The Below-Ground Competitive Ability and Allelopathic Potential of Palmer Amaranth (*Amaranthus palmeri*) in Soybean

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THE BELOW-GROUND COMPETITIVE ABILITY AND ALLELOPATHIC POTENTIAL OF PALMER AMARANTH (*Amaranthus palmeri*) IN SOYBEAN

A Dissertation
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy
Plant and Environmental Science

by
Dwayne Darcy Joseph
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Accepted by:
Dr. Christina Wells, Committee Chair
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ABSTRACT

Palmer amaranth (*Amaranthus palmeri* S. Watson) has quickly become one of the most economically important weeds in South Carolina soybean production. Its ability to rapidly accumulate root and shoot biomass allows it to effectively compete with crops for light, nutrients and water. To better understand the below-ground competition dynamics between soybean and Palmer amaranth, greenhouse and field experiments were conducted. In 2016 and 2017, field studies were initiated with a split-plot 3x2x2 factorial treatment design. Treatments factors consisted of: neighbor (Palmer amaranth, soybean, none), divider (with and without) and irrigation (irrigated and non-irrigated). The response variables measured were soil volumetric water content, leaf stomatal conductance and soybean yield (seed dry weight m\(^{-1}\) row). Differences between trial year and irrigation were observed, likely due to the rainfall differences between years. In general, soil water content was lower in the absence of a soil divider when water availability was limited (non-irrigated). In the non-irrigated field in 2016, Palmer amaranth competition depleted soil moisture more than soybean competition. In irrigated plots, Palmer amaranth reduced soybean stomatal conductance by 12% and 14% on the last 2 sampling dates respectively, compared to intraspecific soybean competition. A 56.8% increase in soybean yield was observed in non-irrigated treatments with Palmer amaranth as a neighbor when a divider was present compared to when a divider was absent. In both fields (non-irrigated and irrigated) and both trial years, Palmer amaranth as a neighbor caused a greater reduction in soybean yield than soybean as a neighbor. In general, the below-ground competition from Palmer amaranth reduced soybean yield more than above-ground competition.
A greenhouse study was performed to evaluate the effect of Palmer amaranth soil incorporated residues on the growth of soybean. The study was arranged in a completely randomized experimental design with 5 treatments and 5 replications. Treatments consisted of soybean grown in varying levels of Palmer amaranth residues or pitted morningglory (Ipomoea lacunosa L.) residues of varying concentrations incorporated into equal amounts of soil. Palmer amaranth residues of 160,000 ppm and 80,000 ppm significantly reduced soybean leaf area by 97% and 94% respectively. Overall, an increase in Palmer amaranth residue in the soil reduced soybean growth and development. This study demonstrated the allelopathic potential of Palmer amaranth residues and the sensitivity of soybean to those residues.
DEDICATION

This dissertation is dedicated to my two daughters, Davina Amerie Joseph and Darcelle Marian Joseph. Daddy loves you both and I truly appreciate the unconditional love you both showed me throughout this process. I hope you both trust in the Lord and believe that with Him all things you put your mind to are possible. I would also like to dedicate this dissertation to my wife Nichole Dixon-Joseph for her dedication, patience and love throughout this process.
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CHAPTER ONE
REVIEW OF LITERATURE

THE HISTORY OF SOYBEAN

Soybean [Glycine max (L.) Merr.], along with corn and wheat is the most cultivated agronomic crops in the United States and the world. As of 2018, the United States accounts for about 34% (108 million metric tons) of the world’s soybean production (USDA 2018) and is the largest exporter of raw soybeans in the world. Brazil (86.8 million metric tons), Argentina (53.4 million metric tons), China (12.2 million metric tons) and India (10.5 million metric tons) are also among the top 5 soybean producing countries. Kentucky, Minnesota, Ohio, Pennsylvania and Wisconsin are the chief soybean producing U.S states with the largest average plantation sizes in the country. In terms of yield, Illinois, Iowa, Indiana, Minnesota and Nebraska produce the highest-yielding soybean crops. The world’s principal source of animal protein feed and second largest source of vegetable oil is obtained from processed soybean (USDA 2018). Soybean is a very versatile crop that helps meet the world’s demand for food, feed, biofuel and industrial chemicals. Soybean has enjoyed a steady rise to its massive economic importance today, but it took some time for soybean popularity to grow in the United States.

The Origin and Rise of Soybean in the United States

Linnaeus first mistakenly described soybean as Dolichos soja and Phaseolus max. Upon further study he realized that both D. soja and P. max were the same plant (Ricker and Morse 1948). The correct nomenclature of the plant was debated until 1917, when
Merril proposed the new name, *Glycine max*. The name was widely accepted and has been used ever since (Dupare et al. 2008). The first domestication of soybean can be traced back a little over 3000 years to the eastern half of China (Gibson and Benson 2005). Since then, soybean has been a primary source of food for the Chinese population, with ancient Chinese folklore claiming it was one of the first grains planted by the god of agriculture, Hou Tsi (Dupare et al. 2008). The names “soy”, “soja” and “soya” are thought to be derivatives of the ancient Chinese words “sha” or “sou” which were given to soybean (Dupare et al. 2008).

The first recorded soybean arrived in the United States in 1765 when a seaman named Samuel Bowen returned to Savannah, Georgia from a voyage to China (Hymowitz and Harland 1983). Bowen wrote that the Chinese used soybean to prepare a vermicelli superior to that of the Italians. He also stated that the soybean was an excellent food source for long sea voyages because it was not destroyed by weevils. Samuel Bowen had great intentions for the soybean, including making soy sauce that he would export to England. Bowen didn’t own any land and wasn’t able to plant the soybean himself; instead he asked the surveyor-general of the state of Georgia to plant them on his land.

After its introduction into the United States, soybean took a while to become an agronomic staple. For many years soybean acreage slowly increased, but what really helped its early adoption into the US agronomic landscape was its similarity in production culture to that of corn. Growing soybean in rotation with other crops also provided benefits to the producers and that aided in popularity. The greatest surge in soybean production
occurred after World War II, when corn producers began growing soybean and its production moved into the “corn-belt” region of the United States. Soybean’s popularity continued to grow exponentially as multiple uses for the bean were discovered. Currently, soybean is the most harvested row crop in the United States, with a 35.9 million hectare area for harvest (USDA 2018). The states of Illinois, Iowa, Indiana, Minnesota and North Dakota account for more than 46% of the total soybean harvest area in the country. Meanwhile, the south-eastern states, including South Carolina account for less than 10% of the country’s soybean harvest.

SOYBEAN PRODUCTION IN SOUTH CAROLINA

In 2018, the USDA reported that South Carolina planted approximately 166000 hectares with soybean, a 5% increase from the previous year. In South Carolina, the majority of soybean is grown in the Coastal Plains region. Coastal Plain soils generally have a sandy loam texture, making them well-drained following rain events. Soil texture types vary across the state as one moves from the coast towards the mountains. The soil across the state developed over a series of different landforms that rise form the Atlantic coast and move through the undulating Piedmont to the foothills of the Blue Ridge mountains. The soils of South Carolina are categorized as coast, coastal plain, sandhills, Piedmont and Blue Ridge. The soils of the Coastal Plains region tend to be sandy or coarse textured making them more productive due to the clay layer of the soil being less than 35 cm (Clemson 1993).
To obtain a profitable yield, South Carolina producers must decide on the best variety of soybean to grow. Proper variety choice involves balancing high yields and pest susceptibility or resistance. The presence of soil nematodes across the state makes the decision of soybean variety even more important. Variety type needs to be chosen based on the producer’s location, soil type, pest levels and yield goals. Clemson Research and Extension recommends planting a full season soybean between early May and early June with a maturity group V-VII for optimal production yields statewide.

The major priority of any soybean producer is crop profitability. Profit margin can be severely hindered by pests that adversely affect crop health and growth. A 2003 survey of soybean producers in South Carolina found that 57% listed weeds as the most limiting factor affecting soybean yields (Norsworthy 2003) Nematodes and insects were identified by 24% and 19% of producers as the most important pests in their fields. Many factors can contribute to the level of pest infestation in a soybean field. For weeds, chemical and mechanical control are the primary methods of control. Chemical control by herbicide application is the most popular way to kill and control weeds. The combination of herbicide modes-of-action along with proper application timing (pre-emergence and post-emergence) can effectively control the majority of weeds in a field. Mechanically, tillage has been a major weed control technique for decades. Tillage can be loosely defined as the mechanical manipulation of the soil and plant residues to prepare a seedbed for crop planting (Shrestha et al. 2006). Tillage effectively kills any weeds in a field before planting, making the initial control of weeds easier by providing a relatively “clean” field for planting. During recent times, reduced-till and no-till soil preparation practices have
become more popular as producers try to minimize input costs. With the widespread adoption of these new tillage practices, a shift in weed species and populations has occurred, resulting in a change in weed management needs. Reduced-till and no-till practices also leave increased residues from crops or weeds in the field before planting. In the case where the weed may be allelopathic, a reduction in crop health and growth may be experienced.

ECONOMICALLY IMPORTANT WEEDS OF SOUTH CAROLINA

Soybean producers identified the most problematic weeds in South Carolina row crop production as sicklepod (Senna obtusifolia), Palmer amaranth (Amaranthus palmeri) and morningglory (Ipomoea spp.) [Norsworthy 2003]. Since the last extensive survey was conducted, there has been a significant shift towards Palmer amaranth as the most problematic weed, eclipsing sicklepod, morningglory and any grass weeds. If left uncontrolled, weeds can have an adverse effect on soybean yields. The economic importance of weed management cannot be understated. Producers must control weeds as early as possible to ensure the protection of their crop yields.

Pitted Morningglory

Pitted morningglory [Ipomoea lacunosa (L.)] is a sparsely pubescent twining annual with ovate leaves (Stephenson et al. 2006). The plant is prevalent in the southeast United States including South Carolina and is typically found in agricultural fields, roadsides and woodland margins (SWSS 1998). Its prevalence in the agricultural setting has increased in recent years due to its tolerance to glyphosate. Traditionally, glyphosate
has always been a weak performer on pitted morningglory. Glyphosate efficacy is usually inadequate and variable when applied alone between the recommended rates of 0.84 - 1.26 kg ae ha\(^{-1}\) (Norsworthy et al. 2001). Reduced susceptibility to glyphosate can be attributed to poor foliar absorption through the plant cuticle. The plant’s leaf pattern and vining nature cause leaf overlap that limits the exposure to herbicides, effectively limiting the amount of herbicide that enters the plant.

Pitted morningglory exhibits prolonged vegetative growth, making it extremely competitive during the early reproductive stages of soybean growth (Senseman and Oliver 1993). An explosive growth rate also aids the plant when in competition with a crop. At about 8 weeks after emergence, pitted morningglory accumulated enough biomass to actively outcompete soybean for light and soil moisture (Mathis 1977). The vining nature of pitted morningglory causes crop lodging; it wraps around the crop, resulting in a reduction in harvest efficiency and growth rate. Koger and Reddy (2005) reported that pitted morningglory has the ability to reduce crop yield by up to 81%. Pitted morningglory, like many other weeds, is a prolific seed producer. Under no competition, a plant was able to produce between 10,000 and 15,000 seeds or about 52 million seeds per hectare (Norsworthy and Oliver 2002).

Sicklepod

Sicklepod \(\textit{Senna obtusifolia} \) (L.) Irwin and Barneby] is an annual, woody, non-undulating legume that can grow up to 2.5 m in height. Sicklepod is an economically-important weed throughout the southeastern United States often causing yield losses in any
cropping system where it is present. The sheer mass and height of a sicklepod plant often allows it to shade out shorter to medium height crops. In soybean production, as little as 8 plants per square meter have been reported to reduce soybean yield by 35% (Thurlow and Buchanan 1972).

