15*, 813-825.

Czarnota, M., Paul, R., Weston, L., & Duke, S. (2003a). Anatomy of Sorgoleone-Secreting root hairs of sorghum species. *International Journal of Plant Sciences, 164*, 861-866.

Czarnota, M., Rimando, A., & Weston, L. (2003b). Evaluation of root exudates of seven sorghum accessions. *Journal of Chemical Ecology, 29*, 2073-83.

Dahlberg, J. (2000). Classification and characterization of sorghum. *Sorghum: Origin, History, Technology, and Production*, 99-130.

Dayan, F. E. (2006). Factors modulating the levels of the allelochemical sorgoleone in sorghum bicolor. *Planta, 224*(2), 339-346.

Dayan, F. E., Howell, J., & Weidenhamer, J. (2009). Dynamic root exudation of sorgoleone and its in planta mechanism of action. *Journal of Experimental Botany, 60*, 2107-17.

Forney, D. R., Foy, C. L., & Wolf, D. D. (1985). Weed suppression in no-till alfalfa (medicago sativa) by prior cropping of summer-annual forage grasses. *Weed Science, 33*(4), 490-497.

Gill, B. S., Appels, R., Botha-Oberholster, A. M., Buell, C. R., Bennetzen, J. L., Chalhoub, B., Chumley, F., Dvorák, J., Iwanaga, M., Keller, B., Li, W., McCombie, W. R., Ogihara, Y., Quetier, F., Sasaki, T. (2004). A workshop report on wheat genome sequencing. *Genetics*, *168*(2), 1087-1096.

Gaylean, M. L., Beauchemin, K. A., Caton, J., Cole, N. A., Eisemann, J. H., Engle, T., Erickson, G. E., Krehbiel, C. R., Lemenager, R. P., &Tedeschi, L. O. (2010). Nutrient requirements of beef cattle. The National Academies Press. Washington, D.C.

Ghani, A., Saeed, M., Hussain, D., Arshad, M., Shafique, M. M., Shah, S. A. S., (2015). Evaluation of different sorghum (Sorghum bicolor L. Moench) varieties for grain yield and related characteristics. *Science Letters*, *3*, 72-74.

Guenzi, W. D., McCalla, T. M., & Norstadt, F. A. (1967). Presence and persistence of phytotoxic substances in wheat, oat, corn, and sorghum Residues. *Agronomy Journal*, *59*(2), 163-165.

Gupta, P. K., Mir, R., Mohan, A., & Kumar, J. (2008). Wheat genomics: Present status and future prospects. *International Journal of Plant Genomics*, 896451.

Kim, K. U., Lee, S. C., & Shin, D. H. (1993). Allelopathic effects of sorghum extract and residues on selected crops and weeds. *Korean Journal of Weed Science*, *14*, 34–41.

Kelley, K., & Sweeney, D. (2005). Tillage and urea ammonium nitrate fertilizer rate and placement affects winter wheat following grain sorghum and soybean. *Agronomy Journal, 97* (3), 690-697.

Knowles, T. C., Hipp, B. W., Graff, P. S., & Marshall, D. S. (1993). Nitrogen nutrition of rainfed winter wheat in tilled and no-till sorghum and wheat residues. *Agronomy Journal, 85*(4), 886-893.

Koricheva, J. (1999). Interpreting phenotypic variation in plant allelochemistry: Problems with the use of concentrations. *Oecologia*, *119*, 467-473.

Machado, S., & Paulsen, G. (2001). Combined effects of drought and high temperature on water relations of wheat and sorghum. *Plant and Soil*, *233*, 179-187.

Mallik, A. U. (2008). Allelopathy: Advances, challenges, and opportunities. In: *Allelopathy in sustainable agriculture and forestry*, 25–38.

Mathur, S. (2017). Sweet sorghum as biofuel feedstock: Recent advances and available resources. *Biotechnology for Biofuels, 10.*

Myer RO, Brendemuhl JH, Gorbet D. (2013) Feeding grain sorghum to swine. Gainesville, FL: University of Florida IFAS Extension. Report number AS-33. 4.

Netzly, D. H., & Butler, L. G. (1986). Roots of sorghum exude hydrophobic droplets containing biologically active Components1. *Crop Science, 26*(4), 775-778.

Nimbal, C. I., Pedersen, J. F., Yerkes, C. N., Weston, L. A., & Weller, S. C. (1996). Phytotoxicity and distribution of sorgoleone in grain sorghum germplasm. *Journal of Agricultural and Food Chemistry, 44*(5), 1343-1347.

Prasad, P. V. V., Boote, K., & Allen, L. (2006). Adverse high temperature effects on pollen viability, seed-set, seed yield and harvest index of grain-sorghum [sorghum bicolor (L.) moench] are more severe at elevated carbon dioxide due to higher tissue temperatures. *Agricultural and Forest Meteorology, 139*, 237-251.

Putnam, A. R., & DeFrank, J. (1983). Use of phytotoxic plant residues for selective weed control. *Crop Protection, 2*(2), 173-181.

Putnam, A. R., & Duke, W. B. (1974). Biological suppression of weeds: Evidence for allelopathy in accessions of cucumber. *Science, 185*, 370-372.

Rimando, A., Kagan, I., Dayan, F., Czarnota, M., & Weston, L. (2005). Chemical basis for weed suppressive activity of sorghum. In: *Semiochemicals in Pest and Weed Control*, 59-70.

Rizvi, S. J. H., Haque, H., Singh, H. K., Rizvi, V. A. (1992). Discipline called allelopathy. In: Allelopathy: Basic and Applied Aspects, 1-10.

Rooney, W., Blumenthal, J. ü, Bean, B., & Mullet, J. (2007). Designing sorghum as a dedicated bioenergy feedstock. *Biofuels, Bioproducts and Biorefining, 1*, 147-157.

Sanford, J. O., & Hairston, J. E. (1984). Effects of N fertilization on yield, growth, and extraction of water by wheat following soybeans and grain Sorghum1. *Agronomy Journal, 76*(4), 623-627.

Sanford, J. O., Myhre, D. L., & Merwine, N. C. (1973). Double cropping systems involving no-tillage and conventional Tillage1. *Agronomy Journal, 65*(6), 978-982.

Sène, M., Doré, T., & Gallet, C. (2001). Relationships between biomass and phenolic production in grain sorghum grown under different conditions. *Agronomy Journal, 93*, 49-54

Sène, M., Doré, T., & Pellissier, F. (2000). Effect of phenolic acids in soil under and between rows of a prior sorghum (sorghum bicolor) crop on germination, emergence, and seedling growth of peanut (arachis hypogea). *Journal of Chemical Ecology, 26*, 625-637.

Staggenborg, S., Whitney, D. A., Fjell, D. L., & Shroyer, J. (2003). Seeding and nitrogen rates required to optimize winter wheat yields following grain sorghum and soybean. *Agronomy Journal, 95*, 253-259.

Uddin, M. R., Park, K., Han, S., & Pyon, J. (2012). Effects of sorgoleone allelochemical on chlorophyll fluorescence and growth inhibition in weeds. *Allelopathy Journal, 30*, 61-70.

USDA-ERS] Economic Research Service. (2019). http://www.ers.usda.gov/data-products/wheat-data.aspx. Accessed 15 July 2020.

USDA- ERS] Economic Research Service. (2020). https://www.ers.usda.gov/topics/crops/wheat/wheat-sector-at-a-glance/. Accessed 15 July 2020.

USDA-NASS] US Department of Agriculture - National Agricultural Statistics Service. (2020). Quick Stats Database. https://quickstats.nass.usda.gov/. Accessed July 23, 2020.

USDA-NRCS] National Resources Conservation Service. (2011). Carbon to Nitrogen Ratios in Cropping Systems. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd331820.pdf. Accessed July 21, 2020.

Wary, R. E., Lamond, R. E., Whitney, D. A., & Kilgore, G. L. (1994). Effects on nitrogen rates on wheat following grain sorghum, wheat, and soybeans, cherokee county, kansas. Kansas State University, Agricultural experiment station, Manhattan.

Warren, J., Stoecker, A., Jones, R., Ramaswamy, K., & Beedy, T. (2017). Economic viability of grain sorghum and corn as a function of irrigation capacity. Oklahoma Cooperative Extension Service. CR-2173.

Westfall, D. G., Havlin, J. L., Hergert, G. W., & Raun, W. R. (1996). Nitrogen management in dryland cropping systems. *Journal of Production Agriculture*, *9*(2), 192-199.

Weston, L. A., & Czarnota, M. (2008). Activity and persistence of sorgoleone, a long-chain hydroquinone produced by sorghum bicolor. *Journal of Crop Production, 4*(2), 363-377.

Weston, L., Alsaadawi, I., & Baerson, S. (2013). Sorghum Allelopathy—From ecosystem to molecule. *Journal of Chemical Ecology*, *39*, 142-153.

Woodhead, S. (1981). Environmental and biotic factors affecting the phenolic content of different cultivars ofSorghum bicolor. *Journal of Chemical Ecology, 7*(6), 1035-1047.

Yang, X., Owens, T. G., Scheffler, B. E., & Weston, L. A. (2004). Manipulation of root hair development and sorgoleone production in sorghum seedlings. *Journal of Chemical Ecology*, *30*(1), 199-213.

CHAPTER 2

Desiccant and growth stage impact on sorghum, and wheat response to sorghum hybrids and desiccant

M. K. Bansal[1], R. W. Heiniger[1], J. D. Burton[2], D. L. Jordan[1], R. Weisz[1], and W. J. Everman[1]

Graduate Research Assistant[1], Professor[1], Professor Emeritus[2], Professor[1], Professor Emeritus[1], and Associate Professor[1]

[1]Department of Crop Science, North Carolina State University

Raleigh, NC 27695-7620

[2]Department of Horticultural Science, North Carolina State University

Raleigh, NC 27695-7620

Abstract

North Carolina is one of the largest meat animal producing states in the United States. Growing demand for grain and increased shipping costs created a need to produce more feed grains in the state. In North Carolina wheat is a grain crop that can be grown in a double crop system with soybean. An alternative to soybean, grain sorghum is a crop that can fit as a double crop with wheat to help increase overall feed grain production. But there were growers concern about including grain sorghum into double crop with wheat due to its large quantity of biomass production and allelopathic potential on wheat. Field experiments were conducted at different locations in 2013 and 2014 in North Carolina to see the effect of desiccants (Glyphosate and sodium chlorate) applied to grain sorghum at various grain fill stages: green or 0% browning, 50% browning, 75% browning, and 100% browning of sorghum seed head, on biomass and yield of sorghum. In addition, study was conducted to determine the effect of sorghum variety (DKS5367 and P83P17) and desiccation (desiccated and nontreated) on subsequent wheat yield. Desiccants applied on green seed head of sorghum affected the sorghum biomass and yield. There was no effect of desiccants on sorghum yield or biomass when applied at 100 percent brown seed head. Applying desiccant at either 50% or 75% brown stage was the best option to desiccate sorghum without affecting its yield. In second study, both sorghum hybrids were not significantly different for biomass production in both years. Desiccation had significant effect on sorghum biomass compared to nontreated in 2013. Subsequently, no effect was observed on sorghum yield due to desiccation compared to nontreated. For the winter wheat, no effect of any summer treatments (sorghum variety or desiccation) was observed on following wheat yield in both years.

Nomenclature: Corn (*Zea mays* L.), Grain sorghum (*Sorghum bicolor* L.), soybean (*Glycine max* L.), wheat (*Triticum aestivum* L.).

Key Words: Double-cropping, biomass, sorghum, wheat, desiccant, allelopathy.

Introduction

Winter wheat in North Carolina is typically planted in a double cropping system in rotation with summer crops such as soybean and corn. Grain demand in state is so high that every year North Carolina imports millions of bushels of grain to meet the needs of local animal industry. Grain sorghum is more heat and water tolerant than corn (Machado and Paulsen, 2001) and soybean and nutrition content of grain sorghum is comparable to corn (Gaylean et al., 2010). So, grain sorghum can fit in with double cropping wheat to reduce the states grain deficit. It can perform better in sandy soils and dry areas compared to corn. Grain sorghum is predominantly grown in the High Plains of the United States and has garnered revitalized interest in North Carolina due to competitive price compared to corn (Balota et al. 2018). In 2011, approximately 2,000 hectares of grain sorghum were grown in North Carolina and a year later planted area increased ten-fold (USDA-NASS, 2020).

Grain sorghum produces a huge quantity of biomass and releases chemicals in the environment that can have phytotoxic effect on following crop (Putnam and Defrank, 1983). This negative impact on following crop could be due to nutrient depletion in the soil or allelopathy. Grain sorghum has a C:N ratio of 60:1 and soil microorganisms need more nitrogen while oxidizing the grain sorghum residue which creates soil deficiencies in nitrogen. This problem can be resolved by adding more fertilizer before planting winter wheat (USDA NRCS, 2011).

Grain sorghum produces allelochemicals and it can produce these chemicals either by roots when plants are still alive or by dead decaying matter (Putnam and Duke, 1974; Putnam and Defrank, 1983). The allelopathic influence of living sorghum and its residues has been observed both in monoculture and multiple cropping systems (Weston et al., 2013). These allelochemicals can accumulate in soil if sorghum is grown continuously over the years in the same field (Weston et al 2013). Sorghum releases large quantities of phytotoxins during early stages of residue decomposition (Alsaadawi et al., 2007). However, phytotoxic studies conducted on decaying residue had shown that the toxicity of decaying residue reduces with decomposition time (Putnam and Defrank, 1983). Guenzi et al. (1967) observed that growth of winter wheat double cropped after sorghum in the Great Plains was strongly inhibited after sorghum. However, the allelopathic potential of decomposing sorghum residue decreased with time and had no effect on wheat seedlings after 28 weeks. Similar effects were seen on weeds. Germination and seedling growth greatly reduced during earlier stages of residue decomposition, but the growth and development improved during later stages of residue decomposition (Weston et al., 2013). Sterile water extracts of sorghum roots inoculated with *Trichoderma viride* or *Aspergillus sp.* resulted in toxicity disappearing in a short time. Conversely, several weeks were required to detoxify the soil after addition of root residues of sorghum with a non-sterile and non-inoculated field soil (Guenzi et al. 1967). Water extract of sorghum residue can also have significant effect on growth reduction. When treated with water extract of sorghum residue germination, shoot, and root growth of radish, wheat, rice, and corn was significantly reduced compared to non-treated (Kim et al., 1993). Seed germination of alfalfa was inhibited by up to 80% when seeds were exposed to sorghum extracts (Chung and Miller 1995). Ben-Hammouda et al. (1995) found that water extract from different sorghum parts seeds, glumes, leaves, stems, and roots differs in their ability to suppress wheat seedling growth with stem being the most allelopathic reducing radicle elongation of wheat by up to 75 percent compared to non-treated. They also found that sorghum cultivar differs among themselves in production of phenolic and their ability to suppress wheat seedling growth.

Sorgoleone is one of the allelochemical produced by sorghum which is most phytotoxic among all. Sorgoleone is produced only by root hairs and proportional to root biomass and cannot be produced if root hairs are absent. Sorghum starts producing sorgoleone through root hairs shortly after the radicle emergence (Czarnota et al., 2003a). Sorgoleone production is a continuous process if root hairs are functional and exudates don't accumulate on root tip and removed constantly (Dayan et al., 2009). Sorgoleone production varied considerably among types of different sorghum cultivars (Uddin et al. 2009). Based on quantitative analysis of sorghum accessions, done by Rimando et al. 2005, sorgoleone concentration ranges from about 40 to 800 $\mu g\ mg^{-1}$ of root extract. Nimbal et al. (1996) reported that production of sorgoleone ranged between 0.67 and 17.8 $mg\ g^{-1}$ of root fresh weight while most of the cultivars produced between 1.5 and 10 $mg\ g^{-1}$ of root fresh weight. Sorghum may produce large quantities of these compounds in both root or shoot tissues, and high concentration of sorgoleone may be observed in the soil following sorghum harvest (Sene et al. 2000). However, the plant growth inhibitory activity of sorghum exudates acts only on in short-term, generally less than eight weeks (Weston and Czarnota 2001). In south eastern US, field observations looking at wheat following grain sorghum in double-cropping system might suggest that sorghum allelopathic chemicals may have a detrimental impact on wheat emergence and growth (R. Weisz, personal communication).

The objectives of this study were to evaluate different desiccants applied at different growth stages in grain sorghum in order to stop plant biomass production and subsequently root production without affecting the yield and to evaluate the effects of desiccation on following wheat yield when wheat was planted following the sorghum.

Materials and Methods

Desiccant and timing study. Experiments were conducted in 2013 at the Caswell Research Station near Kinston, NC, and at the Upper Coastal Plain Research Station near Rocky Mount, NC to determine the efficacy of desiccants applied at different grain fill stages (green or 0% browning, 50% browning, 75% browning, and 100% browning of sorghum seed head) of sorghum. Fields were conventionally tilled at both locations and followed by field disking prior to planting sorghum. Sorghum hybrid Dekalb 'DKS53-67' (Monsanto, Saint-Louis, MO) was planted at each location on a flat seedbed at an averaged depth of 1.9 cm. Sorghum was seeded in 38 cm row spacing using a vacuum planter (Model 1760, John Deere, Moline, IL). Each plot consisted of six rows per plot, 9 m long at both locations. Sorghum was planted at a seeding rate of 267,000 seeds ha^{-1}. Standard fertilization, weeds, disease, and insect management practices as recommended by the North Carolina Cooperative Extension Service were followed. The experimental design was a two-factorial arrangement in a randomized complete block with treatments replicated four times at each location. Main factors consisted of desiccant type, and application stage. Desiccant treatments included glyphosate (Roundup PowerMax®, Monsanto Co., St. Louis, MO) at 860 g ae ha^{-1} and sodium chlorate 750 7.5SL (Defol, Drexel Chemical Co., Memphis, TN) at 6.7 kg ai ha^{-1}. Applications were made in water with a CO2-pressurized backpack sprayer equipped with flat-fan nozzles XR1102 (TeeJet, Wheaton, IL) delivering 140 L ha^{-1} at 165 kPa. Desiccant treatments were applied at four different stages of seed head maturity consisting of: green head or 0% brown head, 50% brown head, 75% brown head, and 100% brown head. Treated rows for each plot were mechanically harvested and yields were adjusted to 13% moisture.

Sorghum hybrids and desiccation study. A second experiment was conducted at the Upper Coastal Plain Research Station near Rocky Mount, NC in 2013 and Lower Coastal Plain Research Station near Kinston, NC in 2014. Conventional tillage was performed at both locations and followed by field disking before planting sorghum. Sorghum hybrids Dekalb 'DKS53-67' (Monsanto, Saint-Louis, MO) and Pioneer 'P83P17' (Corteva agriscience, Johnston, IA) were planted at each location on a flat seedbed at a depth of 1.9 cm in summer of 2013 and 2014 at both locations. Sorghum was seeded at 38 cm row spacing using a vacuum planter (Model 1760, John Deere, Moline, IL). There were six rows per plot of 9 m long at both locations. Sorghum was planted at a seeding rate of 267,000 seeds ha^{-1}. Standard fertilization, weed, disease, and insect management practices as recommended by the North Carolina Cooperative Extension Service were followed. The experimental design was a two-factor factorial arrangement in a randomized complete block with treatments replicated four times at each location. Factors consisted of sorghum hybrid as described previously and desiccant application. Desiccant treatments included glyphosate (Roundup PowerMax®, Monsanto Co., St. Louis, MO) at 860 g ae ha^{-1} or no desiccant. Applications were made in water with a CO2-pressurized backpack sprayer equipped with flat-fan nozzles XR11001 (TeeJet, Wheaton, IL) delivering 140 L ha^{-1} at 165 kPa. Desiccant treatments were applied when seedhead was at 100 percent brown stage. Plots were machine harvested between mid-October and late-October using a combine (Model Delta, Wintersteiger, Ried, Austria) specifically adapted for harvesting small-plot and crop yield was adjusted to 13% moisture.

Two to three weeks after sorghum harvest, the field was mowed once and disked two times to incorporate the sorghum residue. After the field was prepared, wheat was planted in the same plots where previous sorghum treatment plots were planted. Winter wheat variety USG

3251 (UniSouth Genetics, Inc., Dickson, TN) was planted on flat beds in both years at seeding rate of 3,700,000 seeds ha^{-1} in 19 cm rows at a depth of 2.4 cm using a no-till drill (Model 3P606NT, Great Plains Ag., Salina, KS). There were eight rows per plot of 9 m long at both locations. During growth stage 30 (GS 30), when small grains switch from producing tillers to starting reproductive growth, nitrogen was applied at 112 Kg ha^{-1}. Other fertilizer, weed, disease, and insect management practices as recommended by the North Carolina Cooperative Extension Service were followed. Plots were machine harvested in mid-June using a combine (Model Delta, Wintersteiger, Ried, Austria) specifically adapted for harvesting small-plot and crop yield was adjusted to 13% moisture.