Sicklepod is a prolific seed producer whose seeds have a very hard seed coat. This seed coat allows the seeds to disperse and persist through time. Sicklepod seeds have been reported to remain viable in the soil for up to 5 years (Senseman and Oliver 1993). They have the ability to germinate under a wide range of environmental conditions and tillage practices, and their dormancy may be broken by scarification after a tillage event. Sicklepod control is primarily achieved with herbicides and currently there are no documented cases of sicklepod herbicide resistance. However, difficulty in sicklepod control may arise when using a post-emergence application of a non-residual herbicide (Norsworthy and Oliveira 2006)

Palmer amaranth

Palmer amaranth (*Amaranthus palmeri* S. Watson) has rapidly become one of the most widespread and economically important weeds in the southeastern United States. The plant effectively outcompetes any crop with which its growing, eventually leading to significant yield loss and reduced harvest efficiency.

Palmer amaranth is an annual forb that is native to the Sonoran Desert region of the United States (Ehleringer 1983). It is dioecious and usually is wind pollinated, with a male plant producing copious amounts of pollen. Female plants are prolific seed producers, with
a single female plant producing up to 600,000 seeds (Jha et al. 2007). Palmer amaranth seeds are very small; usually about 1-2 mm in size, smooth, round and black (Sauer 1955). The primary mechanism for seed dispersal is gravity but animals, wind, rain and agricultural equipment have all been documented as modes of dispersal.

Palmer amaranth is a C4 plant (Wang et al. 1992). This allows it to have higher rates of photosynthesis than most dicot plants. It also exhibits diapheliotropism which, along with its high photosynthetic rate gives it the ability to rapidly accumulate biomass (Ehleringer and Forseth 1980). Its rapid growth is an important characteristic that helps Palmer amaranth outcompete crop plants. As a desert native, Palmer amaranth has effective drought tolerance mechanisms that allow it to thrive in dry conditions (Whitaker et al. 2010). The plant is able to move water through its xylem more quickly than many other plants (Ehleringer 1985). It can increase the solute concentration of its leaf cells to prolong photosynthesis and maintain positive turgor, allowing its stomates to remain open despite low soil water availability (Ehleringer 1985). Palmer amaranth is adapted to grow under shaded conditions, allowing it to compete successfully under in light-limited environments that occur inside dense crop canopies (Jha et al. 2007).

Palmer amaranth’s emergence as a major agronomic weed is relatively recent. It first appeared in the 1989 annual survey of the Southern Weed Science Society in South Carolina (Webster and Coble 1997). The plant has rapidly developed resistance to glyphosate via several internal mechanisms (Reddy, 2001). Glyphosate resistant Palmer amaranth was first discovered in Georgia in 2004 (Culpepper et al. 2006). Currently, the
plant is documented to be resistant to six herbicide modes-of-action. Some Palmer amaranth biotypes are also reported to have developed resistance to multiple herbicide modes-of-action (Heap 2019). As an obligate out-crosser, herbicide resistance can be readily achieved in Palmer amaranth through the process of gene stacking. The control of Palmer amaranth has become increasingly difficult, but stacking multiple herbicides with different modes-of-action and adding them to a current herbicide program can help slow down the evolution of resistance. Herbicide application timing, rate, and weed seed bank control are other ways of preventing weed resistance. Mechanical weed control is also effective for Palmer amaranth, but it may not be the most efficient means of control for larger fields.

WEED-CROP COMPETITION

The discipline of weed science seemingly revolves around how one desired plant species, often producing a commodity, is affected by an undesirable plant species, often hindering the overall fitness of the desired species. Competition between weeds and crops has existed for centuries, dating back to the book of Genesis in the Bible. The definition of plant competition differs among disciplines, but it’s fair to say that weed-crop competition is a natural, undesirable, ubiquitous, and inevitable phenomenon (Zimdahl 2004). The phenomenon of competition is inevitable when living organisms exist in communities. There’s a dichotomy of perspectives when defining competition between plants: and ecologist’s view and a weed scientist’s view. Ecologists view plant competition through the lens of plant community dynamics, whereas weed scientists view plant competition
through the lens of weed effects on fitness and crop yield in agricultural settings. These views, although different, both attempt to explain how the presence of multiple plant species in a community affects an individual plant’s life and growth.

As mentioned earlier, plant competition has been given many definitions over the years. Grace and Tilman (1990) said that competition’s definition ranges from the narrow to the general, from operational to philosophical, and from phenomenological to mechanistic. Begon et al. (1996) described competition as an interaction between individuals brought about by a shared requirement for a limited resource that leads to a reduction in the performance of at least some of the competing individuals. In this definition, competition between individuals may only occur when there is a limited supply of a resource. Two plants may not be in competition regardless of their physical proximity. If water content, light, and nutrients are sufficient, the needs of both plants are met and no competition occurs. Symbiosis between legumes and grasses has also been documented and provides evidence that not all plant associations are competitive.

Whether allelopathy falls under the umbrella of plant competition remains a subject of debate. “The term interference” was adopted by Harper (1960, 1961) and advocated by Muller (1969) as a term that encompassed both competition and allelopathy. Zimdahl (2004) maintained that allelopathy differs from competition because it relies on the addition of a chemical compound to the environment, whereas competition involves the removal of an essential factor from the environment. In this review, allelopathy will be
treated as a means of plant competition because it helps the allelopathic plant gain an advantage in a competitive setting where resources are limited.

Weed-crop competition can be divided into two categories, above-ground and below-ground each of which has its own sub-categories. Above-ground competition is also referred to as shoot competition and encompasses the competition for light, while below-ground competition is also called root competition and encompasses the competition for water and nutrients.

Above-ground Competition

The competitive ability of a plant can be quantified in a number of ways. Goldberg (1990) expressed competitive ability as a measure of how strongly one plant suppresses other individuals around it or how little the plant itself responds to the presence of other individuals. In above-ground competition, the main resource plants compete for is light. In extreme cases, competition for carbon dioxide may occur, but this is limited to rare occasions when crowded conditions occur. A plant’s ability to effectively compete for light directly relates to its foliar size and total leaf area, and its height. Light interception is essential to maximize photosynthesis, and thus the morphology of a plant plays a major role in determining whether or not it will be competitive for light.

Certain plants have the ability to detect when they are in low light, often due to shading by other plants. The drop in the red to far-red ratio indicates to a plant that a neighbor is present. This signals a series of morphological changes that result in activation of the shade avoidance response. These changes include increased stem elongation rate,
reduced stem diameter, increased apical dominance, and changes in foliage (Page et al. 2010). As plants try to maximize their photosynthetic rate by intercepting more sunlight, a sacrifice is made and crop production is reduced. When plants are exposed to shade, they often optimize light interception by increasing specific leaf area (Evans and Poorter 2001). This reallocation of resources under shade results in a loss of productivity and yield in crops. Under shady conditions, net photosynthetic rate decreases resulting in plant biomass reduction (Cheng and Fleming 2009).

Light competition has been studied in soybean more than in any other crop (Zimdahl, 2004). In general, soybean is a more effective competitor for light than many weeds. Soybean in monoculture quickly forms a canopy, shading out the crop row and effectively preventing susceptible weeds from flourishing. Murphy and Gosset (1981) found that light in the soybean row, three and five weeks after planting averaged 55% and 40% of available light respectively. Weeds that are highly successful in soybean production often have high amounts of leaves within or above the soybean canopy and exhibit good shade tolerance in their lower leaves. In soybean production, short weeds and weeds with conical leaf area densities are weak competitors (Zimdahl 2004). A positive correlation between soybean interference and weed height is seen for most weeds.

Below-ground Competition

Below-ground competition is another way in which two plants can influence one another. When we hear of below-ground competition, our minds go directly to the soil and the roots. The competition for water and nutrients both influence crop productivity. Some
have argued that the competition for below-ground resources is more important to a plant’s overall fitness than for above-ground resources. Donald (1958), after working with two grasses, concluded that root competition had a greater effect than shoot competition on grass fitness and growth. The ability to partition and distinguish between root and shoot competition has become easier as experimental techniques have improved over the years. Researchers have been able to separate nutrient uptake competition from water uptake competition by limiting one of the resources and quantifying the effects on the plant.

The importance of water to crop-weed interactions varies. Kropff et al. (1992) reported that common lambsquarters became more competitive with sugar beet under a water shortage. This increase in competitive ability as soil water decreases is often exhibited in plants that are native to arid or semi-arid regions. The same can be said for Palmer amaranth, which is a desert native. A characteristic that sets Palmer amaranth apart from most weeds is the plasticity of its root system; it can quickly change and adapt root morphology depending on soil moisture availability. Aldrich and Kramer (1997) wrote that the degree of competition for water is determined by the relative root volume of the competing species. To exploit the uneven distribution of mobile nutrients, immobile nutrients and water in the soil, plants must employ different root strategies. These include changes in root surface area, length and spatial arrangement. These metrics collectively determine the volume of soil occupied by the root system (Brown and Scott 1984). Wright et al. (1999) found that Palmer amaranth grown in hydroponics had a greater root length than soybean despite having similar root mass. Palmer amaranth had much finer roots, which led the authors to conclude that it has a greater potential for rapid root extension and
can more quickly occupy a greater volume of soil. This affords Palmer amaranth a greater competitive advantage in the acquisition of water and nutrients, especially when the water availability is limited.

Weed Density & Critical Weed-Free Period

The crop-weed competition dynamic causes significant yield loss when certain criteria are met. Weed density and critical weed-free period play a major role in determining whether weed presence will lead to significant losses in crop production and yield. Weed density (the number of weeds in a given area) is an important factor determining whether weed infestation is a field will lead to yield loss. Weed interference only becomes significant above certain densities and that varies among cropping systems, weed species, and resource availabilities. Generally, there is a correlation between yield reduction and weed density. There is a greater strain on an agroecosystem as it approaches the weed threshold (i.e. the density at which yield reduction occurs) due to the increased competition for finite resources. An abundance of research highlights the densities at which specific weeds will reduce crop yields; however, the weed density-crop yield relationship is not linear. There are instances where a few weeds have no effect. Also, total crop loss usually occurs at less than the maximum possible weed density (Zimdahl 2004). The yield loss potential related to weed density greatly relies on the weed’s proximity to the crop. Different weeds have different spheres of influence in which they are able to affect their neighbor. As the weed and crop become closer, a rivalry for space may occur. Roots often become intertwined in the same soil area, and, on occasion, leaves and stems battle for the
same space. The resulting competition is not for the space itself, but for the resources contained within that space. At this point, proximity becomes a driving factor in the weed-crop competition dynamic.

Zimdahl (1980) defined the critical weed-free period as the time during which weeds must be controlled to prevent economic yield loss. This period varies for different crops, weed species, and geographical areas. Van Acker et al. (1993) used soybean growth stages for three levels of pre-established acceptable yield losses to determine the critical weed-free period in soybean. In general, the critical weed-free period is short; producers often have a very small window in which to control weeds before significant yield losses become inevitable. Studies done in Canada and the mid-west United States have concluded that the soybean critical weed-free period extends from V1 (first trifoliate leaves) to V4 (fourth trifoliate leaves), with minor variations depending on the geographical location (Stroller et al. 1987; Van Acker et al. 1993; Zimdahl 1987; Zimdahl 1980). Timing becomes a very important factor in preventing yield loss; weeds must be controlled before they infringe upon the critical weed-free period. Soybean yield is essentially fixed by V4 and weeds emerging after V4 have a minimal effect on yield. Weeds must still be controlled after V4, to prevent them from setting seed and to increase harvest equipment efficiency.

Allelopathy

Some plants contain allelopathic compounds: chemicals toxic to non-kin and, in some cases, to kin plant species. The phenomenon of allelopathy was first described by Austrian plant physiologist Hans Molish in 1939. Since then, much controversy has
attended the study of allelopathy, with many researchers still questioning its existence and/or relevance (He et al. 2012). Nonetheless, as herbicide resistance continues to spread across agriculture, researchers have taken a renewed interest in allelopathy as an alternative to herbicide application. Putnam and Duke (1974) argued for use of allelopathic crops to suppress weeds in agroecosystems. In agriculture, allelopathy has mainly been observed in rice, but some annual weeds including species of amaranth have also been described as allelopathic (Bhowmik and Doll 1984). Menges (1988) performed experiments where he planted four vegetable crops in soils containing Palmer amaranth residues and he concluded that root and shoot growth of the vegetables was sensitive to the amaranth residues. Redroot pigweed (Amaranthus retroflexus L.) root exudates were also found to inhibit the growth of common bean (Phaseolus vulgaris L.) seedlings (Namdari et al. 2012).

Allelochemicals often occur as root exudates that are released and travel in the soil surrounding the plant. Shoot allelochemicals may also be present in leaves and stem tissue and are released into the soil when the leaves are shed. Allelochemical production can either be constitutive (always present in the plant) or induced (produced in response to perceived competition). Allelochemicals actively stunt neighboring plant growth and germination, resulting in reduced plant fitness, and in a crop-weed setting, in yield reduction (Duke 2015).

Soybeans are important to South Carolina’s economy, soybean production accounted for $99,014,000 in 2018 (USDA 2018). Palmer amaranth competition in
soybean is of great economic importance. The effect of above-ground Palmer amaranth and soybean competition are well documented but the below-ground competition between the two plant species are not. This study was performed to better understand the crop-weed competition dynamic taking place between Palmer amaranth and soybean below-ground. Field experiments were designed to understand how Palmer amaranth affects the soil moisture availability, soybean stomatal conductance and soybean yield. A greenhouse experiment attempted to determine the allelopathic potential of Palmer amaranth soil residues on the growth and fitness of soybean seedlings. The findings from this study will hopefully shed some light on Palmer amaranth’s influence on the water relations soil dynamics in soybean production, eventually leading to similar research in other row crops.
LITERATURE CITED


CHAPTER TWO

THE EFFECT OF PALMER AMARANTH (*Amaranthus palmeri*) COMPETITION ON SOIL MOISTURE AVAILABILITY IN SOYBEAN

ABSTRACT

Palmer amaranth (*Amaranthus palmeri* S. Watson) has become one of the most difficult-to-control weeds in South Carolina soybean production. Palmer amaranth exhibits prolific growth rates allowing it to compete with crops for light, nutrients and water. While much is known about its ability to compete with crops above-ground, few studies have examined its ability to compete with crops below-ground. In 2016 and 2017, field experiments were conducted at Edisto Research and Education Center located near Blackville, SC to evaluate how interspecific competition with Palmer amaranth affects the soil moisture available to soybean. The experiment used a split plot 3 x 2 x 2 factorial design. Treatment factors included neighbor (Palmer amaranth, soybean or no neighbor), divider (with and without), and irrigation (irrigated and non-irrigated). Dividers were plastic sheets placed in the soil between crop and neighbor to eliminate root competition. Differences between trial year and irrigation was observed, likely due to the rainfall differences between years. In general, soil volumetric water content was lower in the absence of a soil divider in the non-irrigated field. In the irrigated field, where water was not limited, there were no significant effects of the competition-excluding divider. In the non-irrigated field in 2016, Palmer amaranth competition depleted soil moisture to a greater extent than intraspecific competition with soybean. As the growing season progressed, Palmer amaranth competition suppressed soybean stomatal conductance more than
intraspecific soybean competition. In irrigated plots, Palmer amaranth competition was associated with a 12% and 14% reduction in soybean stomatal conductance at the last 2 sampling dates compared to intraspecific soybean competition.
INTRODUCTION

Soybean is one of the most economically important row crops in the United States. Production for 2019 is forecasted to reach a record 4.69 billion bushels, with a harvest area of 35.9 million hectares (USDA 2018). Weeds are a significant threat to soybean production in the United States. Weed interference accounted for a 52% yield loss in U.S. soybean production with a monetary value of $17.2 billion averaged across 2007-2013 (Soltani et al. 2017). When weeds are left uncontrolled, more than half of all U.S. soybean production may potentially be lost. Water, light, and nutrients are the three primary resources for which weeds and crops compete. All these resources are essential for the proper growth and development of plants. King (1966) proposed that water is the most critical requirement for plant growth. Zimdahl (2007) suggested that weed species often require more water than crops and are usually more successful in accessing that water. Weed competition affects soybean production in various ways, leading to reduced pod numbers, reduced pod size, smaller seeds, lower seed numbers and decreased harvest equipment efficiency due to weeds remaining in the field at harvest.

To successfully control weeds in a soybean field, producers must implement appropriate management practices. These may include adjusting row widths and selecting appropriate cultivars, tillage intensities, and rotational crops (Norsworthy 2003). The choice of an effective herbicide program is critical to minimizing yield loss from weed interference.
In 2018, soybean was planted on approximately 158,000 hectares in South Carolina, making it the most planted row crop in the state (USDA 2018). Weeds are a major problem in South Carolina soybean production and morningglory (*Ipomoea* spp.), sicklepod (*Senna obtusifolia*) and Palmer amaranth (*Amaranthus palmeri*) are some of the most difficult weeds to control in the state (Norsworthy 2003). Herbicide is the primary weapon of choice by producers to combat the spread of weeds in soybean fields; effective preemergent and postemergent herbicide program can eliminate the majority of weeds in a field.

The overuse of glyphosate shortly after the introduction of glyphosate-resistant cropping systems in the late 1990s resulted in the evolution of glyphosate-resistant weeds (Chahal et al. 2015). The most notable of these is Palmer amaranth, a problematic weed across the southeastern US. Glyphosate-resistant Palmer amaranth was first reported in Georgia in 2004 (Culpepper et al. 2006). Currently, there are populations of Palmer amaranth with documented resistance to multiple herbicide modes-of-action (Heap 2019), giving them the moniker “super weeds”. The speed and evolution of these resistant weed populations pose a serious threat to soybean production as producers must minimize inputs in order to yield a profitable crop.

The relatively recent problem of Palmer amaranth in soybean fields has caused a tremendous strain on production. Palmer amaranth can germinate throughout the growing season, making its control via herbicides very difficult. Being a native of the desert regions of the southwestern US (Ehleringer 1983), it is well-adapted for the hot, humid, and
drought prone South Carolina environment. Its propensity for prolific biomass accumulation gives it an advantage in an agricultural setting. Studies have shown that Palmer amaranth can effectively adjust its root-shoot ratio depending on its environment (Ward et al. 2013). Palmer amaranth is able to accumulate an extensive root system of fine shallow roots when water isn’t limited and deep roots capable of breaking the “hardpan” found in the South Carolina soybean producing regions when soil water may be limited (Wright 1999; Forseth et al. 1984). This root plasticity allows the plant to optimize water uptake regardless of environmental conditions. The below-ground abilities of Palmer amaranth can effectively decrease the water availability in its surrounding rhizosphere. When in competition with soybean, it has the ability to cause varying water stress situations for the crop. This competition for water is intensified in the sandy soils that predominate in the soybean production region of South Carolina. These soils allow for quick water percolation, and, although the region receives adequate rainfall for soybean production, the frequency of the rainfall on these well-drained soils often results in water stressed crops between rain events (Ritchie et al. 2009). When coupled with competition from Palmer amaranth, the perfect conditions for yield reduction in soybean are produced.

When left uncontrolled, at a density of 8 plants m$^{-1}$ row, Palmer amaranth reduced soybean yield by 79% (Horak and Loughin 2000; Bensch et al. 2003). Competition between Palmer amaranth and soybean can be categorized into two groups: below-ground (root) competition and above-ground (shoot) competition. This study focuses on the below-ground competition for water between the two species. This was achieved by separating the two root systems to eliminate competition and by allowing the two roots systems to
mingle and compete. We then observed how these treatments affected soil water availability in the rhizosphere of both species. The overall hypothesis was that Palmer amaranth interspecific competition with soybean would deplete the soil water availability to a greater extent than intraspecific competition with other soybean plants.
MATERIALS AND METHODS

The experiments were performed at Clemson University’s Edisto Research and Education Center (EREC) near Blackville, SC. Field experiments were conducted on a Clarendon Loamy Sand (fine-loamy, siliceous, thermic Plinthic Paleudults) in 2016 and 2017. Soybean variety Asgrow AG75X6 was seeded on June 9, 2016 and Asgrow AG69X6 was seeded on May 30, 2017 in a disc-harrowed then strip tilled soil at 32 seeds per meter using a John Deere 1700 Maxemerge XP Planter (Deere & Company, Moline, IL).

The study was a 3x2x2 split-plot factorial treatment design with a completely randomized experimental design and 3 replications. Treatment factors consisted of three levels of plant neighbor (Palmer amaranth, soybean and none), two levels of soil divider to exclude competition (with divider and without divider) and two levels of irrigation (irrigated and non-irrigated).

Dividers, neighbor plants and Decagon GS1 soil moisture sensors (Decagon Devices, Inc, Pullman, WA) were installed when the soybean crop was at the VC vegetative growth stage. Dividers comprised of 76 cm x 51 cm fluted polypropylene sheets (plastic cardboard) placed parallel and to the right of the soybean row (25 cm away) to a depth of 45 cm in the soil, with the top 6 cm visible above the soil surface. The three neighbor plants were hand planted 51 cm to the right of the soybean row when it was the VC vegetative growth stage. In plots containing a divider, the divider was positioned between the soybean row and the neighbor plant. GS1 soil moisture sensors were placed 30.5 cm in the soil approximately 12 cm away from the soybean row or neighbor plant with the prongs of the
sensor facing the soybean row within the potential root zone of the soybean or neighbor plant. All sensors were connected to Decagon data loggers positioned between plots.

Each plot consisted of a 4.6 m long soybean row with the right adjacent row (0.9m away) stripped off. A soybean row was planted between adjacent plots and acted as a buffer. The study area was kept weed free by hand pulling and mechanical removal between rows throughout the duration of the study. The irrigated field was watered when necessary depending on soil dryness via a central pivot irrigation system.

In 2017, abaxial leaf conductance readings were taken on two leaves of two random soybean plants per plot using a Decagon Sc-1 steady state diffusion porometer (Decagon Devices, Inc, Pullman, WA). Measurements were taken on the youngest fully expanded leaflet of the soybean row plants that were adjacent to the divider and/or to the neighbor plants (competition zone). Measurements were made between 11 am and 1 pm on days when the sky was clear (minimal cloud cover) and wind speeds were below 2.4 km/h.

Soil moisture readings were averaged into 7-day intervals for each GS1 sensor. Soil moisture data was analyzed using the Mixed Model procedure of JMP Pro 12.2 (SAS Institute Inc, Cary, NC). Divider, neighbor, and date (repeated structure) were fixed effects while replication was considered a random effect. Irrigation was analyzed separately and due to weather differences between 2016 and 2017, year was analyzed separately.
RESULTS

Soil Volumetric Water Content

There was a significant effect of the competition-excluding divider (p=0.0118) on soil $\theta_v$ in the non-irrigated field during 2016. When a divider was present, the volumetric water content ($\theta_v$) of the soil decreased from a mean of $0.11 \pm 0.005 \text{ m}^3/\text{m}^3$ to a mean of $0.9 \pm 0.005 \text{ m}^3/\text{m}^3$ (Fig. 2-1). Plots containing Palmer amaranth (AMAPA) as an adjacent neighbor had the lowest soil $\theta_v$, with a mean value of $0.1 \pm 0.006 \text{ m}^3/\text{m}^3$; soybean neighbor plots had a mean soil $\theta_v$ of $0.11 \pm 0.006 \text{ m}^3/\text{m}^3$ (Fig. 2-2). Post-hoc analysis revealed some significant comparisons when the treatment combination of neighbor by divider was examined. The soil $\theta_v$ of AMAPA neighbor plots without a divider was significantly lower from that of AMAPA neighbor plots with a divider (Fig. 2-3). As stated earlier, the presence of a divider increased mean soil $\theta_v$ relative to the absence of a divider, suggesting that root competition from either species reduced water availability to test plants (Fig. 2-1). When no divider was present, AMAPA neighbor plots exhibited a 12% lower mean soil $\theta_v$ when compared to plots containing soybean as a neighbor (Fig. 2-3). The greatest disparity in mean soil $\theta_v$ in plots with and without a divider was observed between 9 and 11 weeks after planting for both soybean and AMAPA neighbor plots (Fig. 2-4).