Data were subjected to analysis of variance (ANOVA) by using the PROC GLIMMIX procedure of SAS (version 9.4; SAS Institute Inc., Cary, NC, 27513). For the first experiment, location, desiccant treatment, application stage and all interactions containing these factors were considered fixed effects whereas replications were considered random effects. In the second experiment, year and location were combined as proposed by Carmer et al. (1989) and referred to as 'environment'. Environment, sorghum hybrids, and desiccant treatment and all interactions containing these factors were considered fixed effects whereas replications (nested within environment) were considered random effects. Mean comparisons were performed using Fisher's Protected LSD test when F-values were statistically significant ($P \leq 0.05$).

Results

Desiccant and timing study. Initial analysis of location, desiccant type, application stage, and their interaction showed a highly significant location effect with high F-value (Table 2). Therefore, statistical analyses were conducted by location. Treating sorghum with different types of desiccants did not have any significant effect on sorghum biomass or sorghum yield at both Rocky Mount and Kinston (Table 3 and 4). A similar pattern was observed for the interaction between application stage and desiccant type at both locations (Table 3 and 4). Desiccants applied at different grain fill stages in Rocky Mount had a significant effect on sorghum residue and sorghum yield. (Table 3). However, yield was the only dependent variable that was affected by stage of desiccant application, and no significant difference was observed in sorghum residue when desiccants were applied at different percentage of browning of sorghum seed head at Kinston (Table 4).

Desiccants applied at a later stage produced more crop biomass than all other growth stages. At 100% browning stage, sorghum produced 32 %, 55%, and 57 % more biomass than 0%, 50%, and 75% seed head browning stage, respectively at Rocky Mount (Figure 1). Whereas, sorghum biomass production was not significantly different irrespective of the stages at which desiccants were applied at Kinston (Figure 1). Irrespective of the desiccant, when applied at green head stage (0 percent browning of sorghum seed head), sorghum yield was almost 28 percent lower compared to l00 percent brown head stage at Rocky Mount (Figure 2). Similar patterns were observed for grain yield reduction between green head and 100% brown head of sorghum treated with desiccants at Kinston (Figure 2). Reduction in yield at Kinston was not as high as observed in Rocky Mount. Sorghum yield was reduced by 12% at Kinston compared to 28% at Rocky Mount (Figure 2).

Sorghum hybrids and desiccation study. The initial analysis of environment (location x year), sorghum hybrids, and desiccant treatment and their interactions showed a highly significant environment effect with high F-value (Table 5). Therefore, statistical analysis was conducted by environment (Table 6). Compared to our first experiment, desiccation had a significant effect on sorghum biomass at Rocky Mount in 2013, where desiccated sorghum produced greater biomass than non-desiccated (Figure 5). But no significant differences in biomass production were observed for desiccation treatments the next year at Kinston. (Table 6). Production of biomass between sorghum hybrids were not statistically significant at both locations (Table 6). Yield of sorghum hybrids, DKS5367 and P83P17, were significantly different at Rocky Mount in 2013 (Table 6). DKS5367 produced significantly greater grain yield than P83P17. Yield of DKS5367 was 8.92 Mg ha^{-1} which is 16 percent more compared to 7.57 Mg ha^{-1} yield of P83P17 (Figure 6). However, no significant difference in yield was observed between the two sorghum hybrids at Lower Coastal Plain in 2014 (Table 6). In the following wheat crop, no significant difference was observed in wheat yield for desiccation treatments or sorghum hybrids in both years (Table 6).

Discussion

The results of these studies should give extension personnel and growers clear guidelines for desiccating sorghum and peace of mind that desiccation timing does not impact wheat growth and yield in the following crop. Sorghum is known to produce allelochemical through roots and other plant parts. Desiccation of sorghum was believed to be required to stop the production of allelochemicals and biomass without affecting its yield. Our research clearly demonstrated that timing of desiccant application to sorghum is an important factor in determining its impact on yield. Previous research found that after flowering, when sorghum was sprayed with glyphosate at 1.6 L ha^{-1}, more than 50 percent yield reduction was observed at 14 days after treatment which corresponds to 25 percent maturity stage (GRDC 2017). They found most of the locations treated with glyphosate at 1.6 L ha^{-1} had no significant reduction in yield at 28 days after flowering (75 percent brown seed head) which also supports our study results. They suggested glyphosate should be applied at physiological maturity to avoid any damage due to crop lodging due to high winds (GRDC 2017). Leaf moisture content of sorghum was reduced to less than 30% in 7 days after treatment of glyphosate at 0.56 kg ha^{-1} without affecting the yield. Similarly, we found that treating sorghum with glyphosate does not impact grain yield when sprayed at above 50 percent maturity of seed head. However, desiccation symptoms in sorghum do not appear until 4 or 5 days after treatment. Applying desiccant when sorghum reaches its physiological maturity, does not affect the sorghum grain yield (GRDC, 2017), which supports the findings of our second experiment. Although production of biomass has mixed results following desiccation, no difference in wheat yield was noticed when it follows sorghum. Even though the findings of our study did not show any significant difference between wheat yield for all factors, these results are significant from a grower's perspective. Concerns about losing yield in winter wheat planted after sorghum were widespread. However, results of our study showed no effect of not desiccating on subsequent wheat yield.

References:

Alsaadawi, I. S., Al-Ekelle, M., & Al-Hamzawi, M. (2007). Differential allelopathic potential of grain sorghum genotypes to weeds. *Allelopathy Journal, 19,* 153-160.

Anonynmous. (2017). Sorghum and the use of a harvest-aid product. https://www.sorghumcheckoff.com/news-and-media/newsroom/2017/09/15/sorghum-and-the-use-of-a-harvest-aid-product/. Accessed July 27, 2020.

Balota, M., Thomason, W., Mehl, H., Cahoon, C., Reay-Jones, F., Taylor, S., & Everman, W. (2018). Revival of grain sorghum in the mid-atlantic. *Crops & Soils, 51*, 32-47.

Ben-Hammouda, M., Kremer, R. J., Minor, H. C., & Sarwar, M. (1995). A chemical basis for differential allelopathic potential of sorghum hybrids on wheat. *Journal of Chemical Ecology, 21*(6), 775-786.

Chung, I., & Miller, D. A. (1995). Allelopathic influence of nine forage grass extracts on germination and seedling growth of alfalfa. *Agronomy Journal, 87*(4), 767-772

Czarnota, M., Paul, R., Weston, L., & Duke, S. (2003). Anatomy of Sorgoleone-Secreting root hairs of sorghum species. *International Journal of Plant Sciences, 164*, 861-866.

Dayan, F. E., Howell, J., & Weidenhamer, J. (2009). Dynamic root exudation of sorgoleone and its in planta mechanism of action. *Journal of Experimental Botany, 60*, 2107-17.

Gaylean, M. L., Beauchemin, K. A., Caton, J., Cole, N. A., Eisemann, J. H., Engle, T., Erickson, G. E., Krehbiel, C. R., Lemenager, R. P., & Tedeschi, L. O. (2010). Nutrient requirements of beef cattle. The National Academies Press. Washington, D.C.

GRDC]. Grain Research and Development Corporation. (2017). Crop desiccation/spray out. https://grdc.com.au/__data/assets/pdf_file/0018/370602/GrowNote-Sorghum-North-11-Desiccation.pdf. Accessed July 27, 2020.

Guenzi, W. D., McCalla, T. M., & Norstadt, F. A. (1967). Presence and persistence of phytotoxic substances in wheat, oat, corn, and sorghum Residues. *Agronomy Journal*, *59*(2), 163-165.

Griffin, J. L., Boudreauxand , J. M., & Miller, D. K. 2010. Herbicides as harvest aids. *Weed Science, 58*, 355–358.

Kim, K. U., Lee, S. C., & Shin, D. H. (1993). Allelopathic effects of sorghum extract and residues on selected crops and weeds. *Korean Journal of Weed Science, 14*, 34–41.

Machado, S., & Paulsen, G. (2001). Combined effects of drought and high temperature on water relations of wheat and sorghum. *Plant and Soil*, *233*, 179-187.

Nimbal, C. I., Pedersen, J. F., Yerkes, C. N., Weston, L. A., & Weller, S. C. (1996). Phytotoxicity and distribution of sorgoleone in grain sorghum germplasm. *Journal of Agricultural and Food Chemistry, 44*(5), 1343-1347.

Putnam, A. R., & DeFrank, J. (1983). Use of phytotoxic plant residues for selective weed control. *Crop Protection, 2*(2), 173-181.

Putnam, A. R., & Duke, W. B. (1974). Biological suppression of weeds: Evidence for allelopathy in accessions of cucumber. *Science, 185*, 370-372.

Rimando, A., Kagan, I., Dayan, F., Czarnota, M., & Weston, L. (2005). Chemical basis for weed suppressive activity of sorghum. In: *Semiochemicals in Pest and Weed Control*, 59-70.

Sène, M., Doré, T., & Pellissier, F. (2000). Effect of phenolic acids in soil under and between rows of a prior sorghum (sorghum bicolor) crop on germination, emergence, and seedling growth of peanut (arachis hypogea). *Journal of Chemical Ecology, 26*, 625-637.

Uddin, M. R., Park, K., Han, S., & Pyon, J. (2012). Effects of sorgoleone allelochemical on chlorophyll fluorescence and growth inhibition in weeds. *Allelopathy Journal, 30*, 61-70.

USDA-NASS] US Department of Agriculture - National Agricultural Statistics Service. (2020). Quick Stats Database. https://quickstats.nass.usda.gov/. Accessed July 23, 2020.

USDA-NRCS] National Resources Conservation Service. (2011). Carbon to Nitrogen Ratios in Cropping Systems. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd331820.pdf. Accessed July 21, 2020.

Weston, L. A., & Czarnota, M. (2008). Activity and persistence of sorgoleone, a long-chain hydroquinone produced by sorghum bicolor. *Journal of Crop Production, 4*(2), 363-367.

Weston, L., Alsaadawi, I., & Baerson, S. (2013). Sorghum Allelopathy - From ecosystem to molecule. *Journal of Chemical Ecology, 39*, 142-153.

Table 1. Planting and harvesting dates.

Year	Location	Sorghum		Wheat	
		Planting	Harvesting	Planting	Harvesting
2013	Rocky Mount	June 14	Oct 18	Nov 7	June 13
2014	Kinston	May 22	Oct 7	Oct 28	June 10

Table 2. Two-way ANOVA results of desiccant and timing study for sorghum biomass and yield for different locations, stage of herbicide application and herbicide type[a].

Effect	df	Biomass		Yield	
		F ratio	Prob>F[b]	F ratio	Prob>F
loc	1	35.30	<.0001	40.62	<.0001
stage	3	4.56	0.0066	8.67	<.0001
loc*stage	3	12.95	<.0001	1.08	0.3663
desiccant	1	3.21	0.0791	1.68	0.2008
loc*desiccant	1	2.00	0.1632	0.35	0.5543
stage*desiccant	3	1.92	0.1385	0.87	0.4620
loc*stage*desiccant	3	0.98	0.4107	0.93	0.4334

[a]Abbreviations: loc, location; df, degrees of freedom.

[b]Source values lower than 0.05 are statistically significant.

Table 3. One-way ANOVA results of desiccant and timing study for sorghum biomass and sorghum yield at Rocky Mount in 2013[a].

Effect	df	Biomass		Yield	
		F ratio	Prob>F[b]	F ratio	Prob>F
stage	1	12.56	<.0001	6.88	0.0017
desiccant	3	4.01	0.0566	1.89	0.1817
stage*desiccant	3	1.69	0.1966	0.76	0.5275

[a]Abbreviations: df, degrees of freedom.

[b]Source values lower than 0.05 are statistically significant.

Table 4. One-way ANOVA results of desiccant and timing study for sorghum biomass and sorghum yield at Kinston in 2013[a].

Effect	df	Biomass		Yield	
		F ratio	Prob>F[b]	F ratio	Prob>F
stage	1	2.80	0.0614	3.54	0.0297
desiccant	3	0.14	0.7104	0.27	0.6093
stage*desiccant	3	1.46	0.2514	1.18	0.3376

[a]Abbreviations: df, degrees of freedom.

[b]Source values lower than 0.05 are statistically significant.

Table 5. Two-way ANOVA results of sorghum hybrids and desiccation study for sorghum biomass, sorghum yield and wheat yield at all locations and year[a].

Effect	df	Sorghum biomass		Sorghum yield		Wheat yield	
		F ratio	Prob>F[b]	F ratio	Prob>F	F ratio	Prob>F
env	1	289.68	<.0001	295.20	<.0001	34.11	<.0001
hyb	1	1.56	0.2162	3.90	0.0526	0.15	0.6981
env*hyb	1	0.17	0.6819	7.46	0.0082	0.15	0.7030
trt	1	2.22	0.1414	1.73	0.1926	0.54	0.4649
env*trt	1	1.88	0.1755	1.44	0.2353	0.59	0.4462
hyb*trt	1	0.81	0.3704	0.49	0.4880	0.00	0.9566
env*hyb*trt	1	0.82	0.3685	0.51	0.4770	0.42	0.5181

[a]Abbreviations: df, degrees of freedom; env, environment; hyb, hybrid; trt, treatment.

[b]Source values lower than 0.05 are statistically significant.

Table 6. One-way ANOVA results of sorghum hybrids and desiccation study for sorghum biomass, sorghum yield and wheat yield[a].

Year	Location	Effect	df	Sorghum biomass		Sorghum yield		Wheat yield	
				F ratio	Prob>F[b]	F ratio	Prob>F	F ratio	Prob>F
2013	Rocky Mount	hyb	1	1.51	0.2272	13.14	0.0009*	0.16	0.6881
		trt	1	4.49	0.0412*	3.75	0.0606	0.62	0.4366
		hyb*trt	1	1.80	0.1883	1.18	0.2837	0.14	0.7142
2014	Kinston	hyb	1	0.33	0.5710	0.24	0.6276	0.00	0.9903
		trt	1	0.01	0.9364	0.01	0.9392	0.00	0.9540
		hyb*trt	1	0.00	0.9961	0.00	0.9909	1.22	0.2779

[a]Abbreviations: df, degrees of freedom; hyb, hybrid; trt, desiccation.

[b]Source values lower than 0.05 are statistically significant.

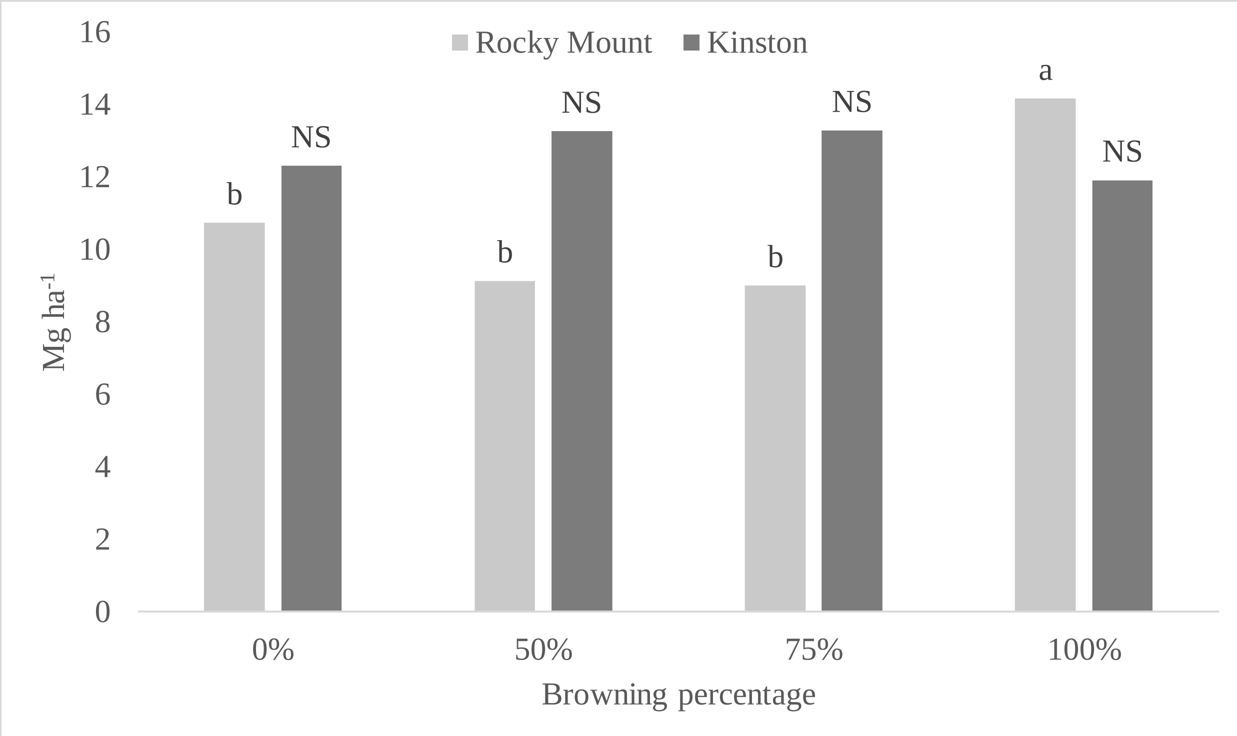

Figure 1. Sorghum biomass at different % browning of seed head at Rocky Mount and Kinston of desiccant and timing study.

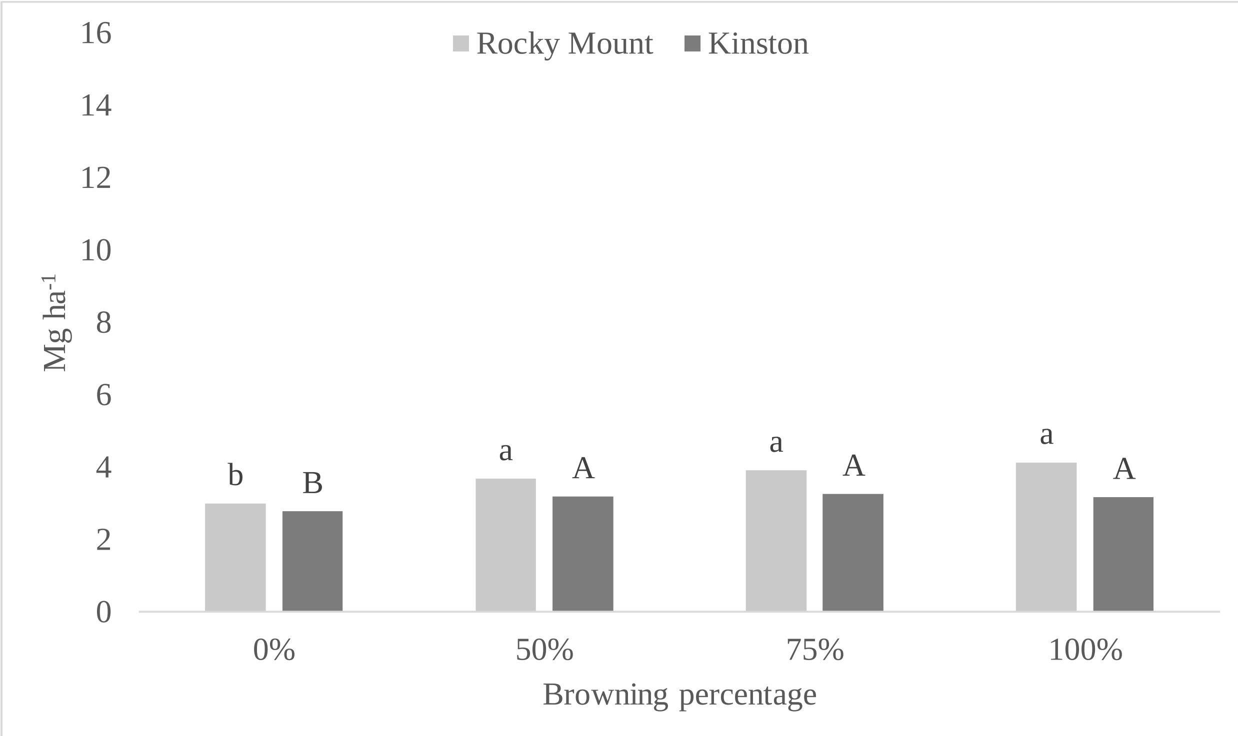

Figure 2. Sorghum yield at different % browning of seed head at Rocky Mount and Kinston of desiccant and timing study.