In 2016, the effect of divider (p=0.0691) and neighbor (p=0.6499) on soil $\theta_v$ were not significant in the irrigated field. There was a significant effect of sampling date (p<0.001) and the three-way treatment combination of divider by neighbor by sampling date (p=0.005). A 16% decrease in mean $\theta_v$ was observed when comparing AMAPA
neighbor plots without a divider (0.18 ± 0.01 m³/m³) to AMAPA neighbor plots with a divider present (0.15 ± 0.01 m³/m³). As was observed in the non-irrigated field, between 9 and 11 weeks after planting, the greatest disparity in soil θv was observed when comparing the two levels of divider in soybean or AMAPA (Fig. 2-5).

During the 2017 trial year there was no significant effect of divider (p=0.5891) or neighbor (p=0.2136) on soil θv in the non-irrigated field. There was a significant effect of sampling date (p<0.001). The largest disparity in mean soil θv in AMAPA plots with and without a divider was observed approximately 13 weeks after planting (Fig. 2-6).

In 2017, there was a significant effect of sampling date (p<0.001) on soil θv in the irrigated field. There was no significant effect of divider (p=0.7874) or neighbor (p=0.3658) on soil θv in the irrigated field. The mean soil θv in AMAPA plots was reduced by 25% from a mean of 0.18 ± 0.02 m³/m³ when a divider was present to a mean of 0.13 ± 0.02 m³/m³ when a divider was not present.

Leaf Stomatal Conductance

**Non-Irrigated Field**

There was not a significant effect of divider (p=0.1492) on stomatal conductance at the first sampling date in the non-irrigated field (Fig. 2-7). There was a significant reduction (Fig. 2-8) in the mean stomatal conductance of soybean in AMAPA neighbor plots (320.9 ± 21.1 mmol m⁻² s⁻¹) compared to soybean neighbor plots (256.2 ± 21.1 mmol m⁻² s⁻¹). At the second sampling date in the non-irrigated field, there was a significant
AMAPA as a neighbor was able to reduce soybean row stomatal conductance by 22% from a mean of 1063.4 ± 57.7 mmol m⁻² s⁻¹ in control plots to a mean of 834.6 ± 57.7 mmol m⁻² s⁻¹ in AMAPA plots (Fig. 2-9). When compared to the control, soybean as a neighbor reduced soybean row mean stomatal conductance by 11% from 1063.4 ± 57.7 mmol m⁻² s⁻¹ to 944 ± 57.7 mmol m⁻² s⁻¹ (Fig. 2-8).

_Irrigated Field_

There were no overall significant differences in stomatal conductance among treatments during the first sampling date in the irrigated field. During the second sampling date in the irrigated field, there was a significant effect of divider (p=0.0463) on stomatal conductance. Plots containing dividers had a mean stomatal conductance of 1150.7 ± 33.7 mmol m⁻² s⁻¹ and plots without dividers had a mean stomatal conductance of 1247.4 ± 33.7 mmol m⁻² s⁻¹. There was not a significant effect of neighbor (p=0.1495). During the final sampling date, a significant effect of neighbor (p=0.0021) on stomatal conductance was observed in the irrigated field. The mean stomatal conductance in AMAPA neighbor plots was 1055.7 ± 33.7 mmol m⁻² s⁻¹ and the mean stomatal conductance in soybean neighbor plots was 1223.6 ± 33.7 mmol m⁻² s⁻¹, a significant increase of 167.9 mmol m⁻² s⁻¹ (Fig. 2-9).
DISCUSSION AND CONCLUSION

The primary objective of this study was to quantify the effects of Palmer amaranth and soybean competition on the soil moisture availability in a soybean field. The effects of competition differed among years and irrigation levels. Years differed markedly in the timing and extent of rain events (Table 2-1). Not only the difference in total rainfall during the growing season but the manner of those rainfall events. There was a 64.6 mm rainfall decrease between 2016 (484.3 mm) and 2017 (419.7 mm) and the rain event patterns were dissimilar. In 2016, there were shorter periods of rain with heavy downpours and longer intervals between rain events. Almost half of the rainfall for the growing season was observed in September, when water uptake by both plant species was decreasing. In 2017, rain events were more prolonged with steady drizzles, with multiple days of steady rain. This was especially the case in late June into late July. This difference in the rain events may have contributed to the differences observed between year and irrigation.

As expected, when water was not limited, the presence of a divider had no significant effect on the volumetric water content of the soil. The divider was used to separate the two root systems of competing plants. Rohrig and Stutzel (2001) stated that plant competition is the result of two or more plants trying to efficiently acquire a limited resource in an agrosystem. In the non-irrigated field, when water was a limiting resource, soil water content was reduced when the root systems of crop and weed were allowed to compete. This was expected because water wasn’t in limited supply. In 2016, in the non-irrigated field, the conditions were conducive for Palmer amaranth to be very competitive
with soybean thereby having the largest effect on the volumetric water content of the soil by reducing it by the greatest amount in the study.

The periods between rain events coupled with the sandy loam soils present at the test site provided soil conditions in which mild water stress was likely. This condition was ideal for Palmer amaranth, as native of the Sonoran Desert where rainfall events are few and far between with rare intense downpours. Soil moisture conditions by no means got to a critical level in this study but it had been documented that Palmer amaranth can increase its leaf solute concentration to prolong photosynthesis and keep positive leaf turgor thereby allowing stomates to remain open under low soil water conditions (Ehleringer 1985). In times of low soil water availability, Palmer amaranth has been shown to produce deep roots that penetrate below the “hardpan” (compacted soil zone) to acquire water and nutrients (Place et al. 2008). This study suggested that in a well-watered environment, Palmer amaranth may be an inferior competitor for water than soybean however when water becomes limited, it is more efficient in the acquisition and utilization of the available water, allowing it a greater ability to accumulate biomass in a water stressed environment. Forseth et al. (1984) reported that desert Palmer amaranth had a relatively low root:shoot ratio, suggesting that priority was placed on vegetative growth and reproduction when water levels were low. However, when water is not limiting, Palmer amaranth partitioned a greater proportion of total biomass to root production than soybean. (Wright et al. 1999).

When irrigated, soybean effectively left soils with lower values of volumetric water content although all the differences were not statistically significant, both trial years had
soybean plots with lower soil volumetric water content than Palmer amaranth plots. A possible explanation for this can be made when observing intraspecific and interspecific competition in cropping systems. Carvalho and Christoffoleti (2008) argued that intraspecific competition may be highly intense because like individuals in population have identical needs, therefore, making soybean water uptake in monoculture much higher than in competition. Interspecific competition becomes more important when levels for the ambient resources are limiting for both species (Ricklefs 2008). This dynamic was at play in the non-irrigated field when the competing soybean was able to lower the leaf stomatal conductance of the row crop soybean to a greater extent than Palmer amaranth (Fig. 2-13).

In this study, leaf stomatal conductance was used to quantify the level of plant stress the soybean row was under due to the competition from a neighbor plant. Studies have shown that stomatal conductance can be an accurate predictor of a plant’s active transpiration rates often caused by a water stressed environment (Berger et al. 2013; Miyashita et al. 2005; Yunusa et al. 2008). As Palmer amaranth plants got larger and the growing season progressed, they began negatively impacting the leaf stomatal conductance of the soybean row. At the last sampling date, Palmer amaranth as a neighbor reduced soybean stomatal conductance by 14% compared to when soybean was the neighbor in the irrigated field (Fig. 2-15). Soybean when grown in monoculture has an increased competitive capacity. It is forced to germinate, emerge and intercept sunlight at a greater intensity than if it was grown alone. This allows for an initial competitive advantage over Palmer amaranth which takes a longer time to emerge and grow due to its small seed size.
Carvalho and Christoffoleti (2008) noted that dry beans were better competitors than five *Amaranthus* spp. when subjected to a replacement series study.

This study produced some expected outcomes within the non-irrigated field and some unexpected outcomes within the irrigated field. Palmer amaranth reduces soil volumetric water content to the greatest extent as water availability in the soil becomes low (mild water stress conditions). More can be done to improve the experimental design of this study including having greater densities of Palmer amaranth serving as competition because the densities used were not able to achieve the desired effect on soil volumetric water content and soybean stomatal conductance. Studies where significant differences were observed from Palmer amaranth competition had greater weed densities than was used in this study. Soil volumetric water content collection methods may also be improved to get a more concise picture of the soil moisture distribution in the rhizosphere. A suggestion to use soil probes that can be used in different plots and reduces the risk of data loss from unforeseen events in the field such as animal interference may also offer a more precise and reliable way to measure soil volumetric water content.


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Table 2-1. Monthly rainfall, irrigation and mean daytime high temperature at Edisto REC during the 2016 and 2017 soybean growing season.

Table 2-2. ANOVA and Fixed Effect Tests for the non-irrigated field in 2016.

Table 2-3. ANOVA and Fixed Effect Tests for the irrigated field in 2016.
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Table 2-4. ANOVA and Fixed Effect Tests for the non-irrigated field in 2017.

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Table 2-5. ANOVA and Fixed Effect Tests for the irrigated field in 2017.
Figure 2-1. Mean soil volumetric water content as affected by the presence or absence of a divider in the non-irrigated field in 2016 & 2017.
Figure 2-2. Mean volumetric water content as affected by a plant neighbor [Palmer amaranth (AMAPA), soybean or none] in the non-irrigated field in 2016 & 2017.
Figure 2-3. Mean soil volumetric water content as affected by the presence or absence of a divider and neighbor (Palmer amaranth, soybean or none) in the non-irrigated field in 2016.
Fig. 2-4. Mean soil volumetric water content change over time as affected by the presence or absence of a divider in Palmer amaranth (AMAPA) and soybean neighbor plots in the non-irrigated field during the 2016 growing season.
Fig. 2-5. Mean soil volumetric water content change over time as affected by the presence or absence of a divider in Palmer amaranth (AMAPA) and soybean neighbor plots in the irrigated field during the 2016 growing season.
Fig. 2-6. Mean soil volumetric water content change over time as affected by the presence or absence of a divider in Palmer amaranth (AMAPA) and soybean neighbor plots in the non-irrigated field during the 2017 growing season.
Figure 2-7. Soybean row mean stomatal conductance as affected by the presence or absence of a divider in the non-irrigated field at the 08/01/2017 and 08/15/2017 sampling dates.
Figure 2-8. Soybean row mean stomatal conductance as affected by a plant neighbor [Palmer amaranth (AMAPA), soybean or none] in the non-irrigated field at the 08/01/2017 and 08/15/2017 sampling dates.
Figure 2-9. Soybean row mean stomatal conductance as affected by a plant neighbor [Palmer amaranth (AMAPA), soybean or none] in the irrigated field at the 07/31/2017, 08/07/2017 and 09/14/2017 sampling dates.
Figure 2-10. Soybean row mean stomatal conductance as affected by the presence or absence of a divider in the irrigated field at the 07/31/2017, 08/07/2017 and 09/14/2017 sampling dates.
Figure 2-11. Mean volumetric water content as affected by a plant neighbor [Palmer amaranth (AMAPA), soybean or none] in the irrigated field in 2016 & 2017.
Figure 2-12. Mean soil volumetric water content as affected by the presence or absence of a divider in the irrigated field in 2016 & 2017.
Figure 2-13. Mean soil volumetric water content as affected by the presence or absence of a divider and neighbor (Palmer amaranth, soybean or none) in the non-irrigated field in 2017
Figure 2-14. Mean soil volumetric water content as affected by the presence or absence of a divider and neighbor (Palmer amaranth, soybean or none) in the irrigated field in 2016.
Figure 2-15. Mean soil volumetric water content as affected by the presence or absence of a divider and neighbor (Palmer amaranth, soybean or none) in the irrigated field in 2017.
ABSTRACT

In soybean production, Palmer amaranth interference can significantly reduce crop yield depending on the degree of infestation. The majority of competition studies performed on soybean and Palmer amaranth have all centered on the above-ground competition for light and how that affects the yield of soybean. Field studies focusing on the below-ground competition for water and nutrients and their effects on soybean yield are limited. In 2016 and 2017, field experiments were conducted at the Edisto Research and Educational Center near Blackville, SC to evaluate the effect of interspecific below-ground competition between Palmer amaranth and soybean affects soybean yield. The treatment design was a split plot 3x2x2 factorial. The treatment factors consisted of neighbor (Palmer amaranth, soybean, no neighbor), competition-excluding soil divider (with and without) and irrigation (irrigated and non-irrigated). Dividers were plastic sheets placed in the soil between crop and neighbor to eliminate root competition. The response variable measured was soybean yield (soybean seed dry weight). In the non-irrigated field in 2016, the presence of a divider increased the yield of soybean plants by 16.5%. In 2016 in the irrigated field, the divider effect was significant ($p=0.0058; \alpha=0.05$). When a divider
was present, soybean yield was significantly higher (546.7 g ± 33.03) than in treatments without a divider present (390.2 g ± 33.03). A 56.8% yield increase was observed when below-ground competition from Palmer amaranth was eliminated (divider present). In both fields (non-irrigated and irrigated) and both years (2016 and 2017) Palmer amaranth as a plant neighbor caused a greater reduction in soybean yield than soybean as a neighbor. The presence of a divider increased the mean yield across both years and irrigation levels. Overall, below-ground (root) competition from Palmer amaranth reduced soybean yield more than above-ground (shoot) competition.
INTRODUCTION

One of the most studied topics in weed science is competition, more specifically, the aspect of how weeds negatively impact the growth, production and yield of the crop. Begon et al. (1996) defined competition in an agroecosystem as the interaction between individuals brought about by a shared requirement for a limited resource. This competition leads to a reduction in performance of one or both of the competing individuals. Light, water and nutrients are all in limited supply, and the competitive plant gets the better opportunity to achieve the goal of seed production. In the case of an agronomic crop like soybean, whose seed yield is used as a measure of its productivity, growers strive to increase that seed production while minimizing the potential for yield loss.

In South Carolina and the greater south-eastern United States, Palmer amaranth (*Amaranthus palmeri*) has swiftly become a problem weed. In soybean production, Palmer amaranth interference can significantly reduce soybean yield, depending on the level of infestation in a field (Bensch et al. 2003, Klingaman and Oliver 1994). The effects of interspecific competition in soybean have been researched and documented. Soybean morphology, canopy width and yield are affected to varying extents by competition with other individuals (Klingaman and Oliver 1994). The majority of the research on soybean competition has centered on the effect of above-ground competition on soybean yield. Above-ground competition mainly arises from one individual shading the other from sunlight. Shade responses vary with plant species. Soybean plants are very sensitive to shading (Wu YS et al. 2017). Fan Yuanfang et al. (2019) reported that soybean shading
affects leaf morphological parameters and decreases leaf photosynthesis. As important as light interception and above-ground competition are, below-ground resource competition has been reported to have a greater influence on productivity than above-ground competition in many plants (Wilson 1988).

Root morphology has an important effect on a plant’s ability to take up water at the expense of a neighboring competitor. Wright et al. (1999) reported that Palmer amaranth had greater root length and finer roots compared to soybean, despite having a similar overall root mass. They concluded that Palmer amaranth showed a greater potential for rapid root expansion, allowing its roots to occupy a larger area of soil compared to those of a similar-sized soybean plant. They suggested that Palmer amaranth had a competitive advantage over soybean for water uptake and nutrient acquisition. In an agricultural setting, nutrients and water availability can be supplemented, but in the presence of a weed with a competitive advantage over the crop, the manipulation of those essential requirements may become costly.

Depending on soil texture and depth, competition for water can vary drastically. Sandy soils are the predominant soil type in the soybean growing regions of South Carolina and most of the coastal plains in the south-eastern United States. These soils lack the ability to retain much soil water after a rain or irrigation event. The water quickly percolates through the upper profiles of the soil where the majority of soybean root growth occurs. Palmer amaranth, being native to the Sonoran Desert in the south-western United States (Ehleringer 1983), has shallow roots near the soil surface that intercepts sporadic rainfall.
and deep tap roots that can mine for water reserves in times of drought (Forseth et al. 1984). Weed species often require more water than crops (Zimdahl 2007) and Palmer amaranth’s root morphology gives it a competitive edge when competing against agronomic crops. As a C4 plant, Palmer amaranth can accumulate root and shoot mass very quickly, especially in the hot temperatures of South Carolina during the summer months.

The ability to distinguish the effects of above-ground and below-ground competition on soybean yield is difficult in a field setting. Attempts have been made in the greenhouse by placing barriers in the soil to prevent interference of plant roots with each other. In this experiment, we tried to observe how the interspecific competition for soil water between Palmer amaranth and soybean affects soybean yield. The studies were performed in the field to mimic the actual dynamics present in South Carolina soybean production. Plastic barriers were placed in the soil to eliminate the influence of one root system on the other. Moisture sensors monitored soil water content throughout the growing season. We only measured soybean yield as the response to root and shoot competition.
MATERIALS AND METHODS

The experiments were performed at Clemson University’s Edisto Research and Education Center (EREC) near Blackville, SC. Field experiments were conducted on a Clarendon Loamy Sand (fine-loamy, siliceous, thermic Plinthaque Paleudults) in 2016 and 2017. In 2017 the non-irrigated field experiment was conducted on a Fuquay Sand (loamy, siliceous, thermic Arenic Plinthic Paleudults). Soybean variety Asgrow AG75X6 was seeded on June 9, 2016 and Asgrow AG69X6 was seeded on May 30, 2017 in a disc harrowed then strip tilled soil at 32 seeds per meter using a John Deere 1700 Maxemerge XP Planter (Deere & Company, Moline, IL).

The study was a 3x2x2 split-plot factorial treatment design with a completely randomized experimental design containing 3 replications in 2016 and 5 replications in 2017. Treatment factors consisted of three levels of plant neighbor (Palmer amaranth, soybean and none), two levels of soil divider (with divider and without divider) and two levels of irrigation (irrigated and non-irrigated) that served as the whole-plot factor.

Dividers were installed when the soybean (crop row) was at the VC vegetative growth stage. Dividers consisted of 76 cm x 51 cm fluted polypropylene sheets (plastic cardboard) placed parallel and to the right of the soybean row (25 cm away) at a depth of 45 cm in the soil with the top 6 cm being visible above the soil surface. The three neighbor plants were hand planted 51 cm to the right of the soybean row when it was at the VC vegetative growth stage. In plots containing a divider, the divider’s position was between the soybean row and the neighbor plant.
Plots consisted of a 4.6 m long soybean row with the adjacent row to the right (0.9 m away) stripped off. A soybean row existed between plots and acted as a buffer. The study area was kept weed free by hand pulling and hoeing between rows throughout the duration of the study. The irrigated field got watered when necessary depending on soil dryness via a central pivot irrigation system.

Soybean row plants within the competition zone were harvested on November 9, 2016 and October 1, 2017. In 2016, 9 cm of the soybean row was harvested and in 2017, 76 cm of the soybean row was harvested. Soybean were hand threshed in 2016 and threshed using a portable soybean thresher in 2017. Seeds were dried for 72 hours at 50 °C after threshing and soybean yield (seed dry weight) were then recorded.

Yield amounts for 2016 were adjusted to accommodate for the changes made in the 2017 harvest. Soybean yield data was subjected to ANOVA with neighbor and divider as fixed effects and replication as a random effect. Year and irrigation were analyzed separately. Treatment means were separated using Fisher’s LSD using JMP Pro 12.2 (SAS Institute Inc, Cary, NC). The effects of root and shoot competition were calculated as follows; A= yield with the control (no root or shoot competition); B= yield with divider present, p. amaranth neighbor (shoot competition and no root competition) and C= yield with no divider present, p. amaranth neighbor (shoot and root competition). The effect of root and shoot competition was calculated with the formula: A-C. The effect of shoot competition only was calculated with the formula: A-B. The effect of root competition only was calculated with the formula: (A-C)-(A-B).
RESULTS

Field studies are able to give an exact picture and provide identical conditions that are experienced in a producer’s field; however, environmental variability was high across trial years. For this reason, the trial year was analyzed and will be presented separately. The yield data from 2016 was adjusted to reflect the changes made in the yield process in 2017 (increased sample area). On average, greater soybean yields were obtained in the first trial year (2016) than the second trial year (2017). In 2016, the growing season months (June-September) on average had more rainfall (484.3 mm) than in the same period in 2017 (419.7 mm). On average the mean daytime high temperatures for June-September in 2016 was higher than the mean daytime highs for the same period in 2017 (Table 3-1).

In 2016, there was not a significant effect of divider (p=0.3232) or neighbor (p=0.1516) in the non-irrigated field; however, the presence of a divider increased the yield of soybean plants in the soybean row. There was a 16.5% increase in yield from a mean of 495.9 g m⁻¹ row in treatments with no dividers to a mean of 577.8 g m⁻¹ row in treatments with a divider present (Fig.3-1). Palmer amaranth (AMAPA), when placed as the plant neighbor adjacent to the soybean row, reduced soybean yields the most (Fig.3-2). AMAPA, as a neighbor, decreased soybean yield by approximately 33% compared to when no neighbor was present. Soybean as the plant neighbor decreased yield in the soybean row by 12% when compared to the control treatment. Soybean yield increased by 90% in treatments containing AMAPA as a neighbor when a divider was present compared to treatments with AMAPA as neighbor without a divider. The soybean row adjacent to
neighboring AMAPA plants with no divider consistently had the lowest yields in the non-irrigated field in 2016.

In 2016, divider (p=0.0058) was significant; however, neighbor (p=0.1287) and the treatment combination of neighbor by divider (p=0.8843) was not significant in the irrigated field. Soybean yields were significantly higher in treatments without a divider (513.2 g m\(^{-1}\) row) than treatments with a divider (719.7 g m\(^{-1}\) row) (Fig.3-3). Similar to what was observed in the non-irrigated field, AMAPA as a plant neighbor had the greatest effect on soybean yield by lowering it the most (Fig.3-4). Treatments containing AMAPA as a neighbor resulted in a mean yield of 563.2 g m\(^{-1}\) row. A yield difference of 149.1 g m\(^{-1}\) row was observed when comparing treatments containing soybean as a neighbor versus AMAPA as a neighbor. Some significant differences were observed when examining the treatment combination of divider by neighbor. As noted in the non-irrigated field, an increase in soybean yield can be observed between treatments containing AMAPA as a neighbor with a divider present compared to AMAPA as a neighbor without a divider present. A difference of 249.2 g m\(^{-1}\) row representing a 56.8% yield increase was observed from the aforementioned treatment comparison. AMAPA as a neighbor with no divider when compared to soybean as a neighbor with no divider resulted in yields of 438.6 g m\(^{-1}\) row and 621.1 g m\(^{-1}\) row respectively. This difference represents a 41.6% increase in yield when no divider is present and the plant neighbor changes from AMAPA to soybean.

In 2017, a significant effect of neighbor (p=0.0097) was observed in the non-irrigated field. Similar to the previous trial year, treatments containing dividers resulted in
soybean plants in the crop row having higher yields than those where no divider was present (Fig. 3-1). A 12% increase in the mean yield was seen between treatments without a divider (262.5 g m\(^{-1}\) row) versus treatments with a divider (294.6 g m\(^{-1}\) row). Similar to 2016, plots containing AMAPA as a neighbor resulted in the soybean row having the lowest yields (Fig. 3-2). When compared to the control treatments, there was a significant difference in the mean soybean yield when AMAPA was the neighbor. A yield decrease of 66.1 g m\(^{-1}\) row was observed when comparing the control treatment to the AMAPA neighbor treatment. Treatments containing AMAPA as a neighbor with and without a divider exhibited similar results as the previous year; the presence of the divider raised the yield of the soybean in the soybean row from 215 g m\(^{-1}\) row to 268.4 g m\(^{-1}\) row. Similar to what was previously observed, when no divider is present, AMAPA as a neighbor reduced soybean yield (215 g m\(^{-1}\) row) more than soybean as a neighbor (277.6 g m\(^{-1}\) row) representing a statistically significant difference.