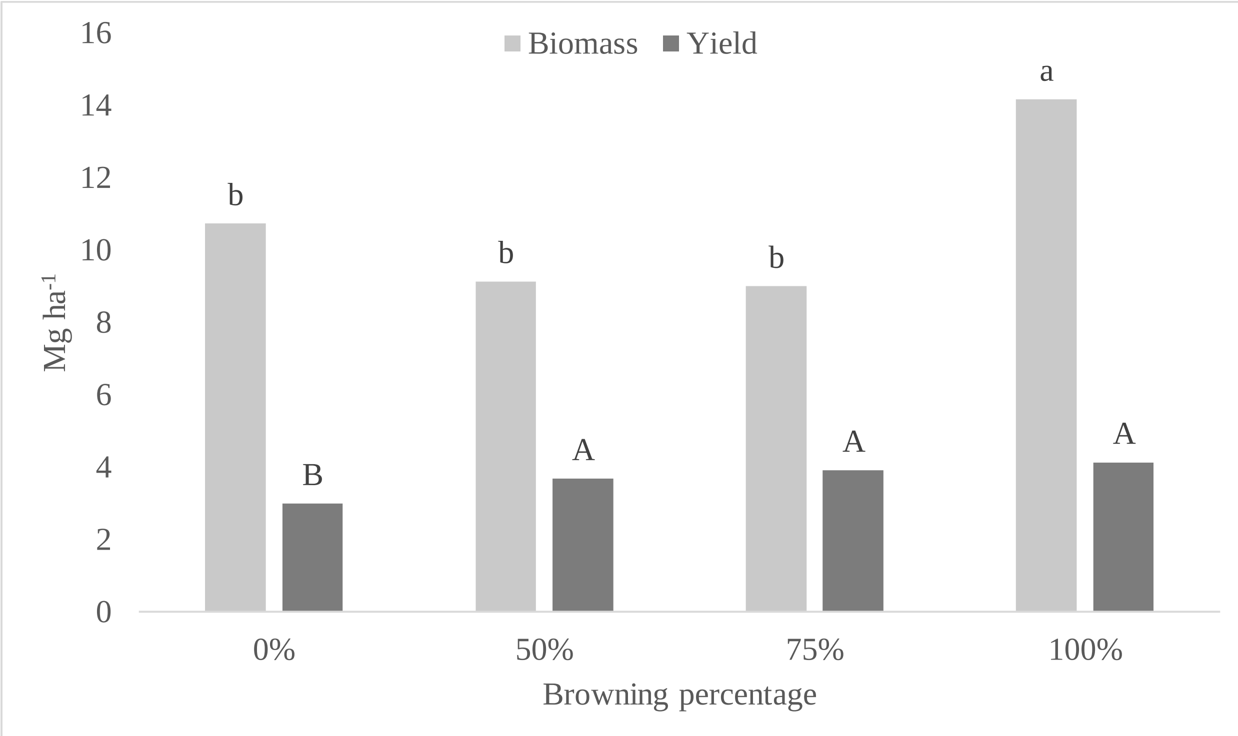

Figure 3. Sorghum biomass and yield at different % browning of seed head at Rocky Mount of desiccant and timing study.

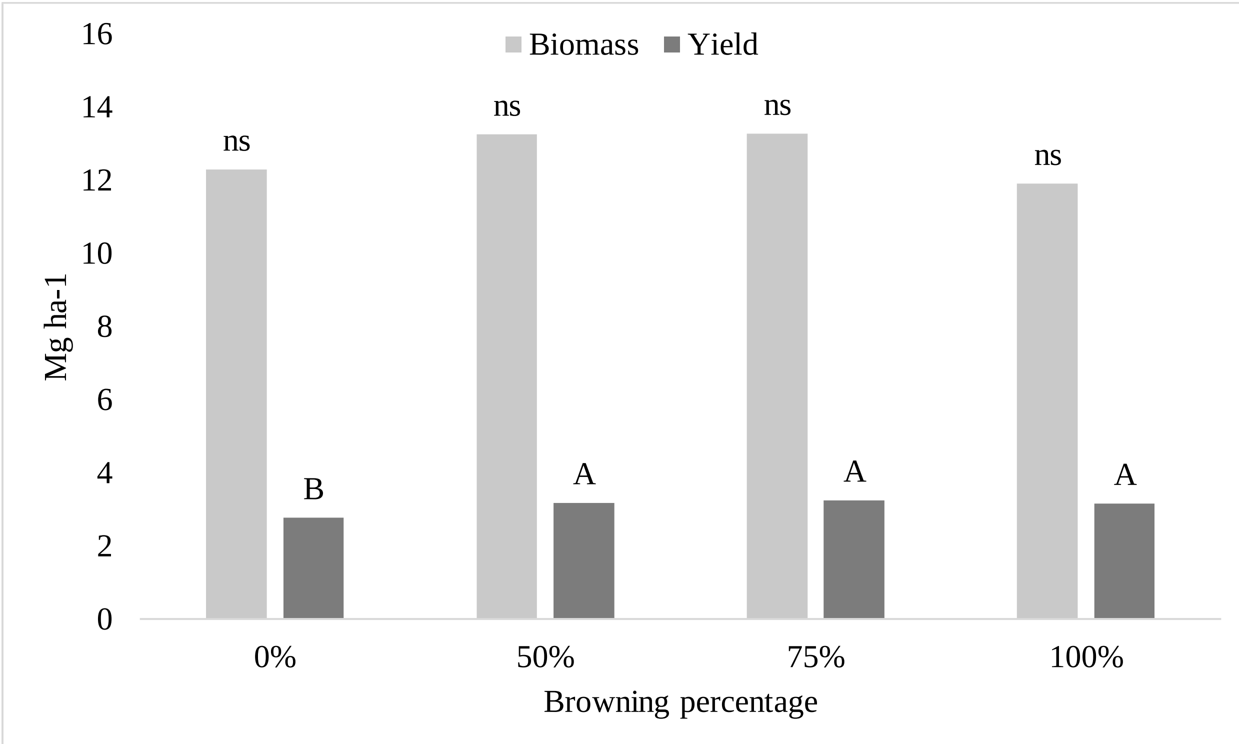

Figure 4. Sorghum biomass and yield at different % browning of seed head at Kinston of desiccant and timing study.

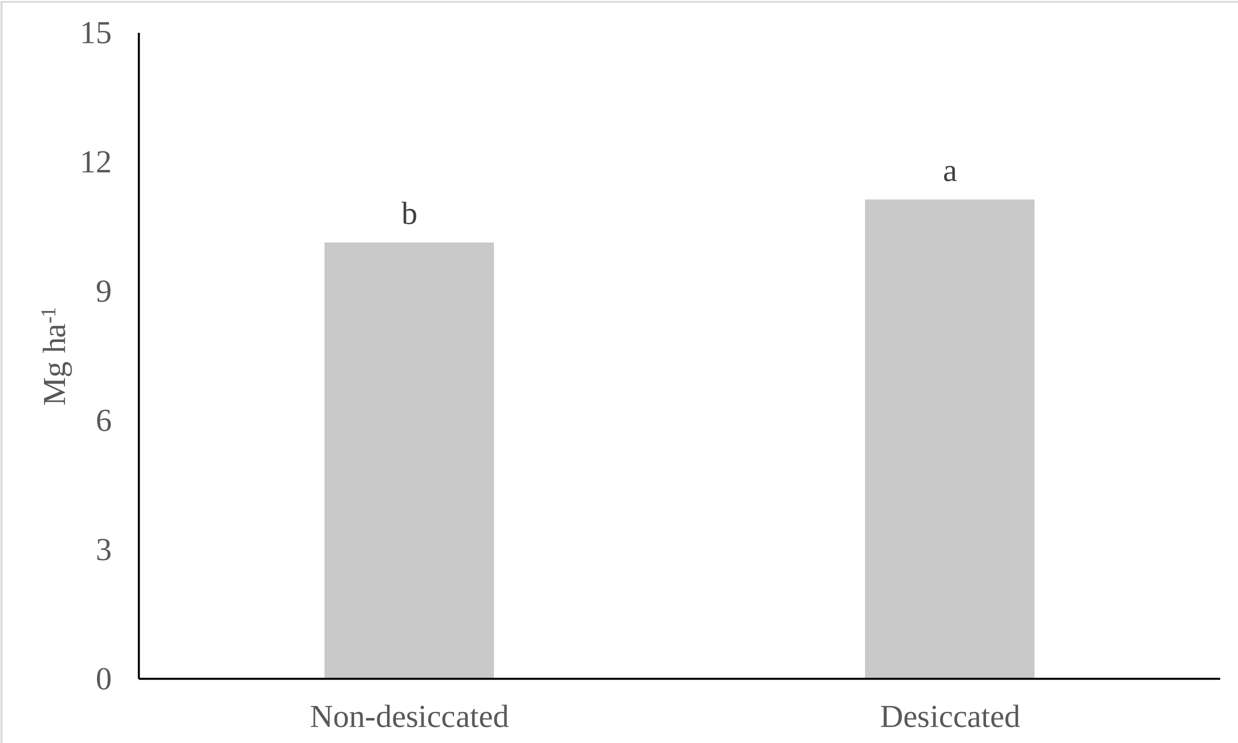

Figure 5. In sorghum hybrids and desiccation study, sorghum biomass affected by desiccation treatment at Rocky Mount in 2013.

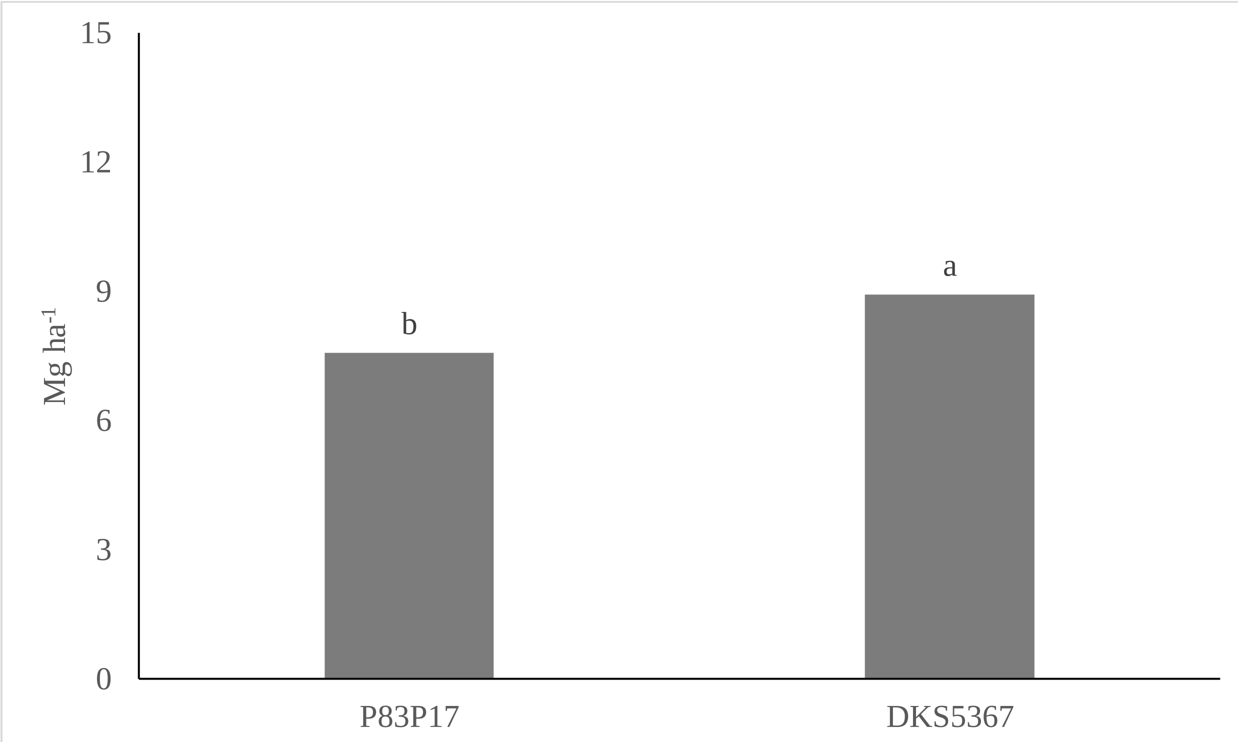

Figure 6. Grain yield of two different sorghum hybrids at Rocky Mount in 2013 of sorghum hybrids and desiccation study.

CHAPTER 3

Wheat growth and yield response to previous sorghum and corn hybrids and pre-plant nitrogen fertilization

M. K. Bansal, R. W. Heiniger, R. Weisz, D. L. Jordan,

W. J. Everman[1] and J. D. Burton[2]

Graduate Research Assistant, Professor, Professor Emeritus, Professor,

Associate Professor[1], and Professor Emeritus[2]

[1]Department of Crop Science, North Carolina State University,

Raleigh, NC 27695-7620

[2]Department of Horticultural Science, North Carolina State University

Raleigh, NC 27695-7620

Abstract

In North Carolina, wheat (*Triticum aestivum* L.) is grown in a double crop system with soybean (*Glycine max* L.). Due to high demand for grain from state's animal industry, every year grain is imported from other states to fulfill the need. An, alternative to soybean, grain sorghum (*Sorghum bicolor* L.) is a crop that can fit as double crop with wheat to help increase overall grain production. But there were growers concern about including grain sorghum into double crop with wheat due to its large quantity of biomass production and allelopathic potential on wheat. Field experiments were conducted at Upper Coastal Plain Research Station near Rocky Mount, NC in 2013, 2014 and 2015, and at Caswell Research Station and Lower Coastal Plain Research Station near Kinston, NC in 2014 to evaluate the effect of sorghum/corn hybrid and pre-plant nitrogen rates on different wheat factors. Sorghum hybrids: 'DKS5367' and 'P83P17', and corn hybrid 'DKC6067' were planted in summer of each year. P83P17 produced higher quantity of residue followed by DKS5367 and DKC6067 at most of the locations. In contrast, corn produced more yield compared to DKS5357 and P83P17 at most of the locations. After harvest, residue of summer crop was incorporated into the plots and wheat hybrid USG3251 was planted on same plots followed by application of pre-plant nitrogen at 17, 34, 51, and 68 Kg ha^{-1}. Summer crop hybrid had effect on wheat tiller biomass at 2 out 5 locations. No effect of summer hybrids was observed on tiller nitrogen content and wheat yield was different at 2 out of 5 locations. Only Rocky Mount, in 2013, had effect of summer hybrids on both wheat tiller biomass and wheat yield. In 2014, Rocky Mount and Lower Coastal Plain, summer hybrids did not have any significant effect on tiller biomass or wheat yield. All other locations had only one significant variable out the two either tiller biomass or wheat yield. Combing data over years, locations, and hybrids, and dividing summer crop residue into different levels (10-15, 15-20, 20-

25, and 25-30 Mg ha^{-1}) had significant effect on wheat yield. With increase in summer crop residue there was decrease in wheat yield. Wheat yield was 2.93, 3.03, 2.66, and 2.56 Mg ha^{-1} at summer crop residue of 10-15, 15-20, 20-25, and 25-30 Mg ha^{-1}, respectively. At the same time, there was no significant difference was observed between corn and both of sorghum hybrids on following wheat yield.

Nomenclature: Grain sorghum (*Sorghum bicolor* L.), soybean (*Glycine max* L.), wheat (*Triticum aestivum* L.).

Key Words: Double-crop, residue, sorghum, wheat, corn, nitrogen.

Introduction

The United States ranks third and sixth in wheat and grain sorghum production worldwide, respectively. High grain demand from local animal industry in state makes every year importing millions of bushels of grain and makes state grain deficit. Grain sorghum is more heat and water tolerant than corn and soybean and nutrition content of grain sorghum relative comparable to corn. So, grain sorghum can fit in with double cropping wheat to reduce the states grain deficit. It can perform better in sandy soils and dry area compared to corn. Grain sorghum recently gained renewed interest in North Carolina where it is used primarily as an animal feedstock. In 2012, 20,000 ha of grain sorghum were grown in North Carolina, an estimated 10-fold increase over 2011 (USDA-NASS, 2020).

In the southeastern US, winter wheat is typically planted in a double cropping system in rotation with summer crops such as soybean or corn. Crop residue from the previous crop is generally incorporated into soil before wheat planting. This crop residue left near the surface or incorporated can affect the nitrogen requirement in both reduced tillage and no tillage cropping system (Kelley and Sweeney, 2005). Grain sorghum produce large quantity of biomass which can affect the following crop. This negative impact on following crop could be due to nutrient depletion in the soil or allelopathy. Grain sorghum has C:N ratio of 60:1 and soil microorganism need more nitrogen while oxidizing the grain sorghum residue which can make nitrogen immobilize in soil (USDA NRCS, 2011). Wheat become deficient in nitrogen when planted as double crop in rotation with sorghum compared to a continuous wheat system (Chad et al., 2000). Wheat growth and yield was reduced about 15 and 20 percent when it followed sorghum compared planted after soybean, respectively (Sanford et al., 1973). To optimize the winter wheat growth followed by grain sorghum additional nitrogen needs to be applied to soil to enhance the residue decomposition. However, nitrogen rate varies and depends on previous crop (Wary et al., 1994; Staggenborg et al., 2003). Warry et al., reported lower wheat yield, when N was applied either pre-plant or 70 pounds per acre at later stages, in sorghum-wheat rotation compared to rotations with corn, soybean, and wheat. They found that there was no effect of previous crop when higher rates of nitrogen (160lb per acre) is applied at later stages of wheat growth. At lower rates of applied nitrogen wheat yield and nitrogen uptake was less compared to higher rates under wheat-sorghum compared with wheat-wheat cropping system (Knowles et al., 1993).

Grain sorghum produces allelochemicals and it can produce these chemicals either by roots when plants are still alive or by dead decaying matter (Putnam and Duke, 1974; Putnam and Defrank, 1983). The allelopathic influence of living sorghum and its residues has been observed both in monoculture and multiple cropping systems (Weston et al., 2013). These allelochemicals can accumulate in soil if sorghum is grown continuously over the years in the same field (Weston et al 2013). Sorghum releases large quantities of phytotoxins during early stages of residue decomposition (Alsaadawi et al., 2007). However, phytotoxic studies conducted on decaying residue had shown that the toxicity of decaying residue reduces with decomposition time (Putnam and Defrank, 1983). Guenzi et al. (1967) observed that growth of winter wheat double cropped after sorghum in the Great Plains was strongly inhibited after sorghum. However, the allelopathic potential of decomposing sorghum residue decreased with time and had no effect on wheat seedlings after 28 weeks. Similar effects were seen on weeds. germination and seedling growth greatly reduced during earlier stages of residue decomposition, but the growth and development improved during later stages of residue decomposition (Weston et al., 2013). Sterile water extracts of sorghum roots inoculated with *Trichoderma viride* or

Aspergillus sp. resulted in toxicity disappearing in a short time. Conversely, several weeks were required to detoxify the soil after addition of root residues of sorghum with a non-sterile and non-inoculated field soil (Guenzi et al. 1967). Water extract of sorghum residue can also have significant effect on growth reduction. When treated with water extract of sorghum residue germination, shoot, and root growth of radish, wheat, rice, and corn was significantly reduced compared to non-treated (Kim et al., 1993). Seed germination of alfalfa was inhibited by up to 80% when seeds were exposed to sorghum extracts (Chung and Miller 1995). Ben-Hammouda et al. (1995) found that water extract from different sorghum parts seeds, glumes, leaves, stems, and roots differs in their ability to suppress wheat seedling growth with stem being the most allelopathic reducing radicle elongation of wheat by up to 75 percent compared to non-treated. They also found that sorghum cultivar differs among themselves in production of phenolic and their ability to suppress wheat seedling growth. Several factors influence sorghum allelopathy including nitrogen and plant part (Staggenborg et al., 2003). Soil fertility might play an important role in production of sorghum allelopathic compounds. Nitrogen deficiency can affect the growth of plant more than photosynthesis thus allowing more carbohydrates available for synthesis of phenolic compounds. (Koricheva 1999). However, to overcome the allelopathy by adding fertilizers had mixed results. Bhowmik and Doll (1984) reported that adding supplements of nitrogen and phosphorus to various allelopathic residues did not alleviate the negative effects of the residues on crop growth. Sène et al. (2001) reported improving nitrogen nutrition also increased the concentration of both phenols and the total phenol pool size. They concluded that environmental factors that promote growth and grain yield also enhance the total phenol synthesis in sorghum vegetative parts.

The objective of this study was to evaluate the effect of different sorghum and corn hybrids and pre-plant nitrogen rates in wheat on following winter wheat yield components and yield.

Materials and Methods

A study was conducted at the Upper Coastal Plain Research Station near Rocky Mount, NC in 2013, 2014 and 2015, and at Caswell Research Station and Lower Coastal Plain Research Station near Kinston, NC in 2014. Fields were tilled followed by disking prior to planting sorghum and corn at all location and years. Sorghum hybrids Dekalb 'DKS5367' (Monsanto, Saint-Louis, MO) and Pioneer 'P83P17' (Corteva agriscience, Johnston, IA), and corn hybrid Dekalb 'DKC6067' (Monsanto, Saint-Louis, MO) was planted at each location on a flat seedbed at an average depth of 1.9 cm in summer of every year at all locations (Table 1). Sorghum and corn were seeded in 38, and 76 cm row spacing respectively, using a vacuum planter (Model 1760, John Deere, Moline, IL). Each plot consisted of six rows for sorghum and three rows for corn. Plots were 9 m long at all locations and years. Sorghum and corn were planted at seeding rate of 267,000 and 70,000 seeds ha^{-1}, respectively. Seeding plates and settings adjustments for the six-row planter were selected according to the recommendations provided by the planter technical manual. Standard fertilization, weed, disease, and insect management practices as recommended by the North Carolina Cooperative Extension Service were followed. A week before harvesting, 3ft section of outer row of each plot was selected and plants were cut from the soil line using machete. Plants were stored in mesh harvest bags and dried at 60^{o}C for 3 days. Dry plant biomass was recorded after 3 days. The following week, the middle four out of six rows of sorghum plots were machine harvested between mid-October and late-October using a combine (Model Delta, Wintersteiger, Ried, Austria) specifically adapted for harvesting small-plot (Table 1). Corn was hand harvested from the middle one out of three rows and shelled, 2 days later, using a single corn sheller (Model SCS-2, Agriculex, Inc., Ontario, Canada). Grain moisture of both sorghum and corn was recorded using a handheld grain moisture analyzer (Model mini GAC, DICKEY-john, Auburn, IL), and yield of both sorghum and corn was adjusted to 13% moisture.

Two to three weeks after sorghum harvest, the field was mowed once followed by disking two times to incorporate the sorghum residue. After the field was prepared, wheat was planted in the same plots where previous sorghum and corn hybrids were planted. Immediately after planting wheat, nitrogen treatments were applied at 17, 34, 51, and 68 Kg ha^{-1}. Treatments were applied using 32% liquid nitrogen with a CO_2-pressurized backpack sprayer equipped with Tee-Jet nozzles TTI11001 (TeeJet, Wheaton, IL) delivering 40 L ha^{-1} at 103 kPa. Winter wheat variety USG 3251 (UniSouth Genetics, Inc., Dickson, TN) was planted on flat beds in all years. Wheat was planted at seeding rate of 3,700,000 seeds ha^{-1} in 19 cm rows at a depth of 2.4 cm using a no-till drill (Model 3P606NT, Great Plains Ag., Salina, KS). There were eight rows per plot of 9 m long at both locations. At growth stage 30 (GS 30), a 3ft section of outer row of each plot was measured and wheat tillers were cut from soil line using a gardening knife or clippers. Tillers were counted and stored in brown paper bags and placed in a dryer at 60°C for 2 days. Tiller biomass was recorded using a precision scale (Model PB3001-S, Mettler Toledo, Columbus, OH). 5 g of tillers from each plot were stored and sealed in zip lock bags and shipped to Waters Agriculture Laboratories in Warsaw, North Carolina for nitrogen analysis. One day following tiller collection, topdress nitrogen was broadcast at 112 Kg ha^{-1}. Other standard fertilization, weeds, disease, and insect management practices as recommended by the North

Carolina Cooperative Extension Service were followed. Plots were machine harvested in mid-June using a combine (Model Delta, Wintersteiger, Ried, Austria) specifically adapted for harvesting small plots. Grain moisture was recorded using a handheld grain moisture analyzer (Model mini GAC, DICKEY-John, Auburn, IL) and yield was adjusted to 13% moisture.

Data were subjected to analysis of variance (ANOVA) by using the PROC GLIMMIX procedure of SAS (version 9.4; SAS Institute Inc., Cary, NC, 27513). Year and location were combined as proposed by Carmer et al. (1989) and referred to as ‘environment’. Environment, sorghum/corn hybrids, and nitrogen rates and all interactions containing these factors were considered fixed effects whereas replications (nested within environment) were considered random effects. Mean comparisons were performed using Fisher’s Protected LSD test when F-values were statistically significant ($P \leq 0.05$).

Results and Discussion

Summer crop: Initial analysis of environment (location x year), hybrids, and their interaction showed a highly significant environment effect with high f-value (Table 2). Therefore, statistical analysis was conducted by environment.

Residue of summer planted hybrids under each environmental condition was statistically significant. At four out five locations, both of the sorghum hybrids produced higher biomass than corn (Table 3). The difference among sorghum and corn residue production can be attributed to species traits (McClure et. al., 2008). Generally, sorghum tends to produce more crop biomass than corn and hence can leave behind more residue after harvest. Sorghum hybrid ‘P83P17’ produced the highest amount of residue among all the three hybrids at all locations and years except at Rocky Mount in 2013 where residue of P83P17 was not statistically different from sorghum hybrid 'DKS5367' (Table 3). P83P17 produced 55%, 35%, and 20% more residue than DKS5367 at all locations in 2014 and, 73%, 31 %, 61 %, and 27 % more residue than corn at Rocky Mount in 2013 and 2014, Caswell, and Lower Coastal Plain in 2014, respectively (Table 3). Similarly, sorghum hybrid 'DKS5367' produced 78%, 19% and 16% more residue than corn at Rocky Mount in 2013, Caswell, and Lower Coastal Plain, respectively (Table 3). Generally, corn produced the least residue among all hybrids tested excluding one incidence at Rocky Mount in 2014, where it produced 13% more residue than DKS5367 (Table 3). The range of residue production of each hybrid was, P83P17: 18.6-25.1 Mg ha^{-1}, DKS5367: 13.9-25.8 Mg ha^{-1}, and corn: 13.2-16.0 Mg ha^{-1} (Table 3). Lower Coastal Plain produced the lowest amount of residue and in 2013 at Rocky Mount was the highest residue production for each hybrid (Table 3).

In contrast to residue, yield of corn was highest among all hybrids at most of the locations except Rocky Mount in 2013 (Table 4). Corn yield was almost 20%, 14%, 147%, 26%, and 86% more than P83P17 at Rocky Mount in 2013, 2014, and 2015, and Caswell, and Lower Coastal Plain in 2014, respectively. Similarly, it produced 12%, 600%, 37%, and 165% more yield than DKS5367 at Rocky Mount in 2014, 2015, and Caswell, and Lower Coastal Plain in 2014 (Table 4). Only incidence of corn producing less yield than any sorghum was recorded at Rocky Mount in 2013, yield of corn was 7% less compared to DKS5367 (Table 4). Yield differences between sorghum and corn hybrids is due primarily to the character of species traits. Much more efforts were devoted to breeding corn compared to breeding sorghum and developing new hybrids of corn resulted in larger increases in corn yield when compared to grain sorghum over past few decades (McClure et. al, 2008). Generally, corn produces higher yield than sorghum. However, two locations, yield difference between corn and both of sorghum hybrids was much higher than other locations. In 2014, Lower Coastal Plain, we observed a high population of grass weeds. Generally, corn is more competitive with weeds than sorghum (Aseefa et. al, 2014 and Zimdahl, 2004). Differences in yield observed could be a result of a hybrid's ability to compete with weeds. In 2015, Rocky Mount, there was unexpected attack of sugarcane aphid and it was not noticed until later in the season. Sugarcane aphid is a pest of sugarcane, first discovered in Texas in 2013. It affected both sorghum hybrids and contributed towards the highest grain yield differences between corn and sorghum at Rocky Mount in 2015. Among the sorghum hybrids, yield follows a similar pattern as observed with residue production. P83P17 yield was significantly greater than DKS5367 at most locations but no significant difference was observed at Rocky Mount in 2014. DKS5367 outperformed P83P17 in terms of yield at Rocky Mount in 2013 (Table 4).

Winter wheat: Initial analysis of environment (location x year), summer hybrids, nitrogen rates, and their interaction showed a highly significant environment effect with a high f-value (Table 2) for the dependent variable: tiller biomass, tiller % N, and wheat yield. Therefore, statistical analysis was conducted by environment (Table 5).

Tiller biomass production was affected by summer hybrids at Rocky Mount in 2013 and 2015 (Table 6). No statistically significant difference was observed in tiller % N content for summer hybrids at any location (Table 6). Yields of winter wheat following summer hybrid was statistically significant at two out of five locations, at Rocky Mount and Caswell in 2013 and 2014, respectively (Table 6). The effect of pre-plant nitrogen rates on tiller biomass was only significant at Rocky Mount in 2014. Otherwise, no significant effect was observed at any other location. A study conducted by Wary et. al (1994) observed wheat applied with only pre-plant nitrogen following sorghum and corn had differences in yield with wheat producing more yield after corn compared to sorghum. They suggested when nitrogen is applied later in the season in addition to pre-plant nitrogen, differences in wheat yield become less evident with increasing rate of topdress nitrogen. Wheat yield gets optimized after applying 78 Kg ha^{-1} of nitrogen. It could be possible nitrogen applied at growth stage 30 might have mitigated any earlier effect shown, if any, on wheat yield. Similar to the summer hybrid effect on tiller % N content, no significant difference of nitrogen rates was observed on tiller % N content (Table 6). Likewise, pre-plant nitrogen rates did not impact the wheat yield at any location (Table 6). Interaction between summer hybrids and pre-plant nitrogen rate was not statistically significant for any of the measured wheat variable (Table 6).

Winter wheat tiller count data was collected at Rocky Mount in 2013 and 2015. Tiller count was affected by summer hybrid only at Rocky Mount in 2013. Nitrogen rates did not impact the tiller count at any location. Similarly, interaction between summer hybrids and nitrogen rates were not significant at both locations. Production of tillers was greater after corn compared to both of sorghum hybrids (Table 7).

In 2013, Rocky Mount, wheat following corn produced almost 15% and 26% more tillers compared to wheat following DKS5367 and P83P17, respectively (Figure 1). However, tiller biomass production was 30% more in wheat followed by corn compared to P83P17 and no significant difference was observed between wheat tiller biomass following corn or DKS5367 (Figure 2). Wheat yield followed the same pattern of tiller biomass. Wheat following corn yield was 12% more than following P83P17. And, no difference in wheat yield was observed following either corn and DKS5367 or DKS5367 and P83P17 (Figure 2). There was no significant effect between corn and sorghum hybrids on following wheat tiller biomass and wheat yield at Rocky Mount in 2014 (Figure 3). In 2014 at Caswell, tiller biomass was not impacted by previous summer hybrids. No yield differences in wheat were observed following either sorghum hybrid. However, wheat yield was almost 10% more following corn compared to sorghum hybrids (Figure 4). As mentioned earlier, no differences were found between corn and any sorghum hybrid on following wheat tiller biomass and yield at Lower Coastal Plain in 2014. In 2015, Rocky Mount, earlier in the winter season we observed differences between tiller biomass following different summer hybrids, with greater biomass following corn than P83P17. However, later in the season, no effect was observed on the wheat yield following any of the summer hybrid (Figure 5).

There were mixed effects of summer crop hybrids on different traits following winter wheat. However, in any significant effect observed on wheat traits, there were a significant difference between corn and sorghum hybrid P83P17. At the same time, in most events showing significant effects on wheat traits, corn and sorghum hybrid DKS5367 were not significantly different. Also, in most events, neither sorghum hybrids significantly affected wheat variables. As mentioned earlier, we found P83P17 produced the greatest amount of crop residue followed by DKS5367 and finally corn. Looking at our data and initial analysis, residue was the most important factor in affecting the wheat. Therefore, data were pooled over locations, years, and hybrids. Pearson's correlation analysis was performed between different dependent variables of summer crop and wheat (Table 8). We observed significant correlations between summer crop residue for both tiller biomass and wheat yield with correlation coefficients of -0.31 and -0.30, respectively. As expected, wheat tiller biomass and wheat yield were positively correlated with correlation coefficient value of 0.29. To investigate the relationship between summer crop residue and its effect on following wheat, we pooled the summer crop residue data over summer hybrids, locations, and years and divided the summer crop residue into 4 levels: 10-15, 15-20, 20-25, and 25-30 Mg ha^{-1} and analyzed. Analysis of variance showed a significant effect of residue level on wheat yield (Table 9). Wheat planted in fields having lower levels of summer crop residue present produced significantly higher yield compared to wheat planted into greater levels of summer crop residue (table or figure). There was no significant difference observed between wheat yields with summer residues less than 20 Mg ha^{-1}, afterwards yield reduced significantly. Wheat yield was 2.93, 3.03, 2.66, and 2.56 Mg ha^{-1} following summer residues of 10-15, 15-20, 20-25, and 25-30 Mg ha^{-1}, respectively (Table 10). Analysis of variance of summer hybrid and nitrogen rates, data pooled over year and locations, shows no significant effect of summer crop (corn/sorghum) and pre-plant nitrogen applied in wheat on wheat yield (Table 11). Residue of both corn and sorghum has high C:N ratio. Soil microorganisms need more nitrogen to oxidize the residue present in the soil which can immobilized nitrogen for the next crop (USDA NRCS, 2011). Wheat planted in fields with an abundance of previous crop residue of high C:N ratio can become deficient in nitrogen and can affects its yield. It could be possible that summer crop residue with higher C:N ratio might be affecting the following wheat yield irrespective of the summer hybrid.

References:

Alsaadawi, I. S., Al-Ekelle, M., & Al-Hamzawi, M. (2007). Differential allelopathic potential of grain sorghum genotypes to weeds. *Allelopathy Journal*, *19*, 153-160.

Assefa, Y., Roozeboom, K., Thompson, C., Schlegal, A., Stone, L., & Lingenfelse, J, E. (2014). Corn and grain sorghum comparison: all things considered. Oxford, UK: Elsevier

Ben-Hammouda, M., Kremer, R. J., Minor, H. C., & Sarwar, M. (1995). A chemical basis for differential allelopathic potential of sorghum hybrids on wheat. *Journal of Chemical Ecology*, *21*(6), 775-786.

Chad, M. R., James, P. S., & Gary, M. P. 2000. Allelopathy of sorghum on wheat under several tillage systems. *Agronomy Journal*, *92*, 855–859.

Chung, I., & Miller, D. A. (1995). Allelopathic influence of nine forage grass extracts on germination and seedling growth of alfalfa. *Agronomy Journal*, *87*(4), 767-772.

Guenzi, W. D., McCalla, T. M., & Norstadt, F. A. (1967). Presence and persistence of phytotoxic substances in wheat, oat, corn, and sorghum Residues. *Agronomy Journal*, *59*(2), 163-165.

Kim, K. U., Lee, S. C., & Shin, D. H. (1993). Allelopathic effects of sorghum extract and residues on selected crops and weeds. *Korean Journal of Weed Science*, *14*, 34–41.

Kelley, K., & Sweeney, D. (2005). Tillage and urea ammonium nitrate fertilizer rate and placement affects winter wheat following grain sorghum and soybean. *Agronomy Journal*, 97 (3), 690-697.

Knowles, T. C., Hipp, B. W., Graff, P. S., & Marshall, D. S. (1993). Nitrogen nutrition of rainfed winter wheat in tilled and no-till sorghum and wheat residues. *Agronomy Journal, 85*(4), 886-893.

Koricheva, J. (1999). Interpreting phenotypic variation in plant allelochemistry: Problems with the use of concentrations. *Oecologia, 119,* 467-473.

McClure, A., Ebelhar, S., Lee, C., Nafziger, E., & Wyciskalla, T. (2008). Grain production in mid-south. http://www.utcrops.com/sorghum/sorghum_images/MidsouthGrainSorghumProd.pdf. Accessed July 29, 2020.

Putnam, A. R., & DeFrank, J. (1983). Use of phytotoxic plant residues for selective weed control. *Crop Protection, 2*(2), 173-181.

Putnam, A. R., & Duke, W. B. (1974). Biological suppression of weeds: Evidence for allelopathy in accessions of cucumber. *Science, 185*, 370-372.

Sanford, J. O., & Hairston, J. E. (1984). Effects of N fertilization on yield, growth, and extraction of water by wheat following soybeans and grain Sorghum1. *Agronomy Journal, 76*(4), 623-627.

Sanford, J. O., Myhre, D. L., & Merwine, N. C. (1973). Double cropping systems involving no-tillage and conventional Tillage1. *Agronomy Journal, 65*(6), 978-982.

Sène, M., Doré, T., & Gallet, C. (2001). Relationships between biomass and phenolic production in grain sorghum grown under different conditions. *Agronomy Journal, 93*, 49-54.

Staggenborg, S., Whitney, D. A., Fjell, D. L., & Shroyer, J. (2003). Seeding and nitrogen rates required to optimize winter wheat yields following grain sorghum and soybean. *Agronomy Journal, 95*, 253-259.

USDA-NASS] US Department of Agriculture - National Agricultural Statistics Service. (2020). Quick Stats Database. https://quickstats.nass.usda.gov/. Accessed July 23, 2020.

USDA-NRCS] National Resources Conservation Service. (2011). Carbon to Nitrogen Ratios in Cropping Systems. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd331820.pdf. Accessed July 21, 2020.

Wary, R. E., Lamond, R. E., Whitney, D. A., & Kilgore, G. L. (1994). Effects on nitrogen rates on wheat following grain sorghum, wheat, and soybeans, cherokee county, kansas. Kansas State University, Agricultural experiment station, Manhattan.

Westfall, D. G., Havlin, J. L., Hergert, G. W., & Raun, W. R. (1996). Nitrogen management in dryland cropping systems. *Journal of Production Agriculture, 9*(2), 192-199.

Weston, L., Alsaadawi, I., & Baerson, S. (2013). Sorghum Allelopathy—From ecosystem to molecule. *Journal of Chemical Ecology*, *39*, 142-153.

Zimdahl, R, L. (2004). Weed-Crop Competition: A Review. Oxford, UK: Blackwell Publishing.

Table 1. Planting and harvesting dates.

Year	Location	Sorghum/Corn		Wheat	
		Planting	Harvesting	Planting	Harvesting
2013	Rocky Mount	June 14	Oct 18	Nov 7	June 13
	Rocky Mount	May 28	Oct 22	Nov 4	June 19
2014	Caswell	May 22	Oct 7	Oct 28	June 10
	Lower Coastal Plain	May 22	Oct 7	Oct 28	June 10
2015	Rocky Mount	June 9	Oct 21	Nov 12	June 27

Table 2. One-way ANOVA results for summer crop yield of different hybrids across all locations[a].

Effect	Residue			Yield		
	df	F ratio	Prob>F[b]	df	F ratio	Prob>F
env	3	274.39	<.0001	4	514.17	<.0001
hyb	2	121.22	<.0001	2	355.31	<.0001
env*hyb	6	54.52	<.0001	8	89.89	<.0001

[a]Abbreviations: df, degrees of freedom; env, environment; hyb, summer crop hybrid.

[b]Source values lower than 0.05 are statistically significant

Table 3. Summer crop residue of different hybrids at all locations[a].

Hybrid	Rocky Mount		Caswell	LCP[a]
	2013	2014	2014	2014
	Mg ha^{-1}			
P83P17	25.1 a	21.0 a	21.2 a	18.6 a
DKS5367	25.8 a	13.9 c	15.7 b	15.6 b
DKC6067	14.5 b	16.0 b	13.2 c	13.5 c

[a]Abbreviations: LCP, Lower Coastal Plain.

Means within a column followed by the same letters are not different according to Fisher's Protected LSD test at $P \leq 0.05$.

Table 4. Summer crop yield of different hybrids at all locations[a].

Hybrid	Rocky Mount			Caswell	LCP[a]
	2013	2014	2015	2014	2014
	Mg ha^{-1}				
P83P17	7.0 c	5.5 b	1.7 b	6.5 b	5.7 b
DKS5367	9.0 a	5.1 b	0.6 c	6.0 c	4.0 c
DKC6067	8.4 b	6.3 a	4.2 a	8.2 a	10.6 a

[a]Abbreviations: LCP, Lower Coastal Plain.

Means within a column followed by the same letters are not different according to Fisher's Protected LSD test at $P \leq 0.05$.

Table 5. Two-way ANOVA results of winter wheat for different environments in NC[a].

Effect	df	Tiller biomass		Tiller % N		Wheat yield	
		F ratio	Prob>F[b]	F ratio	Prob>F	F ratio	Prob>F
env	4	76.45	<.0001	330.11	<.0001	42.87	<.0001
hyb	2	9.07	0.0002	1.00	0.3679	3.35	0.0363
env*hyb	8	2.05	0.0417	0.33	0.9547	0.35	0.9453
n-rate	3	2.86	0.0376	0.39	0.7570	1.00	0.3951
env*n-rate	12	0.98	0.4730	0.32	0.8241	0.70	0.7485
hyb*n-rate	6	0.71	0.6424	0.77	0.5943	0.89	0.5022
env*hyb*n-rate	24	0.50	0.9785	0.80	0.7309	0.90	0.6058

[a]Abbreviations: df, degrees of freedom; env, environment; hyb, summer crop hybrids; n-rate, nitrogen application rate; %, N, percent nitrogen.

[b]Source values lower than 0.05 are statistically significant

Table 6. One-way ANOVA results of winter wheat for different locations and year[a].

Year	Location	Effect	df	Tiller biomass		Tiller % N		Wheat yield	
				F ratio	Prob>F[b]	F ratio	Prob>F	F ratio	Prob>F
2013	Rocky Mount	hyb	2	7.05	0.0022	0.85	0.4331	3.60	0.0309
		n-rate	3	0.39	0.7602	1.10	0.3604	0.21	0.8868
		hyb*n-rate	6	1.15	0.3505	0.71	0.6399	0.26	0.9556
2014	Caswell	hyb	2	2.11	0.1305	0.47	0.6288	4.66	0.0135
		n-rate	3	0.38	0.7697	1.26	0.2974	2.55	0.0653
		hyb*n-rate	6	0.41	0.8663	1.66	0.1482	0.18	0.9799
	Lower Coastal Plain	hyb	2	1.21	0.3070	0.44	0.6483	0.46	0.6353
		n-rate	3	0.66	0.5800	0.07	0.9772	0.50	0.6816
		hyb*n-rate	6	0.51	0.7980	1.08	0.3833	0.56	0.7627
	Rocky Mount	hyb	2	0.71	0.4976	0.26	0.7756	1.27	0.2930
		n-rate	3	4.60	0.0085	0.41	0.7442	0.65	0.5891
		hyb*n-rate	6	0.57	0.7520	0.25	0.9554	0.48	0.8164
2015	Rocky Mount	hyb	2	7.33	0.0018	0.02	0.9784	0.47	0.6263
		n-rate	3	2.84	0.0485	0.25	0.8603	0.74	0.5343

Table 6 (Continued).

hyb*n-rate	6	0.76	0.6079	0.72	0.6365	1.17	0.3413

[a]Abbreviations: df, degrees of freedom; env, environment; hyb, summer crop hybrids; n-rate, nitrogen application rate; %, N, percent nitrogen.