In 2017, there was a significant effect of the treatment combination of divider by neighbor (p=0.0211) in the irrigated field. Soybean that had AMAPA as a neighbor with a divider had a much higher yield (370.5 g m\(^{-1}\) row) than when there was not a divider present (232.1 g m\(^{-1}\) row), a difference of 138.4 g m\(^{-1}\) row. There were significant differences between treatments without a divider and either soybean or AMAPA as a neighbor. A mean yield of 347.6 g m\(^{-1}\) row was observed when soybean was the neighbor with no divider and 232.1 g m\(^{-1}\) row when the neighbor changed to AMAPA with no divider, a significant difference of 115.5 g m\(^{-1}\) row. There was a positive response to the presence of a divider as was previously recorded (Fig. 3-5). In treatments containing a divider, the mean soybean
yield was greater (331.8 g m\(^{-1}\) row) compared to treatments without a divider present (318.8 g m\(^{-1}\) row). AMAPA as a neighbor resulted in the adjacent soybean crop having the lowest yield compared to soybean as a neighbor and the control (Fig.3-4).

Overall, the results showed that the presence of a divider increased the mean soybean yield regardless of irrigation or trial year. AMAPA was consistently the neighbor that lowered soybean yield the most irrespective of irrigation or trial year. When no divider was present, AMAPA reduced soybean yield more than soybean as a neighbor regardless of irrigation or trial year. Overall, root competition from AMAPA impacted soybean yield more than shoot competition.
DISCUSSION AND CONCLUSION

Soybean yield can be affected by various factors including light, water, pests and nutrients among others. Light interception is the greatest above-ground factor affecting yield with water and nutrient uptake being the greatest below-ground factors affecting yield. In this experiment, Palmer amaranth’s presence didn’t have an effect on soybean height (data not presented). The height of soybean plants adjacent to the neighboring Palmer amaranth plants (5 plants m\(^{-1}\) row) in the “competition zone” showed no distinct differences in height when compared to the rest of the crop row and the control treatments. The aggressive growth habits of Palmer amaranth eventually led to plants that were taller than the soybean canopy but at a density of 5 Palmer amaranths m\(^{-1}\) row, there was still adequate light reaching the soybean canopy with minimal to insignificant shading during the majority of the day. Soybean being a very shade sensitive plant is able to solar track (diaheliotropism), giving it an advantage in capturing the sunlight needed for photosynthesis (Kao and Forseth 1992). Yao X et al. (2017) reported that the soybean in their study adapted to alterations in the light environment brought on by taller crops in an intercropping system by making morphological and physiological changes thereby enhancing soybean productivity. A study performed by Carvalho and Christoffoleti (2008) found that when water and soil resources are not limiting, dry beans (*Phaseolus vulgaris* L.) were able to be more competitive than five *Amaranthus* species when both species proportions were equal. By controlling the limited below-ground resources, they were able to show that dry bean was a superior competitor than *Amaranthus* spp. above-ground.
In this study, when Palmer amaranth was allowed to compete with soybean (no divider present), the Palmer amaranth was able to significantly lower soybean yields. There were also reductions in soybean yield when below-ground competition was eliminated (divider present) representing the effect of above-ground competition but these were not as pronounced as that of the below-ground competition effect. Palmer amaranth root (below-ground) competition consistently caused greater yield loss than shoot (above-ground) competition for both trial years and irrigation regime (Table 3-2). What makes Palmer amaranth such a better below-ground competitor than soybean? When the root systems of Palmer amaranth and soybean were allowed to inter-mingle and compete for the same water, there were several factors that gave Palmer amaranth an advantage. The distribution of water and nutrients are generally uneven in the soil. A plant’s root length, surface area and spatial arrangement allows it to exploit these unevenly distributed resources in the rhizosphere (Wright et al. 1999). Palmer amaranth is a C4 plant and desert native and is able to develop a vast root system that can quickly and efficiently utilize water during periods of sporadic rain that occurs in its native habitat. These attributes of Palmer amaranth root architecture allow it to successfully compete with agricultural row crops in the southeast U.S. (Berger et al. 2015; Forseth et al. 1984; Ritchie et al. 2009). Wright et al. (1999) showed that Palmer amaranth had greater root lengths than soybean despite having similar masses. In this study, Palmer amaranth had noticeable finer roots than soybean which gave Palmer amaranth a potential for more rapid root extension allowing it to occupy a much larger soil volume than soybean. This indicates that Palmer amaranth possesses the ability to accumulate large amounts of root mass coupled with the root
plasticity to mine deep for water in times when soil water is low. Giving it a greater competitive advantage in the acquisition of nutrients and water especially when those resources are in a limited supply. In this study, water availability in the irrigated and non-irrigated fields never got to critical levels and although root distribution wasn’t measured, it was assumed that Palmer amaranth roots remained relatively shallow within the upper 30 cm of the soil profile; therefore, allowing the extension of Palmer amaranth roots well into the rhizosphere occupied by the soybean crop row. Zimdahl (2007) said that weed species typically require more water than crops and are usually more successful in accessing that water, a point that may have been highlighted by this study.

In an agricultural setting, an advantage that Palmer amaranth holds is its ability to emerge after planting and late into the growing season essentially escaping control methods particularly with herbicide application. The most critical period in soybean production that becomes important in relation to maximizing yield is the seed filling stage. During this stage, grain growth enters a linear phase and most grain mass accumulates (Zheng, Chen and Han 2009). At this stage, water uptake must be maximized by the plant as photosynthesis and transpiration are increased. Interference at this point of water uptake will have a detrimental effect on yield. When this period coincides with Palmer amaranth’s rapid growth and expansion (up to 1 inch per day) there is an ideal situation to drastically affect yield. As was previously noted, competition is pronounced when a resource becomes limited, in this study there were periods when water wasn’t severely limited but in late August 2016 and 2017, seed filling was occurring, and these were the some of the driest months of the growing season at Edisto REC (Table 3-1). When you combine that with the
a rapidly growing Palmer amaranth plant, there was the perfect environment for maximized soybean yield losses.

Much more needs to be done to fully understand the below-ground dynamic that Palmer amaranth and soybean competition presents. Palmer amaranth biomass have been noted to have an allelopathic potential (Menges 1988) leading to questions of whether it produces root exudates capable of plant growth inhibition. These questions can only be answered by more experiments and studies. From the results of this study we can conclude that root (below-ground) competition from Palmer amaranth is the key factor driving the reduction of soybean yield in an agricultural setting.
LITERATURE CITED


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<td>19.1</td>
</tr>
<tr>
<td>July</td>
<td>81</td>
<td>108.9</td>
<td>45.7</td>
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<td>August</td>
<td>77.7</td>
<td>66.8</td>
<td>38.1</td>
</tr>
<tr>
<td>September</td>
<td>215.9</td>
<td>163.5</td>
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</tr>
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</table>

Table 3-1. Monthly rainfall, irrigation and mean daytime high temperature at Edisto REC during the 2016 and 2017 soybean growing seasons.

<table>
<thead>
<tr>
<th>Neighbor</th>
<th>Non-Irrigated Shoot</th>
<th>Root</th>
<th>Irrigated Shoot</th>
<th>Root</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>g m⁻¹ row</td>
<td>g m⁻¹ row</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AMAPA</td>
<td>164.9 26.6</td>
<td>267.1 53.4</td>
<td>0 6.1</td>
<td>249.2 138.4</td>
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<tr>
<td>Soybean</td>
<td>91.2 0</td>
<td>168.4 17.4</td>
<td>0 99.5 182.5 0</td>
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</tr>
</tbody>
</table>

Table 3-2. The reduction of soybean (crop row) yield in grams m⁻¹ row by adjacent Palmer amaranth and soybean (neighbor) shoot and root competition in 2016 and 2017.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F Ratio</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
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<td>190080.00</td>
<td>38016.0</td>
<td>2.3158</td>
<td>0.1083</td>
</tr>
<tr>
<td>Error</td>
<td>12</td>
<td>196992.00</td>
<td>16416.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. Total</td>
<td>17</td>
<td>387072.00</td>
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<table>
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<td>Neighbor</td>
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<td>1</td>
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<td>2</td>
<td>99868.444</td>
<td>3.0418</td>
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Table 3-3. ANOVA and Fixed Effect Tests for the non-irrigated field in 2016.
Table 3-4. ANOVA and Fixed Effect Tests for the irrigated field in 2016.

<table>
<thead>
<tr>
<th>Source</th>
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<th>Prob &gt; F</th>
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</thead>
<tbody>
<tr>
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<td>Error</td>
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<td>117845.33</td>
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</tr>
</thead>
<tbody>
<tr>
<td>Neighbor</td>
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<td>2</td>
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<td>1</td>
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<td>0.0058*</td>
</tr>
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Table 3-5. ANOVA and Fixed Effect Tests for the non-irrigated field in 2017.

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</tr>
<tr>
<td>C. Total</td>
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<th>F Ratio</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neighbor</td>
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Table 3-6. ANOVA and Fixed Effect Tests for the irrigated field in 2017.

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</thead>
<tbody>
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<td>9641.39</td>
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<td>0.0596</td>
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<tr>
<td>Error</td>
<td>24</td>
<td>93018.40</td>
<td>3875.77</td>
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<td>C. Total</td>
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<td>141225.37</td>
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<table>
<thead>
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<th>F Ratio</th>
<th>Prob &gt; F</th>
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<tr>
<td>Neighbor</td>
<td>2</td>
<td>2</td>
<td>12168.867</td>
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<td>0.2287</td>
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<tr>
<td>Divider</td>
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<td>1</td>
<td>740.033</td>
<td>0.1909</td>
<td>0.6660</td>
</tr>
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<td>Divider*Neighbor</td>
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<td>2</td>
<td>35298.067</td>
<td>4.5537</td>
<td>0.0211*</td>
</tr>
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</table>
Figure 3-1. Mean soybean yield as affected by the presence or absence of a divider in the non-irrigated field in 2016 and 2017.
Figure 3-2. Mean soybean yield as affected by a plant neighbor [Palmer amaranth (AMAPA), soybean or none] in the non-irrigated field in 2016 and 2017.
Figure 3-3. Mean soybean yield as affected by the presence or absence of a divider in the irrigated field in 2016 and 2017.
Figure 3-4. Mean soybean yield as affected by a plant neighbor [Palmer amaranth (AMAPA), soybean or none] in the irrigated field in 2016 and 2017.
CHAPTER FOUR
THE SENSITIVITY OF SOYBEAN SEEDLINGS TO PALMER AMARANTH
(Amaranthus palmeri) AND PITTED MORNINGGLORY (Ipomoea lacunosa)
RESIDUES IN THE SOIL.