[b]Source values lower than 0.05 are statistically significant

Table 7. One-way ANOVA results for wheat tiller count and n-rate on wheat yield at Rocky Mount[a].

Effect	df	Prob>F[b]	
		2013	2015
hyb	2	0.0018	0.1011
n-rate	3	0.6606	0.3089
hyb*n-rate	6	0.8419	0.8455

[a]Abbreviations: hyb, summer crop hybrid; n-rate, nitrogen application rate.

[b]Source values lower than 0.05 are statistically significant

Table 8. Correlation results between summer crop residue and different wheat factors when pooled over environments, hybrids, and nitrogen rates.

Variable	P>F[a]	Correlation Coefficient
summer crop residue vs wheat tiller count	0.0876	-0.22246
summer crop residue vs wheat tiller biomass	<0.0001	-0.30759
summer crop residue vs wheat yield	<0.0001	-0.29738
wheat tiller biomass vs wheat yield	<0.0001	0.29272

[a]Sourse values lower than 0.05 are statistically significant

Table 9. One-way ANOVA results of summer crop residue on wheat yield when summer crop residue is divided into 4 different levels when pooled over environments, hybrids, and nitrogen rates.

Effect	F ratio	P>F[a]
level	13.70	<.0001
n-rate	0.42	0.7397
level*n-rate	0.49	0.8806

[a]Sourse values lower than 0.05 are statistically significant

Table 10. Effect of summer crop residue on winter wheat yield when pooled over environments, hybrids, and nitrogen rates.

Summer crop residue (Mg ha^{-1})	Wheat yield (Mg ha^{-1})[a]
10-15	2.9344 a
15-20	3.0332 a
20-25	2.6585 b
25-30	2.5565 b

[a]Means within a column followed by the same letters are not different according to Fisher's Protected LSD test at $P \leq 0.05$.

Table 11. One-way ANOVA of residue of summer hybrids on wheat yield when pooled over environments and nitrogen rates[a].

Effect	df	F ratio	P>F[a]
hyb	2	2.58	0.0771
n-rate	3	0.49	0.6876
hyb*n-rate	6	0.54	0.7803

[a]Abbreviations; hyb, summer crop hybrids.

[b]Means within a column followed by the same letters are not different according to Fisher's Protected LSD test at $P \leq 0.05$.

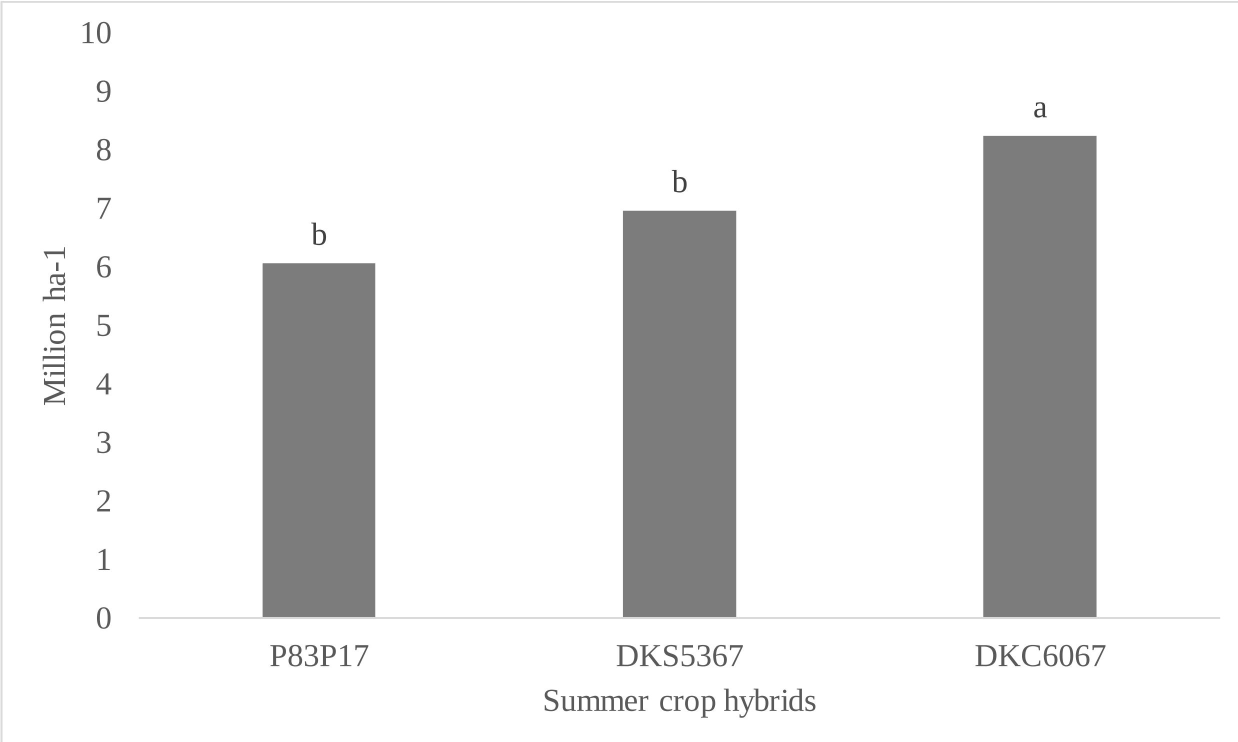

Figure 1. Wheat tiller count following summer crop hybrids at Rocky Mount in 2013.

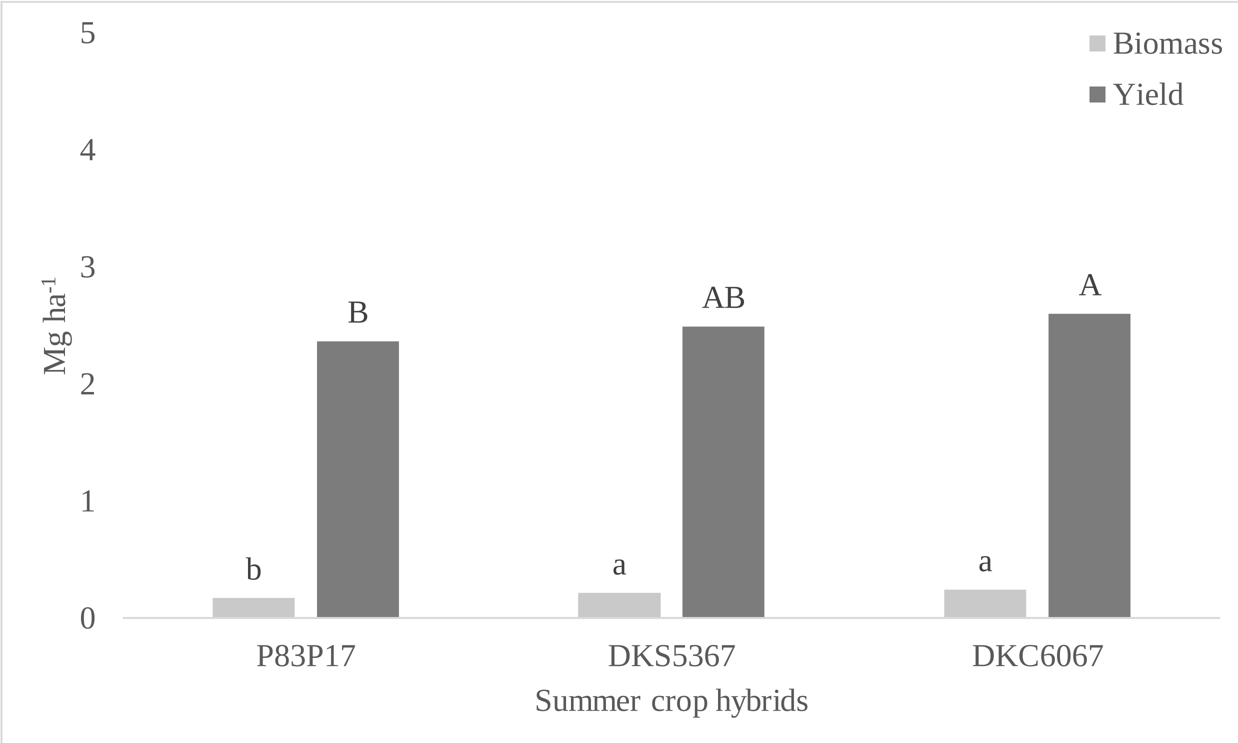

Figure 2. Wheat tiller biomass and yield following summer crop hybrids at Rocky Mount in 2013.

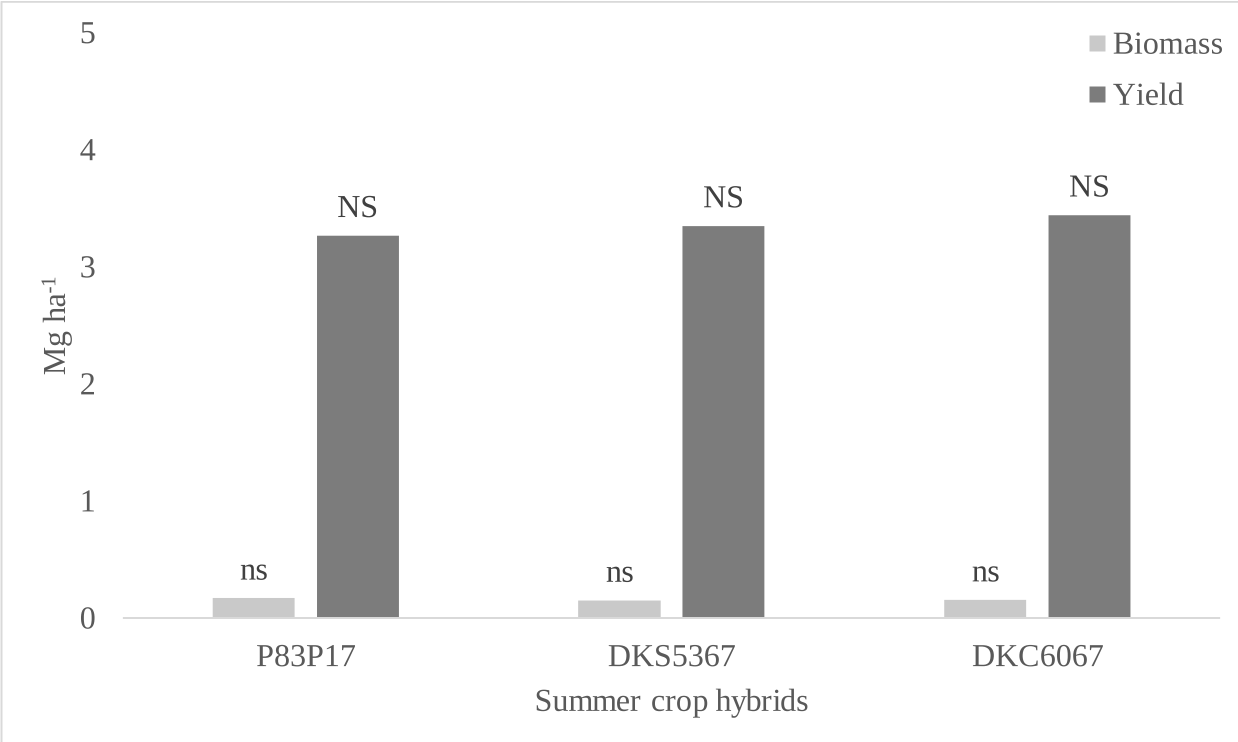

Figure 3. Wheat tiller biomass and yield following summer crop hybrids at Rocky Mount in 2014.

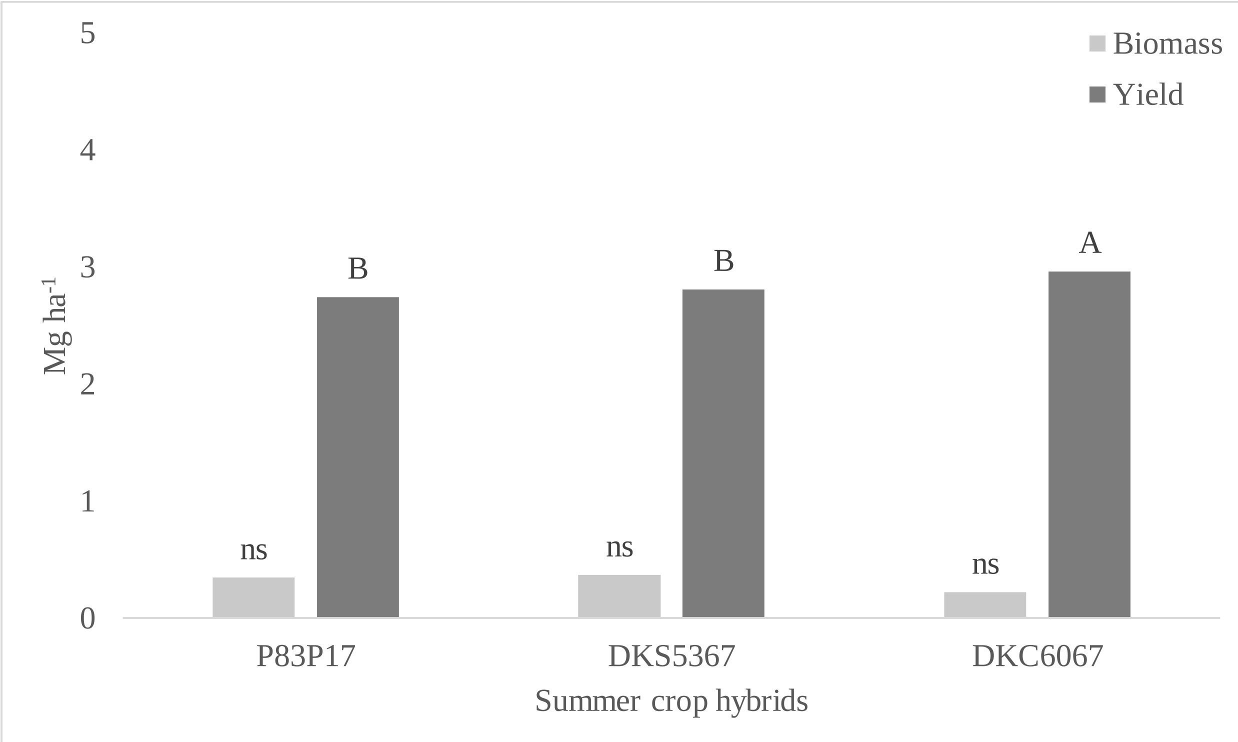

Figure 4. Wheat tiller biomass and yield following summer crop hybrids at Caswell in 2014.

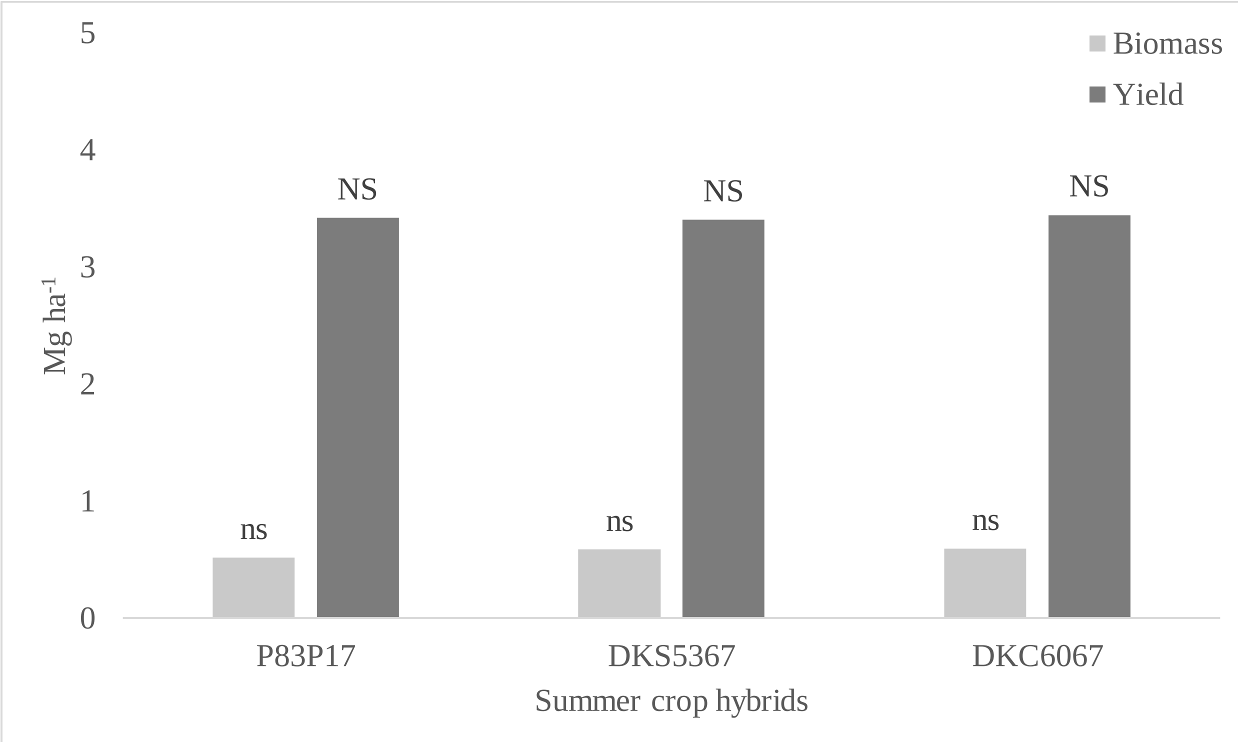

Figure 5. Wheat tiller biomass and yield following summer crop hybrids at Lower Coastal Plain in 2014.

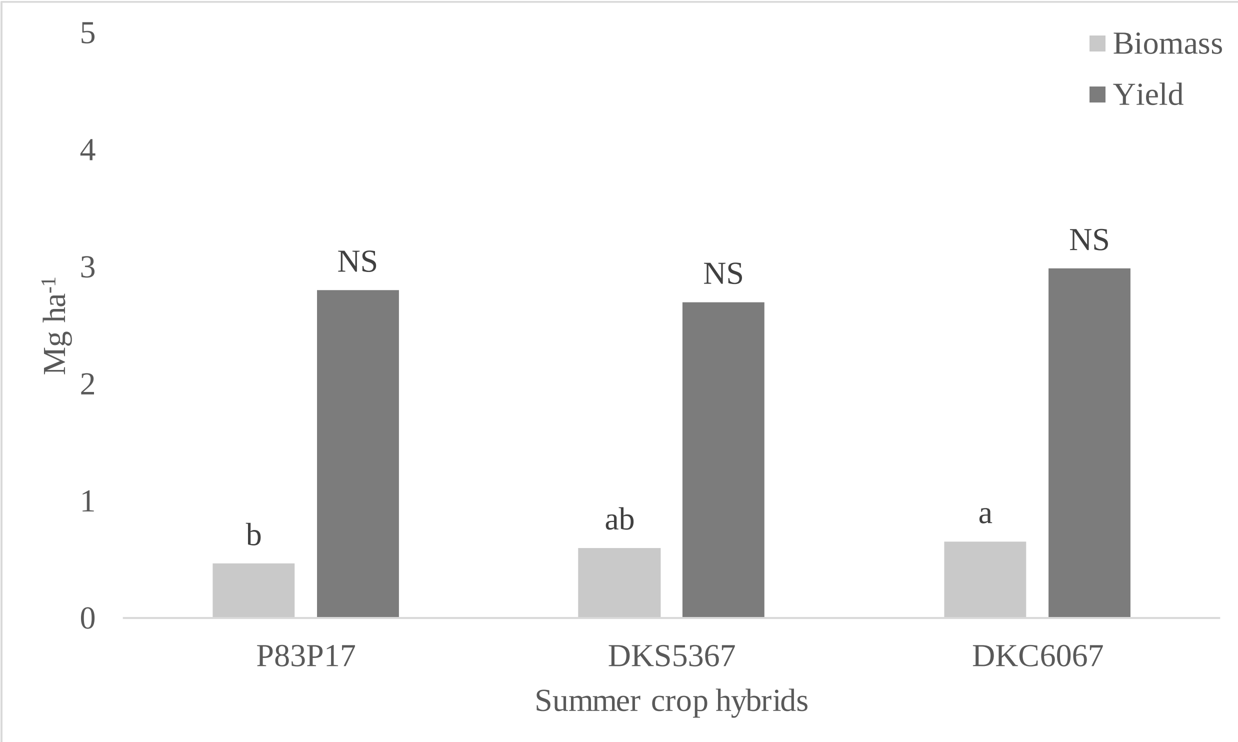

Figure 6. Wheat tiller biomass and yield following summer crop hybrids at Rocky Mount in 2015.

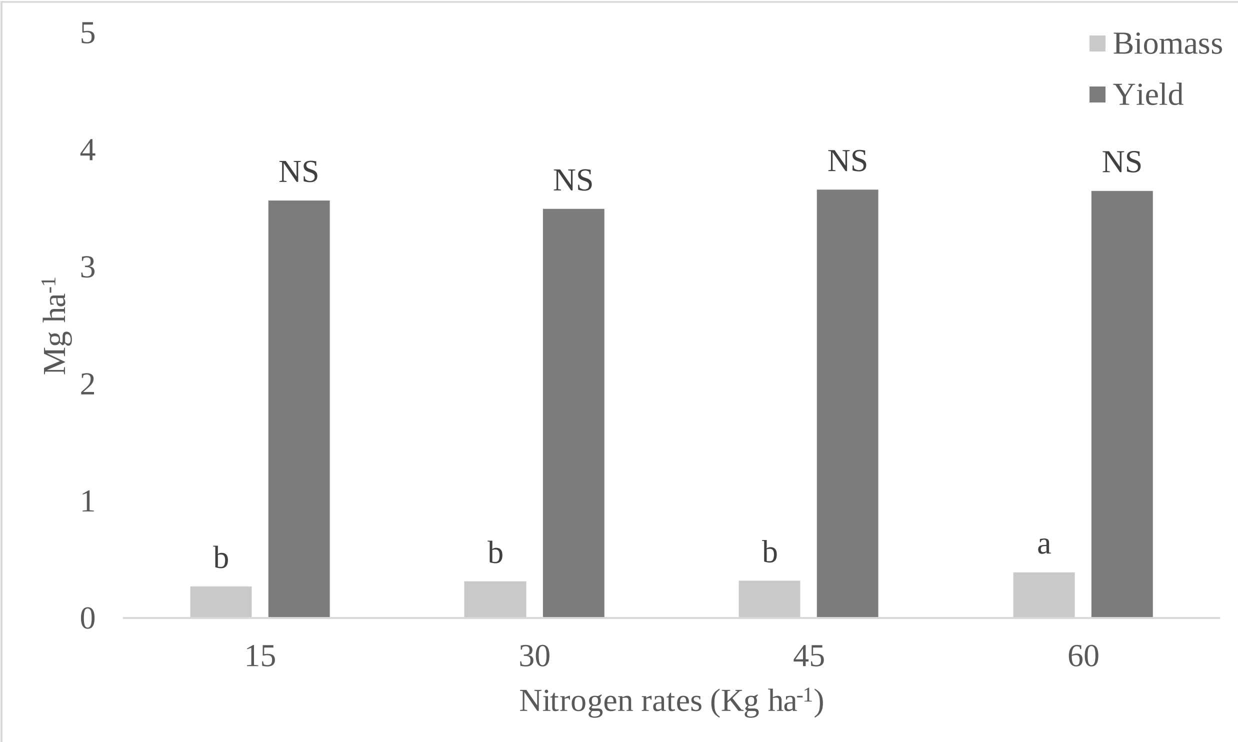

Figure 7. Wheat tiller biomass and yield as affected by pre-plant nitrogen in wheat at Rocky Mount in 2014.

CHAPTER 4

Sorgoleone (Sorghum root exudate) herbicidal activity on different weed/wheat species and various wheat groups

M. K. Bansal[1], T. E. Besançon[2], J.D. Burton[3], and W. J. Everman[1]

Graduate Research Assistant[1], Assistant Professor[2], Professor Emeritus[3], and Associate Professor[1]

[1]Department of Crop Science, North Carolina State University

Raleigh, NC 27695-7620

[2]Department of Plant Biology, Rutgers University

New Brunswick, NJ 08901

[3]Department of Horticultural Science, North Carolina State University

Raleigh, NC 27695-7620

Abstract

Sorgoleone is an important allelochemical of the oily droplets exuded from root hairs of Grain sorghum (*Sorghum bicolor* L.). It can persist in soil for longer period due to its hydrophobic nature and ability to be strongly adsorbed onto soil organic matter. It has proven herbicidal activity on many weeds and crops. Growers concerns have been raised that sorghum residues may have a detrimental effect on emergence of wheat used as a double crop in the southeastern United States. Laboratory experiments were divided in two studies: 1) weed/wheat species [(italian ryegrass (*Lolium multiflorum*), large crabgrass (Digitaria sanguinalis), large crabgrass (Digitaria sanguinalis), sicklepod (*Senna obtusifolia*), USG3251 (*Triticum aestivum* L.), and Shirley (*Triticum aestivum* L.)], 2) wheat group (soft red, soft white, hard red, and hard white), to evaluate sorgoleone activity. In both studies, sorgoleone was applied at 0 (nontreated), 0.025, 0.05, 0.10, 0.15, 0.20, and 0.30 g L^{-1}, to seeds grown in petri dishes under lab settings. Shoot length (% of nontreated) was used as measure to determine the sorgoleone activity. In weed/wheat species study, shoot length reduction was observed in all weed species. Sorgoleone activity was seen more on grass weeds than on broadleaf weeds. Italian ryegrass was most susceptible weed with growth reduction of 77% at 3 g L^{-1} of sorgoleone. At same dose, large crabgrass was second most susceptible weed showing maximum reduction of 32% followed by velvetleaf, and sicklepod with 25 % and 24% reduction in shoot length, respectively. No effect of sorgoleone was observed on wheat varieties. In wheat group study, only higher sorgoleone dose of 0.2 g L^{-1} and 0.3 g L^{-1} decreased the shoot length by almost 4% and 6%, respectively across all the groups. In between groups, hard red was the one most significantly affected compared to others. At highest dose (0.3 g L^{-1}), hard red had shoot length reduction of almost 13% compared

to 5% and 8% in soft red and hard white. Soft white did not exhibit any effect of different sorgoleone dose on shoot length.

Nomenclature: sorghum (*Sorghum bicolor* L.), italian ryegrass (*Lolium multiflorum*), large crabgrass (Digitaria sanguinalis), large crabgrass (Digitaria sanguinalis), sicklepod (*Senna obtusifolia*), USG3251 (*Triticum aestivum* L.), and Shirley (*Triticum aestivum* L.)

Key words: allelopathy, hard red, hard white, soft red, soft white, sorghum, sorgoleone, weed, wheat

Introduction

Allelopathy can be defined as the production and release of chemical substances by one species that inhibit the growth of another species (Inderjit and Duke, 2003; Weston and Duke, 2003) These allelopathic compounds released by grain crop species can play an important role in the utility of cover crops and intercropping systems where they can act as weed suppressants. Allelopathic compounds have been characterized in a number of plants, such as black walnut (*Juglans nigra*), wheat [*Triticum aestivum* L.), rice (*Oryza sativa* L.), and sorghum (Bertin et al., 2003; Inderjit and Duke, 2003; Duke et al., 2005). Most of the allelochemicals are produced or released into the neighboring environment via root exudation, leaching from leaves and other plant parts, and decomposition of plant parts. Most of these allelochemicals are secondary metabolites such phenolics, terpenoids, alkaloids, coumarins, tannins, steroids and quinones (Weir et al., 2004 and Xuan et al., 2005). Allelochemicals also play a key role in suppressing weeds in crop fields without impairing the environment. These allelochemicals are generally more environment friendly and can become good alternative to synthetic herbicides (Macias et al., 2007).

Sorghum is an important cereal grain crop grown throughout the world. Sorghum is known to have allopathic effect on number of crops and weeds. Allelopathic effect of sorghum was first observed in crops grown in rotation with sorghum (Breazeale, 1924) and later confirmed in several studies (Panasiuk et al., 1986; Putnam et al. 1983; Forney et al. 1985; and Einhellig and Rasmussen 1989. Sorghum species have been reported to produce number of phytotoxins which are exuded from their root systems, leaching from leaves, and other plant parts and played a role in the allelopathic potential of this species (Einhellig, 1996).

‘Sorgaab’(water extract of mature sorghum plants after being soaked in water for 24 h) when sprayed as an herbicide reduced weed dry weight. The effect of Sorgaab has been evaluated to control weeds in various crops like wheat, maize (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), mungbean (*Vigna radiata* L.). Studies demonstrates that weed density of various weed species such as white goosefoot (*Chenopodium album)*, littleseed canarygrass (*Phalaris minor)*, wild oat (*Avena fatua)*, field bidweed (*Convolvulus arvensis)*, and toothed dock (*Rumex dentatus)*, has been reduced when sorgaab is applied as foliar application (Bhatti et al., 2000; Cheema and Khaliq, 2000; Cheema et al.,2004). Cheema and Khaliq (2000) used sorgaab as herbicide in wheat to control weeds. They also observed the reduction in weed biomass when sorghum stalks were incorporated in soil. When sorghum was incorporated in soil as green manure it significantly suppresses the weed population in subsequent alfalfa [*Medicage sativa* L.] crop (Forney et al., 1985). A lab study, done by Guenzi et al (1967), found that root and shoot growth of wheat was inhibited when seeds were soaked in water extracted from roots and stalks of sorghum for 6 hours and allowed to grow in petri dishes.

Netzly and Butler (1986) isolated six compounds belonging to the quinone class of organic compounds from droplets exuded by sorghum root hairs. The exudates caused 85% inhibition of root elongation in lettuce (*Lactuca sativa* L.) but did not affect corn. Recent work identified, Sorgoleone (2-hydroxy-5-methoxy-3-[(Z,Z)-8’,11’,14’-pentadecatriene]-p-benzoquinone) a main component of exudate produced in the root hairs of sorghum species, is responsible for the weed inhibiting properties of sorghum often observed in the field ((Czarnota et al., 2001; Dayan et al., 2007 Dayan et al. 2010; Erickson et al. 2001; Rimando et al., 2003). Sorghum starts producing sorgoleone through root hairs shortly after the radicle emergence (Czarnota et al., 2003a). It is exuded dynamically at the tip of the root hairs as oily droplets that are released directly in the soil. Sorgoleone production is a continuous process if root hairs are functional and exudates don't accumulate on root tip and removed constantly (Dayan et al., 2009). The fact that sorgoleone is released from the roots of sorghum continually during the growing season may prolong the presence of sorgoleone in soil (Weidenhamer, 2005; Dayan, 2006; Dayan et al., 2009). Laboratory studies have confirmed several modes of action to explain herbicidal properties of sorgoleone. Nimbal et al. (1996) reported that sorgoleone acts similar to PSII-inhibitor such as atrazine by binding to the QB-binding niche on the D1 protein and inhibiting photosystem II. But, Dayan et al. (2009), did not find any cross-resistance when testing sorgoleone sensitivity of wild and atrazine-resistant types of redroot pigweed (*Amaranthus retroflexus* L.), suggesting that atrazine and sorgoleone belong to two different families of PSII-inhibitors. Hejl and Koster (2004) observed a significant decrease of plasma membrane H^+-ATPase with increasing sorgoleone dose, leading to disturbance in root metabolism. Sorgoleone has also been found to inhibit 4-hydroxyphenylpyruvate dioxygenase (4-HPPD), causing reduction of the plastoquinone and, consequently, carotenoids pool, and resulting in foliage bleaching of mouse-ear cress [*Arabidopsis thaliana* (L.) Heynh.] (Meazza et al. 2002). Uddin et al., 2009, showed broadleaf weed species were more susceptible than grass weed species when treated with sorghum exudate. Shoot growth reduction of 70-80% was noticed in broadleaf weeds compared to grass weeds. They reported that false cleavers (*Galium spurium* L.), redroot pigweed, curly dock (*Rumex crispus* L.), and lambsquarters (*Chenopodium album*) were the most susceptible among all weed species. Sorgoleone effect on root development of other weed species decreases with time. When weeds were grown in soil containing sorgoleone, it had little effect on root development while still affecting shoot growth after 3 weeks. Previous studies have been done on different weeds and crops, but less work is done specifically on different types of wheat and other weed species.

Therefore, the objective of this study was to evaluate the effect of sorgoleone on shoot length of different grass weeds, broadleaf weeds, and different types of wheat group.

Materials and methods

Two separate laboratory studies were conducted to evaluate the effect of sorgoleone on shoot length of different wheat varieties and weed species. These studies shared similar material preparation methods which are explained followed by study specific methods.

Root Production. Germination frames (28 x 43 cm) were built prior to sorghum seeding. Frames were made from four Bailey sash sections (C.R. Laurence Co., Los Angeles, CA) cut to the proper length and assembled. A piece of aluminum window screen (New York Wire Co., Mt. Wolf, PA) was then cut to length and put in place with a spline inserted into the spline channel. For root collection, approximately 200 g of sorghum seeds were surface sterilized to prevent fungal development during the root production phase by soaking in a 20% sodium hypochlorite solution for 15 min according to the methodology detailed by Czarnota et al. (2003b). Seeds were subsequently removed from the solution and rinsed under a continuous flow of distilled cold water for 10 min. A double layer of cheesecloth was laid on the screen (28 x 43 cm) and humidified under a flow of cold tap water prior to seeding. The screen was then oriented vertically for five min to drain the excess water. Sorghum seeds were then uniformly spread on the cheesecloth. A second double layer of cheesecloth, previously wetted, was laid on top to form a sandwich enclosing the seeds. Screens were then placed in a 10 L nursery vented tray (Kadon Corp., Dayton, OH) on the bottom of which was placed a moistened layer of Vattex-P capillary mat (Hummert International, Earth City, MO). A layer of Weed-X landscape fabric (Dallen Products Inc., Knoxville, TN) was placed between the screen and the capillary mat. The tray containing the germination screen was then placed in a 14 L nursery solid tray (Kadon Corp., Dayton, OH 45439) filled with tap water. The water level was then raised to reach the bottom of the 10 L tray so that the capillary mat remained moist. Trays were then covered with a 122 x 51 cm black seedling heat mat (Hydrofarm Inc., Petaluma, CA) to keep seedlings under darkness and at a temperature of 27°C. Water within the 14 L tray was monitored daily and adjusted to maintain its initial level (excerpt from Thierry Besancon, 2015).

Sorgoleone production. The collection of the oily droplets exuded from the root hairs of sorghum, hereafter referred to as ‘root exudate’, was adapted from a procedure developed by Czarnota et al. (2003b). Seeds were allowed to germinate and grow on the capillary mat system for seven days. During this time, the root system developed through the mesh of the screen and completely covered the bottom side of the screen. Seven days after seeding for cultivated sorghum cultivars, seedling roots were shaved from the screen with a single-edge razor blade and placed in a 1 L beaker. 500 mL of methylene chloride acidified with 0.25% acetic acid was then added to the beaker to extract root exudate by dissolving it. Roots remained in methylene chloride for approximately two min to let sufficient time for sorgoleone extraction to take place (LA Weston, personal communication). Roots were removed, allowed to dry for five min at room temperature, and weighed to determine fresh weight. The remaining methylene chloride crude extract was then decanted through a fluted glass funnel lined with Whatman No 42 filter paper to remove root debris. The filtrated mixture was transferred to a 1 L round-bottom flask and evaporated to dryness using a Büchi® rotary evaporator model R-215 (Büchi Labortechnik AG, Flawil, Switzerland) with water bath at 40°C. The residual dry extract appeared as a golden oily substance remaining on the inside of the flask after complete methylene chloride evaporation. Dry extract was then re-suspended with 2 mL of methylene chloride and transferred with a glass pipette to a pre weighed 40 mL amber glass vial. This procedure was repeated three times to remove any remaining dry extract from the round-bottom flask. The contents of the amber glass vial were concentrated under N2 flow to complete dryness. The vial was subsequently flooded with nitrogen and tightly capped with a PFTE lined cap. Dry weight of the methylene chloride extract was obtained separately for each replicate sample by weighing the vial containing the dry extract with a precision scale (Model AE160, Mettler-Toledo, Columbus, OH) and subtracting the weight of the empty vial. The dry extract was finally stored at -20°C until experiment is conducted (Methodology used by Thierry Besancon, 2015).

Sorgoleone inhibition studies. The study was conducted in two experiments. Seeds of Italian ryegrass (*Lolium multiflorum*), large crabgrass (*Digitaria sanguinalis*), sicklepod (*Senna obtusifolia*), Velvetleaf (*Abutilon theophrasti*), and 2 wheat varieties Shirley (*Triticum aestivum* L.) and USG3251 (*Triticum aestivum* L.) were used to investigate the effect of sorgoleone on various weed species and two commonly planted wheat varieties in North Carolina. A second, separate study to investigate the effect on varieties within different wheat groups used five wheat varieties from each of 4 groups (hard red, hard white, soft red, and soft white) (Table 1).

The following methods for both studies are identical. All work was conducted in a sterile environment under a laminar flow hood. Equipment used in the studies were sterilized using 70% ethanol solution before use. Before germinating, the seeds were surface sterilized with 5% sodium hypochlorite solution for 1 min. Seeds were then rinsed twice with sterilized water to remove the excess sodium hypochlorite. Germination paper was cut to fit 205 cm^2 squared culture-growth plates (Corning, Corning, NY, USA) and moistened with deionized water. 15 g of seed were spread uniformly on germination paper and covered with lid and sealed using the 6.5 cm PM-992 parafilm (Bemis, Oshkosh, WI, USA). Plates were put under laminar flow hood at room temperature. Seeded plates were inspected for germination. At the onset of germination, 0.8% w/v of agar molecular genetic powder (Fishers Scientific, Hampton, NH, USA) was added to seven volumetric flasks with required amount deionized water to make final volume of 450 ml (Table 2). Flasks were then covered with aluminum foil and placed into autoclave-able water-bath trays and subjected to autoclave cycle at 123ºC for 30 min at 103-130 kPa (Burke et al. 2006). After agar solutions were allowed to cool to 45°C, 10 mL of sorgoeone stock solutions is added to each flask at dose of 0 (nontreated), 0.025, 0.05, 0.10, 0.15, 0.20, and 0.30 g L^{-1}. Stock solutions were made by dissolving sorgoleone in methanol the same day as agar preparation (Table 2). Flasks were agitated by gentle swirling and then, using a 5-ml pipette, 10 ml of solution was transferred to each petri-dish of size 20 x100 mm (Corning, Corning, NY, USA). Each dose was replicated in three petri-dishes. Once the agar solution had sat and cooled to a hardened gel (30 min), twenty pre-germinated seed exhibiting visible coleoptile or radicle lengths less than 1 mm were removed from the germination plates with precision forceps and placed onto the hardened solution. Petri-dishes were closed, sealed with parafilm, labeled, and arranged in completely randomized block pattern with three replications in growth chamber at night/day temperature of 18/24ºC. 10 days after treatment, petri dishes were opened, and each seed was measured for coleoptile or shoot length and data was converted into % of nontreated by using following formula:

Shoot length (% of nontreated) = (Observed shoot length/Nontreated shoot length) x 100

All data collected in each experiment were subjected to ANOVA using the PROC GLIMMIX procedure in SAS 9.4 (SAS Institute, Inc., Cary, NC) to test the significance of the fixed effects: experimental run, weed species/wheat varieties/wheat type, treatment (sorgoelone dose), and their interactions. Replications in the model were considered random effects. Mean comparisons were performed using Fisher's Protected LSD test when F-values were statistically significant ($P \leq 0.05$). Only, data on shoot length (% of nontreated) for grass weeds and broadleaf weeds from dose–response assays were regressed over sorgoleone doses using a three-parameter log-logistic model in R software (Ritz et al. 2015; Seefeldt et al. 1995):

$$y = \{d / 1 + \exp[b(logx - loge)]\}$$

where y represents the shoot length (% of nontreated), d is the upper limit, b is the slope of each curve, e is the sorgoleone dose needed for 50% response (i.e., 50% shoot length reduction referred as GR_{50} values), and x is the sorgoleone dose.

Results and Discussion

Weed/wheat species study. Initial analysis of the data showed no significant difference among experimental runs (Table 3). Data was pooled over run and analyzed again with remaining factors. High F statistics observed in ANOVA suggests a significant influence of species and sorgoleone dose independently as well as their interaction on shoot length (Table 4). Among all the weed and wheat species, shoot length of weeds were significantly reduced compared to wheat. Researchers in the past have studied the herbicidal activity of sorgoleone on different type of weeds (Czarnota et. al, 2001, Dayan et. al., 2009, Nimbal et. al., 1996, Uddin et. al., 2009, 2013). They found treating the weeds with sorgoleone reduced the germination and shoot growth in number of weed species under both laboratory, greenhouse, and field conditions (Nimbal et. al., 1996, Uddin et. al., 2009, 2013). After 10 days of sorgoleone treatment shoot length of weeds were reduced significantly in our study (Figure 1 and 2). In hydroponic assays, conducted by

Nimbal et. al., (1996), sorgoleone was phytotoxic to both broadleaf and grass weed species at concentrations as low as 10µM. Similarly, we found that shoot length of weed species was visibly reduced at the lowest dose of sorgoleone (0.25 g L^{-1}) tested compared to the nontreated control (Figure 1 and 2).