ABSTRACT

Reduced-till and no-till soybean production are currently increasing in popularity. As these practices become more widespread, more crop and weed residues are being introduced into the soil. To investigate the effects of weed residue on crop growth, a greenhouse study was conducted to determine the effects of varying concentrations of Palmer amaranth (Amaranthus palmeri) and pitted morning glory (Ipomoea lacunosa) plant residues (aboveground portion of the plant) on soybean production. The study was arranged in a completely randomized experimental design with 5 treatments and 5 replications. Treatments consisted of Palmer amaranth residues and pitted morning glory residues that were each incorporated into soil in concentrations of 20,000, 40,000, 80,000 and 160,000 ppm. A soybean seed was sown in each pot and allowed to grow for 8 weeks before harvesting. Soybean dry weight, leaf area and leaf tissue nutrient content were recorded during the study. There was an overall decrease in soybean dry weight and leaf area as Palmer amaranth residue increased in the soil. In trial 1, Palmer amaranth residues of 160,000 ppm and 80,000 ppm in the soil significantly reduced soybean dry weight by 53% and 38% respectively. In trial 2, Palmer amaranth residues of 160,000 ppm and 80,000 ppm in the soil significantly reduced soybean dry weight by 53% and 38% respectively.
ppm significantly reduced soybean leaf area by 97% and 94% respectively. Pitted morningglory residues had no significant effect on soybean growth. The results of this study demonstrated the allelopathic potential of Palmer amaranth residues and the susceptibility of soybean to the allelochemicals present in those residues. An increase in Palmer amaranth residue was shown to reduce soybean growth and development and may ultimately reduce soybean yields.
INTRODUCTION

Field preparation at the start of the growing season or after harvest varies depending on whether a producer chooses conservative or aggressive methods of soil preparation. Soil preparation may be achieved through conventional tillage or ploughing or by more conservative methods like strip tilling. Disc harrowing followed by strip tilling to create crop rows are sometimes paired together. In soybean (*Glycine max* L. Merr) fields, shallow tilling is practiced for weed control in fall-planted fields. Recently, reduced-till and no-till soybean production have become more popular as producers seek to reduce input costs. A common problem that arises with the reduced and no-till techniques is the incorporation of leftover crop and weed residues (above-ground portion of plants) into the upper soil profile. In many instances, these are viewed as good methods of weed control because the majority of all plants and grasses are killed during these procedures, especially when using a disc harrow. This may generally be a good practice that promotes a healthy soil by recycling the nutrients present in the plant residues; however, in some instances, increased residues from plants known to have inhibitory or allelopathic effects may lead to reduced yield, seed germination and overall crop health (Bhowmik and Doll 1982, 1984; Menges 1988). Although not common in an agricultural setting and, specifically row-crop production, researchers have reported inhibition of crop growth after specific plant residues were incorporated into soil (Menges 1987).

In South Carolina and most of the south-eastern US, Palmer amaranth (*Amaranthus palmeri* S. Watson) has become a nuisance to control in row-crop production. Its ability to
germinate and grow at both ends of the growing season often makes it the first significant
weeds to emerge and the last weed present at harvest. Palmer amaranth is responsible for
yield losses in soybean (Klingaman and Oliver 1994), and its presence at harvest hinders
the proper use of harvesters. Palmer amaranth’s growth habit and its resilience in drought-
prone, low nutrient soils increase its competitiveness with crops (Ward et al. 2013).
Currently, resistance to multiple herbicide modes-of-action (Heap 2019) has aided some
Palmer amaranth biotypes in their pervasive spread as they become increasingly difficult
to control chemically. Since Palmer amaranth has become a relatively recent problem in
the south-east US, research and studies have begun to intensify as information on how to
effectively control this weed is gathered. This information has been used to determine what
mechanisms it employs to aid in its spread and establishment in soybean fields.

An early study done in Wisconsin found that redroot pigweed (Amaranthus
retroflexus), a relative of Palmer amaranth, reduced soybean yield when its residue was
incorporated into soil before planting (Bhowmik and Doll 1982). Other studies have also
shown that Palmer amaranth soil incorporated residues have an inhibitory effect on
cabbage and carrot seedlings (Menges 1988). A possible conclusion from these studies may
be that Palmer amaranth is using some novel chemistry to help it thrive in crop production
fields. That claim may not be made before investigating what is going on in this weed-crop
competition dynamic. As stated earlier, in many instances, the introduction of plant
residues to a soil should promote the healthy growth of plants. This can be attributed to the
introduction of organic matter and nutrients found in the plant residue, similar to the effect
of composting. If the opposite occurs and plant growth and seed germination are
suppressed, we may claim that there are some phytotoxic chemicals being released by the plant residues either from the roots or shoot, that negates the positive effects of the presence of organic matter and nutrients that are being introduced into the soil that result in the promotion of plant growth.

Some plants possess the ability to produce and release allelopathic chemicals in their immediate vicinity that inhibit plant growth and or seed germination of other plants (Pratley 1996; Putnam 1994; Weston 1996). When there is a perceived threat, plants may induce the production of allelochemicals, in other instances, this defense mechanism is constitutive, and those chemicals are produced regardless of a perceived threat or competition from other plants. In some cases, the allelochemicals are only effective on non-kin species (Bais et al. 2003; Hierro and Callaway 2003) to prevent the competition from other plants into its habitat. These allelochemicals are released in different ways; from exudates produced in the plant roots, volatilization, decomposition of residues and from shoot allelochemicals that are released to soil through leaf litter (Chou 1999). The main purpose of these defenses is to give the plant an added advantage when trying to grow and thrive in the presence of other plants.

Studies on the ability of Palmer amaranth to inhibit plant growth are limited. Phenolic acids have been referred to as putative allelochemical (Kato-Noguchi 2011) and their production by Palmer amaranth may suggest the use of allelopathy, however allelopathy is often the result of several compounds working together (Fujii and Hiradate 2007) and their discovery and isolation are beyond the scope of this study. Our objective
with this study was to determine the effect of Palmer amaranth residue on the growth and wellness of soybean plants. This was achieved by performing dose-response experiments with the shoot residues of greenhouse grown Palmer amaranth, pitted morningglory (*Ipomoea lacunosa*) or an inert plastic material incorporated into soil.
MATERIALS AND METHODS

The study was conducted at the Biosystems Research Complex Greenhouse facility of Clemson University located at Clemson, SC in 2017 and 2018. Palmer amaranth and pitted morningglory plants were allowed to grow for 8 weeks in individual plastic pots using a commercial potting soil mix. Plants were harvested at the soil surface level and the shoot material was oven dried for 72 hours at 50 °C. The dried plants were then ground to pass through a 2-mm sieve using a Wiley mill. The resulting ground plant material (residue) were stored in zip-lock bags and refrigerated at 28 °C for subsequent use.

The study was arranged in a completely randomized experimental design that consisted of 5 treatments and 5 replications and the experiment was repeated twice. The 5 treatments consisted of varying weights of plant residue material incorporated into soil. The control treatments contained no plant residue (0 ppm), the 20,000 ppm treatment contained 12g of plant residue material, the 40,000 ppm treatment contained 24g of plant material, the 80,000 ppm treatment contained 48g of plant residue material and the 160,000 ppm treatment contained 96g of plant residue material. Each treatment was thoroughly incorporated into 600g of potting soil mix and then placed in a plastic pot. The 25 plastic pots were then sown with three soybean seeds each (to maximize the probability of seed germination). When all the soybean seedlings reached the unifoliate growth stage, the first emerging seedling was kept for the remainder of the study and the others were removed. The above procedure was repeated using pitted morningglory residues and an inert shredded plastic material.
All the plants (N=75) were allowed to grow for 7 weeks. Plants were watered when necessary using an overhead sprinkler system and subjected to a 16-hour daylight period. After 7 weeks, leaf area measurements were taken for each plant using a LI-COR LI-3100C leaf area meter (LI-COR Biosciences Inc, Lincoln, NE). The shoots of each plant were individually bagged and oven dried for 72 hours at 50 °C. After drying, the dry weight of each plant was recorded and each sample was sent to the Clemson Agricultural Services Lab for plant tissue nutrient analysis tests.

Data collected were analyzed using regression analysis and one-way ANOVA in JMP Pro 12.2 (SAS Institute Inc, Cary, NC). Treatment means were separated using Fisher’s Protected LSD.
RESULTS

*Palmer amaranth residue*

In the Palmer amaranth (AMAPA) residue trials there was an overall decrease in soybean dry weight as the AMAPA residue concentration in the soil increased in both trials 1 and 2. The regression analysis yielded slopes of -5.40 ($R^2 = 0.48$) and -4.97 ($R^2 = 0.81$) respectively (Fig. 4-1). The same trend was observed with the leaf area values where both trials 1 and 2 regression analysis yielded lines with slopes of -501.2 ($R^2 = 0.21$) and -742.7 ($R^2 = 0.75$) respectively (Fig. 4-1).

There were significant effects on soybean dry weight at higher concentrations of AMAPA residue; the mean soybean dry weight steadily decreased as the AMAPA residue in the soil increased. This resulted in the treatments with lower concentrations of AMAPA residue (20,000 ppm and 40,000 ppm) being significantly different to the treatments with higher AMAPA residue concentrations (80,000 ppm and 160,000 ppm). In trial 1, AMAPA residues of 160,000 ppm in the soil reduced soybean dry weight by 53% from a mean of 11.2 g to 5.2 g (Table 4-1). AMAPA residues of 80,000 ppm in the soil reduced soybean dry weight by 38% from a mean of 11.2 g to 6.9 g (Table 4-1). A significant drop in soybean dry weights (33%) was observed when AMAPA residue concentration in the soil was increased from 40,000 ppm to 80,000 ppm, reflecting a treatment mean change from 10.4 g to 6.9 g (Table 4-1). In trial 1, the lower AMAPA concentrations (20,000 ppm and 40,000 ppm) were all statistically similar without any significant differences but as the
concentrations increased exponentially, significance was observed at the top end of the concentration (80,000 ppm and 160,000 ppm).

The trend of a decrease in soybean dry weights as AMAPA residue concentration in soil increased that was observed in trial 1 is comparable to what was observed in trial 2. The treatments containing lower concentrations of AMAPA residue in the soil (20,000 ppm and 40,000 ppm) were similar to each other (Table 4-3) but were significantly different to the treatments containing higher levels of AMAPA residue (80,000 ppm and 160,000 ppm). In trial 2, the mean dry weights of soybean were lower, resulting in the leaf area also being lower than those of trial 1 however no statistical interaction was observed between trials (Fig. 4-1). Trial 2 exhibited greater treatment differences among AMAPA residue concentrations and lower values for leaf area and dry weight but the same trend as trial 1 was ultimately observed.

Soybean leaf area decreased as the AMAPA residue concentration increased. Leaf area being an indicator of plant fitness and growth would be expected to mirror the same overall trend observed with the soybean dry weight. The lower the plant mass the lower the total leaf area measurement is expected to be. In trial 1, the treatments containing 20,000 ppm and 40,000 ppm AMAPA residue in the soil exhibited very similar mean leaf area totals (Table 4-2). There were greater differences in treatment means as the AMAPA residue concentration in the soil increased however those differences weren’t statistically significant. There were no significant differences in treatments but a clear decrease in leaf area was observed as the AMAPA residue concentrations in the soil increased. The
negative slope from the regression analysis clearly highlights this (Fig. 4-1). In trial 2, there were significant differences among treatments that mirrored what was observed with the soybean dry weights. The greatest expected decrease in soybean leaf area was seen between the 160,000 ppm AMAPA residue treatment and the control treatment (0 ppm), where the soybean leaf area was decreased by 97% from 861cm$^3$ to 22cm$^3$ (Table 4-4). A 94% decrease in leaf area was observed between the control (0 ppm) and the 80,000 ppm AMAPA residue treatment. Increases in AMAPA residue in the lower concentration treatments (20,000 ppm and 40,000 ppm) did not achieve large decreases in soybean leaf area; a 21% decrease compared to 49% decrease achieved with the higher concentration treatments (80,000 ppm and 160,000 ppm). In general, there were more pronounced differences among treatments observed in trial 2 than trial 1 however, no significant interaction was observed between trials (Fig. 4-1).

The pattern observed with the nutrient concentration within soybean plant tissue goes contrary to what was expected. As the AMAPA residue concentrations in the soil increased the expected outcome was to see the macronutrient levels become more deficient however the opposite occurred. Phosphorous leaf tissue concentrations showed significant differences among treatments; the treatments containing a higher concentration of AMAPA residues in the soil (80,000 ppm and 160,000 ppm) had greater levels of phosphorous in their tissues. The treatments containing a lower concentration of AMAPA residue in the soil (20,000 ppm and 40,000 ppm) showed significantly lower phosphorous levels in their tissue compared to the other 2 treatments. There was a 546% increase in the levels of soybean plant tissue phosphorous from the control treatment (0 ppm) to the treatment
containing 160,000 ppm AMAPA residue in soil (Table 4-7). Potassium showed a similar increase in concentration in soybean tissue as the AMAPA residue concentration increased. The two treatments containing the higher concentration of AMAPA residue in the soil had potassium levels in the plant that were beyond the range of sufficiency levels in soybean plants (3000 ppm – 6000 ppm). Potassium concentration levels followed the pattern of the previous macronutrients; as the AMAPA residue concentration in the soil increased, the potassium concentration in soybean plant tissue also increased. The treatments containing higher concentrations of AMAPA residue (80,000 ppm and 160,000 ppm) had potassium levels way beyond the sufficient range (>22,500 ppm) and the lower AMAPA concentration treatments (20,000 ppm and 40,000 ppm) had potassium levels falling within the sufficient range for soybean (Table 4-8).