Uddin et. al., (2009, 2013) observed when sorgoleone was applied as a pre-emergence or post-emergence herbicide on different weed species, broadleaf weeds were more susceptible than grass weeds. However, under laboratory conditions, when seeds of barnyardgrass and velvetleaf were grown in petri dishes and treated with sorgoleone, radicle length of barnyardgrass was reduced more than velvetleaf at a sorgoleone dose of higher than 250 µM (Nimbal et. al., 1996). Results of our study indicate that grass weeds were more susceptible than broadleaf weeds under lab conditions which could be attributed to the fact that small seeded species are more susceptible than large seeded species (Uddin et. al, 2013). Italian ryegrass and large crabgrass shoot reduction of 77% and 32%, respectively, at the maximum (3 g L-1) sorgoleone dose tested (Figure 1). Shoot length of Italian ryegrass decreased exponentially with increasing dose of sorgoleone. A similar pattern was observed for large crabgrass (Figure 1). As mentioned earlier, in our study we found, broadleaf weeds were less susceptible than grass weeds. Velvetleaf showed a steep initial decline of 25% in shoot length from 0 to 0.025 g L^{-1}, leveling off with no statistically significant difference in response with increasing dose thereafter (Figure 2). Whereas, shoot length of sicklepod declined gradually as sorgoleone dose increased from <1 g L-1 to >1.5 g L^{-1}, with a maximum reduction of 24% observed at a sorgoleone dose of 2 g L^{-1} (Figure 2).

As mentioned earlier, no significant effect of sorgoleone was observed on wheat varieties tested in this study (Figure 3). In support to our findings, when studied the effect of sorgoleone on crops: barley, wheat, corn, soybean, tomato, and Chinese cabbage, Uddin et. al., (2013) found that activity of sorgoleone on crops were lower compared to weeds. The dose of sorgoleone to reduce shoot growth to fifty percent (GR_{50}) was calculated (Table 5). Considering GR_{50} values it showed that broadleaf species required a higher dose of sorgoleone to reach GR_{50} which ranged from 2.50 to 8.10 g L^{-1} compared to grass species range of 0.08 to 1.08 g L^{-1} (Table 5). Among the four weeds used in this study, Italian ryegrass was most susceptible to sorgoleone with GR_{50} value of 0.08 g L^{-1} and velvetleaf was the least susceptible to sorgoleone with GR_{50} value of 8.1 g L^{-1} (Table 5). The results of this study reveal that sorgoleone inhibited weed species and wheat species showed tolerance to it.

Italian ryegrass is among the most common and most troublesome weeds of wheat across the southern United States (Grey et. al., 2012)). The germination and emergence of Italian ryegrass typically coincides with that of wheat (Hoveland et al. 1976). Liebl and Worsham (1987) found that growth rate and response to nutrients were both greater for Italian ryegrass than for winter wheat. Italian ryegrass also is a prolific seed producer, capable of producing several thousand seeds per plant. Italian ryegrass density of 20 plants per square foot have been found to reduce wheat grain yields in by 38% (Appleby and Brewster, 1992). Studies in North Carolina reported an average yield reduction of 5% for every 10 Italian ryegrass plants per square meter (Liebl and Worsham 1987). Italian ryegrass can reduce wheat yield by 50% or more if left uncontrolled (Brewster et al. 1977). Furthermore, Italian ryegrass is an especially important problem in wheat production due to the widespread presence of herbicide resistant ryegrass populations. Given the potential for yield loss due to interference and widespread resistance, effective control is critical in wheat. Results of our lab study are encouraging towards suppressing the shoot length of Italian ryegrass at different concentrations sorgoleone and it can make sorghum as good alternate to other crops in double crop wheat. However, future additional research needs to perform under field conditions to see the sorgoleone effect on Italian ryegrass and wheat yield.

Wheat group study. Initial analysis of data showed no significant difference for shoot length between experimental runs (Table 6). Therefore, data were pooled over experimental run and analyzed again with remaining factors. A significant influence of wheat varieties and sorgoleone dose independently, as well as their interaction, on shoot length was observed (Table 7). Among all 20 wheat varieties, two wheat varieties Thunder CL and Xerpha showed a significant increase in shoot length compared to the nontreated control (Table 8). This could be possible due to the phenomenon of hormesis, where instead of being toxic allelochemicals can have stimulatory effect at lower dose (Dayan and Duke, 2009). The shoot length of 12 varieties used in this study were not significantly different compared to the nontreated control at all doses evaluated (Table 8). We observed shoot length reduction in only 6 out of 20 varieties used in this study compared to nontreated control. Varieties: Clara, Everest, Puma, Larry, Joe, and Zenda, shown shoot length reduction of 4 %, 6%, 7%, 7%, 8%, and 8 %, respectively when treated with sorgoleone across all doses (Table 8). In 2013, Uddin et. al. observed sorgoleone applied preemergence on different crops: barley, wheat, corn, soybean, tomato, and Chinese cabbage affects the shoot biomass of all. However, they found the reduction in shoot length in crops was much lower compared to weeds used in their study. Most varieties affected by sorgoleone in our study belonged to the hard red wheat group, four out of six, with one each of hard white and soft white (Table 8).

Since the majority of significantly affected varieties belonged to one type of group, we decided to analyze the data by wheat group pooled over varieties (Table 9). There was significant impact of sorgoleone dose on shoot length. Initially, no difference in shoot length was observed in all groups for sorgoleone doses less than 0.15 g L^{-1}. With increasing dose of sorgoleone greater than 0.15 g L-1, shoot length was reduced. Shoot length reductions of 4% and 6%, at sorgoleone dose of 0.2 g L^{-1} and 0.3 g L^{-1}, respectively, were observed across all varieties compared to the nontreated control (Table 9). Supporting our results, Uddin et, al., (2013) found that wheat shoot biomass was reduced by 2.2% and 8.5%, when sorgoleone was applied preemergence in greenhouse experiments at rates of 0.2 kg a.i ha^{-1}, and 0.4 kg a.i ha^{-1}, respectively. These rates correspond to concentration of 0.2 g L^{-1} and 0.4 g L^{-1}. Although the dependent variable in our study was different from theirs, both variables are related to each other as longer shoot length produce more biomass.

Shoot length response to sorgoleone across all wheat groups was also significant. Among the four wheat groups, soft white, soft red, and hard white, were not significantly different from each other (Figure 5). Only, hard red wheat was significantly different from other type of wheat groups (Figure 5). Sorgoleone decreased the shoot length by 6% in hard red wheat compared to the nontreated control. The interaction between sorgoleone dose and wheat group was also significant (Table 10). We did not observe any significant effect between different doses of sorgoleone applied in soft white wheat (Table 11) . In soft red, no significant difference in shoot length was observed until the highest level of sorgoleone dose (0.3 g L^{-1}) was applied with a similar response being observed in hard white wheat (Table 11). Shoot length of soft red hard white was reduced by 5% and 8%, respectively, at a sorgoleone concentration of 0.3 g L^{-1} (Table 11). These results were very similar to the study conducted by Uddin et. al, (2013).

Among all 4 groups, hard red wheat was most affected by sorgoleone. Shoot length in hard red group decreased slowly as the dose of sorgoleone increased. No difference in shoot length was observed up to a dose of 0.1 g L^{-1}. Once the sorgoleone dose reached 0.15 g L^{-1}, an

8% reduction in shoot length was observed compare to the nontreated control (Table 11). Statistically, no difference was observed between 0.15 g L^{-1} and 0.2 g L^{-1}, and 0.2 g L^{-1} and 0.3 g L^{-1}, although shoot length was reduced by 10% and 13% when sorgoleone was applied at 0.2 g L^{-1} and 0.3 g L^{-1}, respectively (Table 11). Results of our study indicate that hard red wheat its more susceptible than soft white under lab conditions. Future research could focus on factors which make hard red wheat more susceptible to sorgoleone than other groups.

References

Appleby, A. P., & Brewster, B. D. (1992). Seeding arrangement on winter wheat (triticum aestivum) grain yield and interaction with italian ryegrass (lolium multiflorum). *Weed* Technology, *6*(4), 820-823.

Bertin, C., Yang, X., & Weston, L. A. (2003). The role of root exudates and allelochemicals in the rhizosphere. *Plant and Soil, 256*(1), 67-83.

Breazeale, J. F. (1924). The injurious after-effects of Sorghum1. *Agronomy Journal, 16*(11), 689-700.

Brewster, B. D., Appleby, A. P., & Spinney, R. L. (1977). Control of italian ryegrass and wild oats in winter wheat with HOE 23408. *Agronomy Journal, 69*(6), 911-913.

Czarnota, M., Paul, R., Dayan, F., Nimbal, C., & Weston, L. (2009). Mode of action, localization of production, chemical nature, and activity of sorgoleone: A potent PSII inhibitor in sorghum spp. root exudates. *Weed Technology, 15*, 813-825.

Dayan FE, Duke SO (2009) Biological activity of allelochemicals. In: *Plant-Derived Natural Products*, 361-384.

Dayan, F.E., Weidenhamer, J.D., Howell, J., 2009. Dynamic root exudation of sorgoleone and its in planta mechanism of action. *Journal of Experimental Botany,60*(7), 2107-2117.

Dayan, F. E., Rimando, A. M., Pan, Z., Baerson, S. R., Gimsing, A. L., & Duke, S. O. (2010). Sorgoleone. *Phytochemistry, 71*(10), 1032-1039.

Dayan, F., Watson, S., & Nanayakkara, N. (2007). Biosynthesis of lipid resorcinols and benzoquinones in isolated secretory plant root hairs. *Journal of Experimental Botany, 58*, 3263-72.

Duke, S., Belz, R., Baerson, S., Pan, Z., Cook, D., & Dayan, F. (2005). The potential for advances in crop allelopathy. *Outlooks on Pest Management, 16*, 64-68.

Einhellig, F. A., & Rasmussen, J. A. (1989). Prior cropping with grain sorghum inhibits weeds. *Journal of Chemical Ecology, 15*(3), 951-960.

Erickson, J., Schott, D., Reverri, T., Muhsin, W., & Ruttledge, T. (2001). GC-MS analysis of hydrophobic root exudates of sorghum and implications on the parasitic plant striga asiatica. *Journal of Agricultural and Food Chemistry, 49*, 5537-5542.

Forney, D. R., Foy, C. L., & Wolf, D. D. (1985). Weed suppression in no-till alfalfa (medicago sativa) by prior cropping of summer-annual forage grasses. *Weed Science, 33*(4), 490-497.

Grey, T., Cutts, G., Sosnoskie, L., & Culpepper, A. (2012). Italian ryegrass (L

olium perenne) control and winter wheat response to POST herbicides. *Weed Technology, 26*, 644-648.

Hejl, A. M., & Koster, K. L. (2004). The allelochemical sorgoleone inhibits root H+-ATPase and water uptake. *Journal of Chemical Ecology, 30*(11), 2181-2191.

Hoveland, C. S., Buchanan, G. A., & Harris, M. C. (1976). Response of weeds to soil phosphorus and potassium. *Weed Science, 24*(2), 194-201.

Inderjit, & Duke, S. O. (2003). Ecophysiological aspects of allelopathy. *Planta*, *217*(4), 529-539.

Liebl, R., & Worsham, A. D. (1987). Interference of italian ryegrass (lolium multiflorum) in wheat (triticum aestivum). *Weed Science*, *35*(6), 819-823.

Macías, F., Molinillo, J., Varela, R., & Galindo, J. (2007). Allelopathy - A natural alternative for weed control. *Pest Management Science, 63*, 327-348.

Netzly, D. H., & Butler, L. G. (1986). Roots of sorghum exude hydrophobic droplets containing biologically active Components. *Crop Science, 26*(4), 775-778.

Netzly, D. H., Riopel, J. L., Ejeta, G., & Butler, L. G. (1988). Germination stimulants of witchweed (striga asiatica) from hydrophobic root exudate of sorghum (sorghum bicolor). *Weed Science*, *36*(4), 441-446.

Nimbal, C. I., Pedersen, J. F., Yerkes, C. N., Weston, L. A., & Weller, S. C. (1996). Phytotoxicity and distribution of sorgoleone in grain sorghum germplasm. *Journal of Agricultural and Food Chemistry, 44*(5), 1343-1347.

Panasiuk, O., Bills, D. D., & Leather, G. R. (1986). Allelopathic influence ofSorghum bicolor on weeds during germination and early development of seedlings. *Journal of Chemical Ecology, 12*(6), 1533-1543.

Putnam, A. R., Defrank, J., & Barnes, J. P. (1983). Exploitation of allelopathy for weed control in annual and perennial cropping systems. *Journal of Chemical Ecology, 9*(8), 1001-1010.

Rimando, A., Dayan, F., & Streibig, J. (2003). PSII inhibitory activity of resorcinolic lipids from sorghum bicolor. *Journal of Natural Products*, *66*, 42-5.

Ritz, C., Baty, F., Streibig, J. C., & Gerhard, D. (2015). Dose-response analysis using R. *PloS One, 10*(12), e0146021.

Seefeldt, S. S., Jens, E. J., & Patrick Fuerst, E. (1995). Log-logistic analysis of herbicide dose-response relationships. *Weed Technology, 9*(2), 218-227.

Uddin, M. R., Kim, Y., Park, S. U., & Pyon, J. (2009). Herbicidal activity of sorgoleone from grain sorghum root exudates and its contents among sorghum cultivars. *Korean Journal of Weed Science, 29*, 229-236.

Uddin, M. R., Park, S. U., Dayan, F., & Pyon, J. (2013). Herbicidal activity of formulated sorgoleone, a natural product of sorghum root exudate. *Pest Management Science, 70*(2), 252-257.

Weidenhamer, J. (2005). Biomimetic measurement of allelochemical dynamics in the rhizosphere. *Journal of Chemical Ecology, 31*, 221-36.

Weir, T. L., Park, S., & Vivanco, J. M. (2004). Biochemical and physiological mechanisms mediated by allelochemicals. *Current Opinion in Plant Biology, 7*(4), 472-479.

Weston, L., & Duke, S. (2003). Weed and crop allelopathy. *Critical Reviews in Plant Sciences, 22*, 367-389.

Xuan, T. D., Tawata, S., Khanh, T., & Chung, I. (2005). Biological control of weeds and plant pathogens in paddy rice by exploiting plant allelopathy: An overview. *Crop Protection, 24*, 197-206.

Table 1. Different wheat group and varieties used in wheat group study.

Group	Variety
Soft white	Jasper
	Ovation
	Xerpha
	Otto
	Puma
Soft red	Dynagro 9811
	Syngenta 547
	Agrimaxx 415
	Progeny turbo
	Seedway 64
Hard red	Zenda
	Joe
	Larry
	Everest
	Wb4458
Hard white	Monument
	Danby
	Clara
	Thunder CL
	Antero

Table 2. Sorgoleone dose and measured volume of agar and water used to prepare treatment of six species for one replication in both studies[a].

Sorgoleone dose (g L^{-1})	Sorgoleone 4.6% WP (g)	Stock solution (mL)	Agar (g)	Water (mL)	Final volume (mL)
0.000	0.000	10	3.60	436.40	450
0.025	0.245	10	3.53	436.22	450
0.050	0.489	10	3.47	436.04	450
0.100	0.978	10	3.34	435.68	450
0.100	1.467	10	3.21	435.33	450
0.200	1.957	10	3.08	434.97	450
0.300	2.935	10	2.81	434.25	450

[a]Abbreviations: g L^{-1}, gram per liter, WP, wettable powder; g, gram; mL, milliliter.

Table 3. Two-way ANOVA results of weed/wheat species study for shoot length (% of nontreated) of different species[a].

Effect	df	F ratio	Prob>F[b]
spp	5	304.26	<.0001
dose	6	74.18	<.0001
spp*dose	30	21.97	<.0001
run	1	0.00	0.9494
spp*run	5	3.94	0.0019
dose*run	6	1.13	0.3430
spp*dose*run	30	1.25	0.1817

[a]Abbreviations: df, degrees of freedom; spp, species.

[b]Source values lower than 0.05 are statistically significant

Table 4. One-way ANOVA results of weed/wheat species study for shoot length (% of nontreated) of different weed/wheat species with data pooled across experimental replications[a].

Effect	df	F ratio	Prob>F[b]
spp	5	282.86	<.0001
dose	6	68.96	<.0001
spp*dose	30	20.42	<.0001

[a]Abbreviations: df, degrees of freedom; spp, species.

[b]Source values lower than 0.05 are statistically significant

Table 5. Regression parameters of weed/wheat species study for different species[a].

Species[a]	Regression parameters[b]		
	d	b	GR_{50}
IR	102.09 (2.54)	1.15 (0.08)	0.08
LC	99.59 (2.69)	0.65 (0.15)	1.08
SP	100.46 (3.33)	0.50 (0.21)	2.50
VL	99.94 (3.52)	0.30 (0.08)	8.10
USG3251	n/a	n/a	n/a
Shirley	n/a	n/a	n/a

[a]Abbreviations: IR, italian ryegrass; LC, large crabgrass; SP, sicklepod; VL, velvetleaf.

[b]Regression equation $y = \{d / 1 + \exp[b(\log x - \log e)]\}$, where y represents the shoot length (% of nontreated), d is the upper limit, b is the slope of each curve, e is the sorgoleone dose needed for 50% response GR_{50} is the effective dose (g L^{-1}) of sorgoleone for 50% shoot length or growth reduction.

Table 6. Two-way ANOVA results of wheat group study response to sorgoleone dose[a].

Effect	df	F ratio	Prob>F[b]
var	19	6.29	<.0001
dose	6	6.93	<.0001
var*dose	114	1.92	<.0001
run	1	2.03	0.1548
var*run	19	1.60	0.0508
dose*run	6	0.23	0.9686
var*dose*run	114	0.28	1.0000

[a]Abbreviations: df, degrees of freedom; var, wheat varieties.

[b]Source values lower than 0.05 are statistically significant

Table 7. One-way ANOVA results of wheat group study when pooled over experimental replications[a].

Effect	df	F ratio	Prob>F[b]
var	19	7.03	<.0001
dose	6	7.80	<.0001
var*dose	114	2.14	<.0001

[a]Abbreviations: df, degrees of freedom; var, wheat varieties.

[b]Source values lower than 0.05 are statistically significant

Table 8. Wheat varieties response to sorgoleone doses in wheat group study.

Wheat		
Group	Variety	Shoot length[a]
Hard white	Thunder cl	105.57 a
Soft white	Xerpha	104.07 a
Soft white	Otto	103 ab
Soft red	Seedway 64	100.01 bc
Soft white	Jasper	99.3167 bcd
Hard red	Wb4458	98.9476 cd
Soft red	Agrimaxx 415	98.5452 cd
Soft white	Ovation	98.1262 cde
Hard white	Antero	97.8214 cde
Soft red	Dynagro 9811	97.31119 cdef
Soft red	Syngenta 547	97.1827 cdefg
Hard white	Monument	96.9857 cdefg
Soft red	Progeny turbo	96.8381 cdefg
Hard white	Danby	96.25 cdefgh
Hard white	Clara	96.0333 defgh
Hard red	Everest	94.6143 efghi
Soft white	Puma	93.419 fghi
Hard red	Larry	93.402 ghi
Hard red	Joe	92.7357 hi
Hard red	Zenda	92.069 i

[a]Means within a column followed by the same letters are not different according to $P<0.05$

Table 9. Shoot length affected by sorgoleone dose across all wheat groups in wheat group study.

Sorgoleone dose (g L^{-1})	Shoot length (% of nontreated)
0	100.000 a
0.025	98.0508 a
0.05	98.3909 a
0.1	97.8883 ab
0.15	99.1879 a
0.2	95.6442 bc
0.3	94.1283 c

[a]Means within a column followed by the same letters are not different according to P<0.05

Table 10. One-way ANOVA results of wheat group study for wheat group and sorgoleone dose[a].

Effect	df	F ratio	Prob>F[b]
group	3	10.84	<.0001
dose	6	5.11	<.0001
group*dose	18	3.13	<.0001

[a]Abbreviations: df, degrees of freedom

[b]Source values lower than 0.05 are statistically significant

Table 11. Sorgoleone dose effect on different wheat group in wheat group study.[a]

Wheat type	Sorgoleone dose (g L^{-1})						
	0	0.025	0.05	0.1	0.15	0.2	0.3
Soft white	100 a-e	98.23 b-e	96.22 c-g	100.36 a-d	102.05 ab	97.33 b-f	102.24 ab
Hard white	100 a-e	100.59 a-c	100.8 a-c	98.80 a-e	99.17 a-e	97.96 b-e	92.41 f-h
Soft red	100 a-e	96.68 c-g	97.35 b-f	95.48 d-g	103.69 a	97.75 b-e	95.15 f-g
Hard red	100 a-e	96.69 c-g	98.66 a-e	96.92 c-g	91.96 gh	89.53 hi	86.72 i

[a]Means within a column followed by the same letters are not different according to $P<0.05$

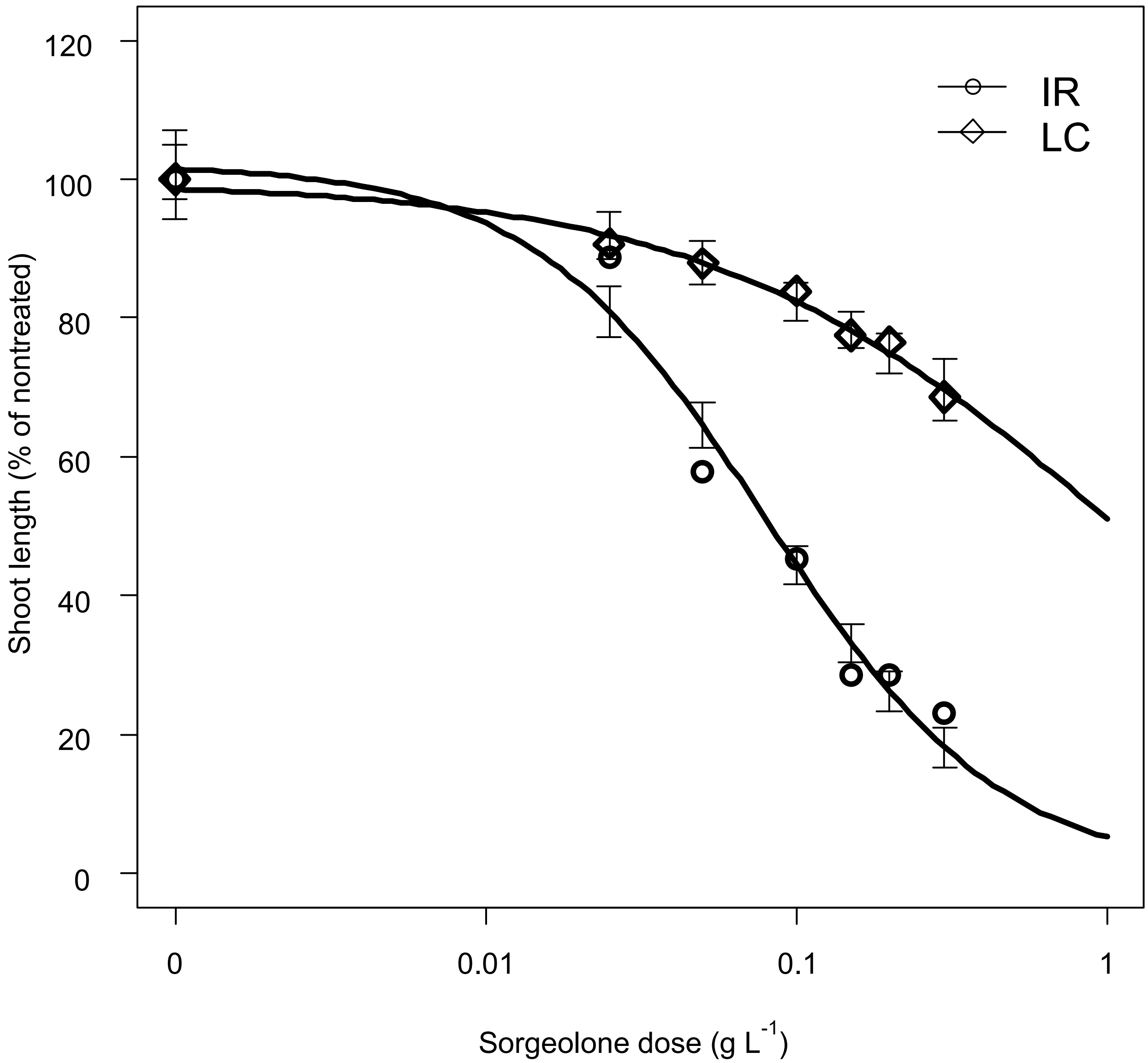

Figure 1. Non-linear regression analysis of grass weeds in weed/wheat species study.

Predicted response can be described as $y = \{d / 1 + \exp [b\ (logx - loge)]\}$, where y represents the shoot length (% of nontreated) , d is the upper limit, b is the slope of each curve, e is the sorgoleone dose needed for 50% response (i.e., 50% shoot length reduction, referred or GR_{50} values, respectively), and x is the sorgoleone dose.

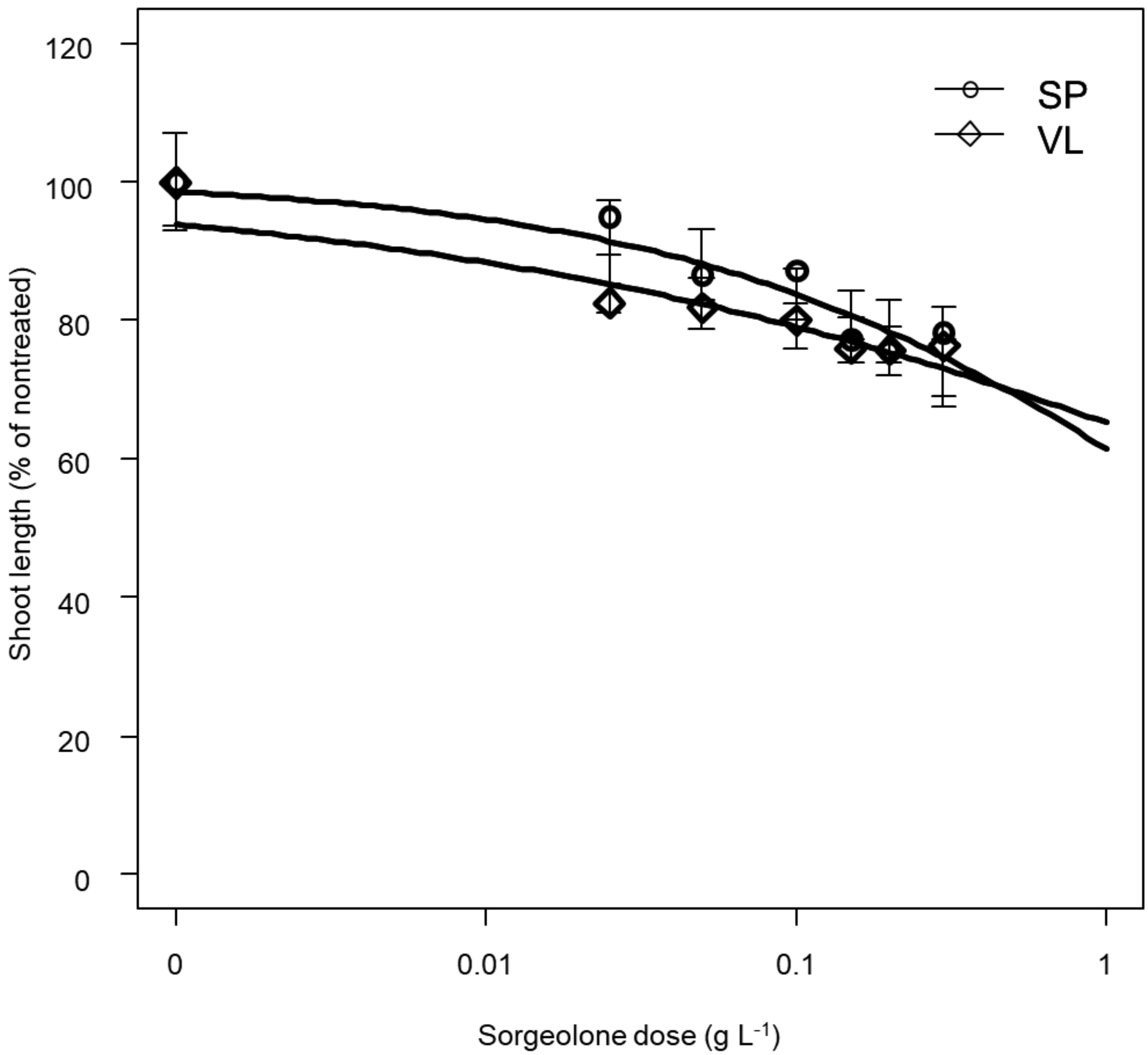

Figure 2. Non-linear regression analysis of broadleaf weeds in weed/wheat species study.

Predicted response can be described as: $y = \{d / 1 + \exp [b (logx – loge)]\}$. where y represents the shoot length (% of nontreated), d is the upper limit, b is the slope of each curve, e is the sorgoleone dose needed for 50% response(50% shoot length reduction), referred or GR50 values, respectively), and x is the sorgoleone dose.

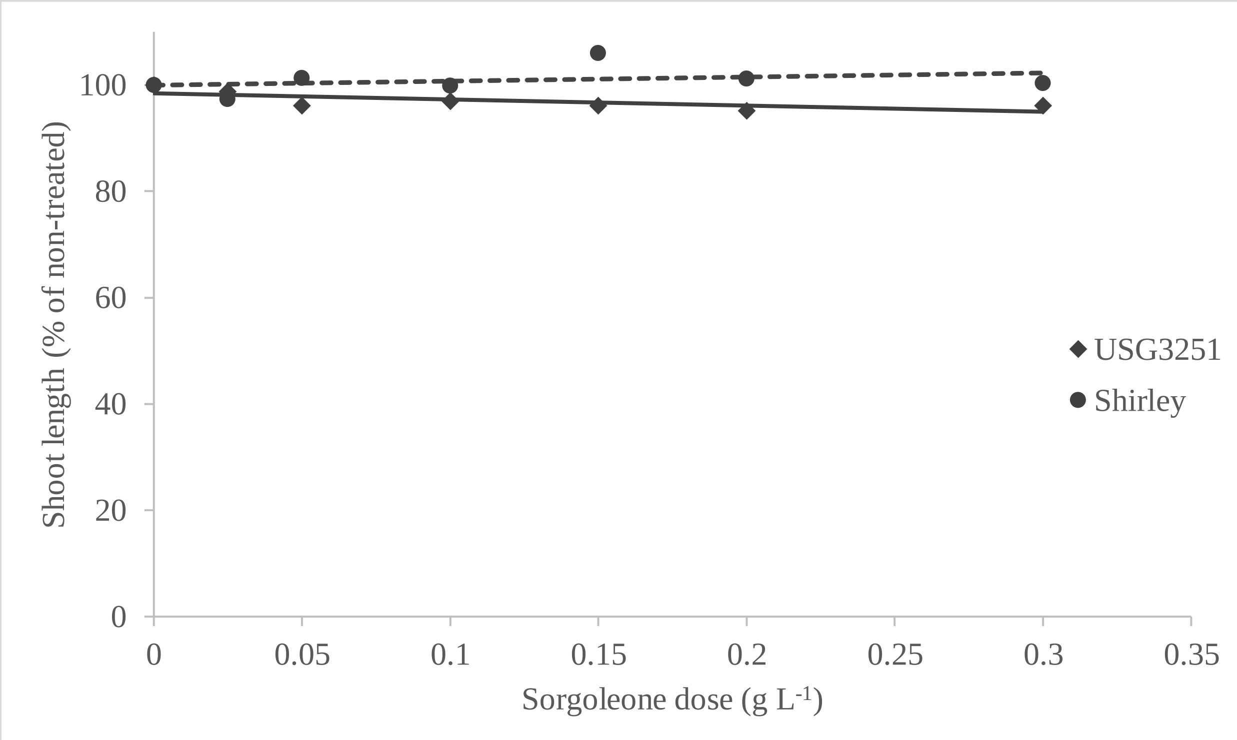

Figure 3. Liner regression of different wheat hybrids in weed/wheat species study.

Predicted response can be described as: Shirley: $y = 7.6816x + 99.957$, $R^2 = 0.098$. USG3251: $y = -11.558x + 98.433$, $R^2 = 0.5091$. y represents the shoot length (% of nontreated) and x is the sorgoleone dose.

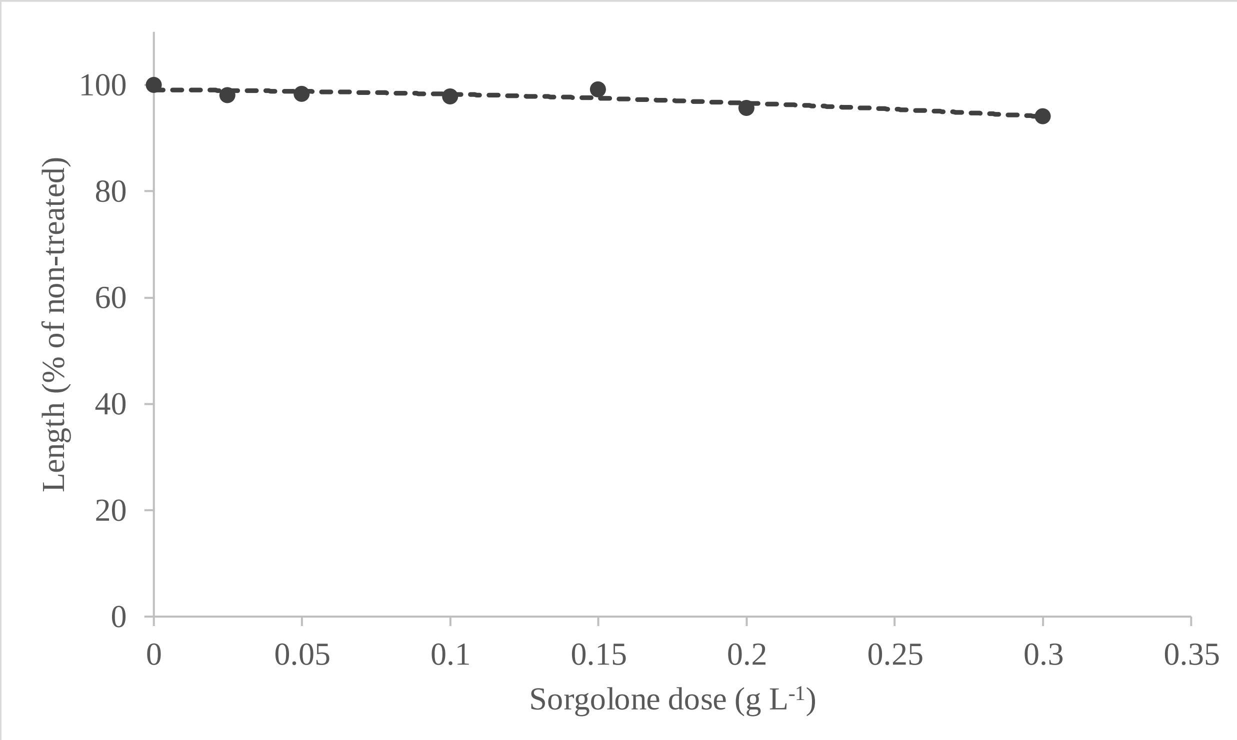

Figure 4. Non-liner regression analysis of sorgoleone dose response when averaged over wheat varieties in wheat study group.

Predicted response can be described as: $y = -41.781x^2 - 4.2412x + 99.101$, $R^2 = 0.777$. where y represents the shoot length (% of nontreated) and x is the sorgoleone dose.

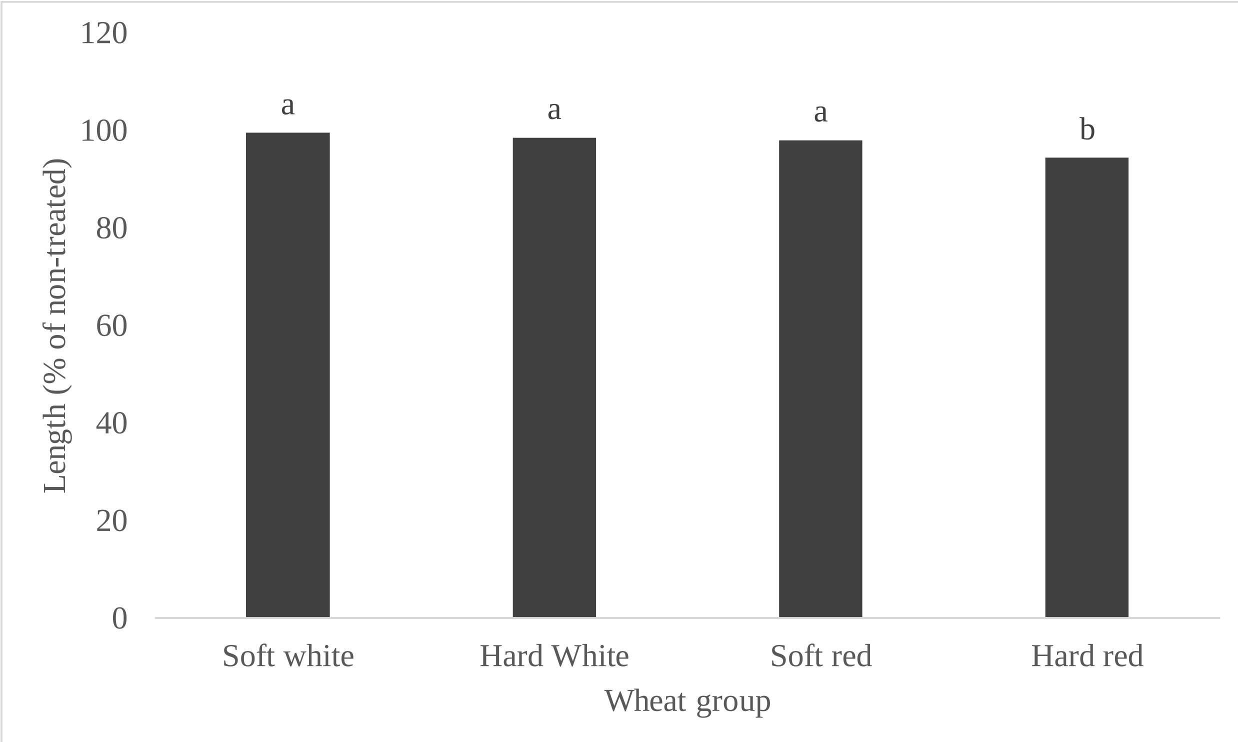

Figure 5. Different types of wheat response across all sorgoleone dose in wheat group study.

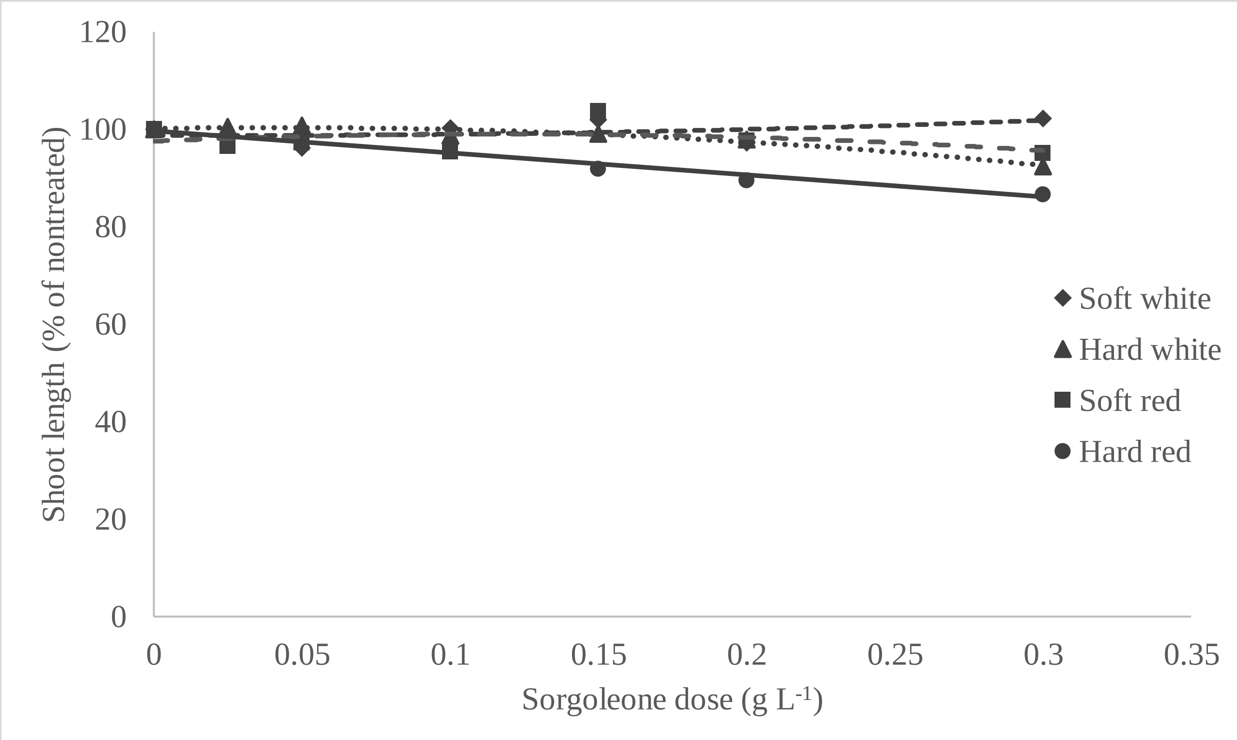

Figure 6. Sorgoleone dose effect on different wheat group in wheat group study. Soft white.

Predicted response can be described as: $y = 41.667x^2 - 2.3997x + 98.788$ with $R^2 = 0.2338$, Hard white equation $y = -115.83x^2 + 9.5266x + 100.15$ with $R^2 = 0.96$, Soft red equation: $y = -104.36x^2 + 24.942x + 97.545$ with $R^2 = 0.1525$, and Hard red equation $y = -45.075x + 99.662$ with $R^2 = 0.9292$