Nitrogen concentration in soybean leaf tissue significantly increased as the AMAPA residue concentration increased among treatments however, unlike the other macronutrients, the 80,000 ppm AMAPA residue concentration treatment was the only treatment to fall within the sufficient range for nitrogen in soybean. The 160,000 ppm AMAPA residue concentration treatment fell really close to the upper limits of the sufficiency range (32,500 ppm – 50,000 ppm) resulting in the remaining 3 treatments being deficient in nitrogen (Table 4-9).

**Pitted Morningglory and plastic residue**

Pitted morningglory (IPOLA) residues showed a different trend when compared to AMAPA. Visually there were slight decreases in soybean dry weights as the IPOLA
residue concentrations increased however these changes weren’t statistically significant. Regression analysis yielded a line with a slope of -3.4 ($R^2 = 0.12$) (Fig. 4-2) versus a -5.4 slope (Fig. 4-1) when AMAPA residues were used. Soybean leaf area, like soybean dry weights had no significant differences between IPOLA residue concentration treatments. The soybean plants didn’t show any visual signs of distress or stunting while they were growing, and all seedlings emerged (VE growth stage) within the first 3-5 days after planting.

Plastic residue (shavings) when added to the soil in the identical treatment concentrations as the previous two plant residues produced no significant differences among treatments. Regression analysis yielded almost flat slopes for both soybean dry weight and leaf area index (Fig. 4-3).
DISCUSSION AND CONCLUSION

The experiment demonstrated that as the concentration of Palmer amaranth residue increased exponentially in the soil the growth rate and overall plant fitness of soybean seedlings decreased. The same was not observed with the incorporation of pitted morningglory residues into the soil. With everything else remaining constant (soil in pots, water applied per pot and light) we can deduce that the Palmer amaranth residue concentration increase is actively inhibiting the growth of soybean seedlings. From the daily observation of individual soybean plants, (data not reported) a case can be made that the suppression of soybean growth may be attributed primarily to slow germination along with slow leaf and stem growth.

It took the control treatment (0 ppm) about 3-4 days for 100% of the seedlings to be at the VE (emergence) growth stage. Within 7 days, 100% of those seedlings were already at the VC (cotyledons) growth stage. As the Palmer amaranth residue concentration increased, there were slight delays in respective treatments reaching those growth stage milestones. There were negligible differences in the growth stages observed between the 20,000 ppm and 40,000 ppm Palmer amaranth residue concentration treatments, with about a 1-day delay between them and the control. A major difference was observed with the 80,000 ppm and 160,000 ppm Palmer amaranth residue concentration treatments; after 7 days the 80,000 ppm treatment had 80% of the seedlings at VE and 20% of the seedlings hadn’t emerged yet. In the 160,000 ppm treatment, after 7 days, 20% of the seedlings were at VC and 80% were yet to emerge.
After 10 days the 0 ppm and 20,000 ppm residue treatments were all at the unifoliate leaf growth stage and appeared healthy with slight variations in height, the 40,000 ppm residue treatment showed a little more pronounced differences in height and appearance compared to the 0 ppm and 20,000 ppm residue treatments. After 10 days, the 80,000 ppm residue treatment had seedlings that were all at VC and the 160,000 ppm residue treatment samples had 40% at VC, 20% at VE and 40% were yet to emerge. Identical concentrations of morningglory and plastic residues did not significantly delay soybean emergence. By observing the emergence and the time it takes for soybean seedlings to reach different growth milestones it is safe to say that the Palmer amaranth residue present in the soil delayed soybean germination and inhibited seedling growth as its concentration increases.

Phenolic acids and associated compounds derived through the shikimic acid pathway are the most common type of growth inhibitors produced in living plants or released by the decomposition of plant parts by microbial action or leaching (Patterson 1981). In this study, the delay in soybean germination resembles the results found by Gardener et al. (1990). They reported that the compound hexanal inhibited soybean germination and subsequent growth. Hexanal is biosynthesized in plants by the action of lipoxygenase and hydroperoxide lyase on linoleic acid in plants (Sekiya et al. 1986). Various other phenolic compounds including caffeic, t-cinnamic, p-coumaric, ferulic, gallic and vanillic acid, at certain concentrations have all been reported as growth inhibitors in soybean (Patterson 1981). Extensive research hasn’t been done on the phenolic compounds present in Palmer amaranth, so definitive answers regarding the specific compounds present in Palmer amaranth tissue residues doesn’t exist but it may be safe to
presume that those phenolic compounds present in Palmer amaranth are the primary drivers behind the inhibition of soybean germination and subsequent soybean growth.

The leaf area accumulation of a plant is directly related to its leaf cell expansion ability (Taiz and Zeiger 2010), this measurement declined as Palmer amaranth residue increased in the soil. Various stress factors and conditions may contribute to the inhibition of leaf cell production and expansion, including water and salt stress (Taiz and Zeiger 2010) among others. In this experiment water levels in all the plants were kept at a sufficient level however the uptake of water by those plants was a parameter not measured. The increased organic matter (Palmer amaranth residue) in the soil may have altered the ability of the soybean seedlings to uptake water, leading to a water stressed environment in their cells. The complexity of the various pathways and circumstances that lead to reduced leaf area are vast however the underlying problem is one that was initiated by the presence of phenolic acids/allelochemicals from Palmer amaranth residues in the soil. Blum and Dalton (1985) reported that the primary detectable effect of phenolic acids on cucumber seedlings was the inhibition of leaf expansion. A reduction in the hydraulic conductivity of cucumber seedlings resulting in reduced water uptake and decreased water potential (Booker et al. 1992) and those are some other primary effect of phenolic acids.

The vast scope of isolating and determining the specific phenolic compounds present in Palmer amaranth plant residues are beyond this study. When pure compounds from fresh Palmer amaranth residue are introduced into the soil, microorganisms facilitate their decay and metabolize these compounds resulting in a vast array of new substances,
some being allelopathic. Further study must be performed to determine what specific compounds or pathways in soil lead to the inhibition of soybean growth by Palmer amaranth residues. This study was able to highlight the presence of inhibitory substances in Palmer amaranth plant residues that soybean producers who use practices that introduce Palmer amaranth residues to their fields should be mindful of. The evidence from this study supports the claim that Palmer amaranth residues introduced to soils can have a significant effect on soybean growth and fitness.
LITERATURE CITED


Figure 4-1. Soybean dry weight and leaf area vs Palmer amaranth residue dose for individual trials.
Figure 4-2. Soybean dry weight and leaf area vs morningglory residue dose for combined trials.

$R^2$: 0.121  
$P$-Value = 0.0135

$R^2$: 0.042  
$P$-Value = 0.1520
Figure 4-3. Soybean dry weight and leaf area vs plastic residue dose for combined trials.
Figure 4-4. Soybean plant growth as affected by Palmer amaranth residue concentration in soil.
<table>
<thead>
<tr>
<th>Dose (ppm)</th>
<th>- Dose (ppm)</th>
<th>Difference</th>
<th>Std Err Dif</th>
<th>Lower CL</th>
<th>Upper CL</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>160000</td>
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<td>1.559</td>
<td>2.750</td>
<td>9.254</td>
<td>0.0010*</td>
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Table 4-1. Differences report for soybean dry weight vs Palmer amaranth residue trial 1.

<table>
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<tr>
<th>Dose (ppm)</th>
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<th>Difference</th>
<th>Std Err Dif</th>
<th>Lower CL</th>
<th>Upper CL</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>20000</td>
<td>160000</td>
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<td>1124.315</td>
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</tr>
<tr>
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<td>160000</td>
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<td>-80.471</td>
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</tr>
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Table 4-2. Differences report for soybean leaf area vs Palmer amaranth residue trial 1.

<table>
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<tr>
<th>Dose (ppm)</th>
<th>- Dose (ppm)</th>
<th>Difference</th>
<th>Std Err Dif</th>
<th>Lower CL</th>
<th>Upper CL</th>
<th>p-Value</th>
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<tbody>
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<td>0</td>
<td>40000</td>
<td>3.712</td>
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<td>2.484</td>
<td>4.940</td>
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</tr>
<tr>
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<td>160000</td>
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<td>1.942</td>
<td>4.398</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>20000</td>
<td>80000</td>
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<td>0.589</td>
<td>1.772</td>
<td>4.228</td>
<td>&lt;.0001*</td>
</tr>
<tr>
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<td>1.590</td>
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<td>3.504</td>
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<td>0.878</td>
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</table>

Table 4-3. Differences report for soybean dry weight vs Palmer amaranth residue trial 2.
<table>
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<th>Dose (ppm) - Dose (ppm)</th>
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<th>Std Err Dif</th>
<th>Lower CL</th>
<th>Upper CL</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 160000</td>
<td>3.987</td>
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</tr>
<tr>
<td>0 - 40000</td>
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</tr>
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<td>1.874</td>
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</tr>
<tr>
<td>20000 - 80000</td>
<td>2.500</td>
<td>1.874</td>
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<td>6.2746</td>
<td>0.1889</td>
</tr>
<tr>
<td>20000 - 40000</td>
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<td>1.874</td>
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<td>0.2855</td>
</tr>
<tr>
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<td>-2.557</td>
<td>4.8936</td>
<td>0.5534</td>
</tr>
<tr>
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<td>1.874</td>
<td>-2.919</td>
<td>4.6296</td>
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</tr>
<tr>
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</tr>
<tr>
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</table>

Table 4-4. Differences report for soybean leaf area vs Palmer amaranth residue trial 2.

<table>
<thead>
<tr>
<th>Dose (ppm) - Dose (ppm)</th>
<th>Difference</th>
<th>Std Err Dif</th>
<th>Lower CL</th>
<th>Upper CL</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
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<td>263.349</td>
<td>-203.542</td>
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</tr>
<tr>
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</tr>
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</table>

Table 4-5. Differences report for soybean dry weight vs pitted morningglory residue combined trials.

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<tr>
<th>Dose (ppm) - Dose (ppm)</th>
<th>Difference</th>
<th>Std Err Dif</th>
<th>Lower CL</th>
<th>Upper CL</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 160000</td>
<td>39.910</td>
<td>263.349</td>
<td>-490.501</td>
<td>570.321</td>
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</tr>
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</table>

Table 4-6. Differences report for soybean leaf area vs pitted morningglory residue combined trial
<table>
<thead>
<tr>
<th>Dose (ppm)</th>
<th>Replications</th>
<th>Mean (ppm)</th>
<th>Std Error</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
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<td>22620</td>
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<td>1878.6</td>
<td>14434</td>
<td>22442</td>
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</table>

Table 4-7. One-way ANOVA means table for soybean leaf tissue phosphorous content.

<table>
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<tr>
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<th>Replications</th>
<th>Mean (ppm)</th>
<th>Std Error</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
</tr>
</thead>
<tbody>
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<td>23033</td>
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<td>1277.1</td>
<td>20531</td>
<td>25975</td>
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<tr>
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</table>

Table 4-8. One-way ANOVA means table for soybean leaf tissue potassium content.

<table>
<thead>
<tr>
<th>Dose (ppm)</th>
<th>Replications</th>
<th>Mean (ppm)</th>
<th>Std Error</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
</tr>
</thead>
<tbody>
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<td>380.5</td>
<td>14877</td>
<td>31096</td>
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</table>

Table 4-9. One-way ANOVA means table for soybean leaf tissue nitrogen content