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Postemergence and Residual Control of Glyphosate-Resistant Palmer Amaranth (Amaranthus Palmeri) with Dicamba

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Postemergence and residual control of glyphosate-resistant palmer amaranth (*Amaranthus palmeri*) with dicamba

By

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On-farm research was conducted in 2011 and 2012 to determine the postemergence and residual control by dicamba of glyphosate-resistant (GR) Palmer amaranth (*Amaranthus palmeri* S. Wats.). Preemergence dicamba at 0, 0.28, 0.56, and 1.1 kg ae ha^{-1} and 0.07 kg ae ha^{-1} flumioxazin was applied at 30, 15 and 0 days prior to planting. Postemergence dicamba at 0.28, 0.56, and 1.1 kg ae ha^{-1} with and without 0.84 kg ae ha^{-1} glyphosate was applied to 5, 10 and 15 cm Palmer amaranth. In addition, a greenhouse experiment was conducted in 2012 to evaluate and confirm the optimum rate for control of Palmer amaranth with a new formulation of dicamba (BAS 18322H). In the greenhouse, dicamba at 0.14, 0.28, 0.56, 1.1, and 2.2 kg ae ha^{-1} was applied to 5, 10, and 15 cm Palmer amaranth.

DEDICATION

I would like to dedicate this work to my parents, Clarence and Sandra Edwards. Throughout my education you have provided support without any hesitation and I deeply thank you for that. I would like to thank Tiffany Key for her encouragement and support. I would also like to extend my gratitude to Tyler and Lori Gann and my niece, Emma Clair for offering kind words of encouragement through the tough times. Without the support of these people and many more, I would not be where I am today.

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CHAPTER I

INTRODUCTION

The introduction of glyphosate-resistant (GR) crops in 1996 fundamentally changed agricultural systems (Owen 2000). Adoption of GR crops was very rapid, and now herbicide-resistant biotechnology has risen to account for 93% of soybean [*Glycine max* (L.) Merr.] production in the U.S. (U.S. Department of Agriculture [USDA] 2012). Prior to the introduction of GR soybean weed control programs were dominated by dinitroaniline and imidazolinones herbicides from 1992 to 1996, along with acetolactate synthase (ALS) inhibitors (Young 2006). The extensive adoption of GR technology led to a reduction in the use of these herbicides (Young 2006; Whitaker et al. 2010) and many growers rely solely on glyphosate as a primary means of weed control (Foresman and Glasgow 2008; Gustafson 2008; Green 2009). This overreliance on glyphosate has resulted in the evolution of numerous GR species, greatly reducing the viability of glyphosate-only herbicide systems (Whitaker et al. 2010). The first documented GR weed from continuous use of glyphosate in a GR crop was horseweed [*Conyza canadensis* (L.) Cronq.] in 2000, only three years after solely relying on glyphosate for weed control (VanGessel 2001). Now, 24 weed species have been reported as GR (Heap 2013). Some of these GR species include: Palmer amaranth [*Amaranthus palmeri* (S.) Wats.], spiny amaranth (*Amaranthus spinosus* L.), tall waterhemp [*Amaranthus tuberculatus* (Moq.)

Sauer], giant ragweed (*Ambrosia trifida* L.), horseweed, goosegrass [*Elusine indica* (L.) Gaertn], Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot.], and johnsongrass [*Sorghum halepense* (L.) Pers.] (Heap 2013).

Palmer amaranth, often called careless weed, is native to the Sonoran Desert, which spans the Mexican states of Sonora and Baja California and parts of southeastern Arizona and California (Ehleringer 1983). Palmer amaranth is one of ten other North American native dioecious *Amaranthus* species, including common waterhemp (*Amaranthus rudis* (S.)), and tall waterhemp, which have become major weeds in row crops (Steckel 2007). Of the *Amaranthus* spp. mentioned, Palmer amaranth has spread the furthest from its origin and is now a problematic weed in all Mid-South and Southeastern states (Steckel 2007). Confirmed GR Palmer amaranth was first reported in Georgia in 2004 (Culpepper et al. 2006) followed by Arkansas, North and South Carolina, Tennessee, and Mississippi (Norsworthy et al. 2008; Scott et al. 2007; Steckel et al. 2008; York et al. 2007; Nandula et al. 2009).

Palmer amaranth is dioecious, meaning that male and female flowers occur on different plants. Research has indicated that these dioecious *Amaranthus* species, especially common waterhemp and tall waterhemp, are able to hybridize and form a highly variable polymorphic species known as *Amaranthus tuberculatus* (Moq.) Sauer (Pratt and Clark 2001). Palmer amaranth can be distinguished by alternate ovate leaves which often have V-shaped variegation, with petioles as long as or longer than the leaf (Steckel 2007). A distinguishable characteristic between female and male Palmer amaranth plants are 3 to 4 mm long sepals which are minutely pointed on the tip as opposed to 2 to 3 mm long lanceolate sepals on the male plant (Bryson and DeFelice

2009). Seed production of Palmer amaranth can be as high as 600,000 seeds per female plant. These seeds have a higher germination rate compared to other *Amaranthus* species (Keeley at al. 1987; Steckel et al. 2004). *A. palmeri* grows rapidly and can reach heights of 2 m or more (Horak and Loughin 2000; Whitaker et al. 2010). Horack and Loughin (2000) reported that out of four *Amaranthus* species tested, *Amaranthus palmeri* had the highest growth rate, accumulating 0.21 and 0.18 cm per growing degree day. Along with rapid growth, Palmer amaranth is able to withstand drought conditions, which allow it to survive and grow during unfavorable conditions (Ehleringer 1983; Place et al. 2008; Wright et al. 1999). It also readily adapts to shading (Jha et al. 2008), which allow it to compete under light-limited environments such as dense crop canopies (Whitaker et al. 2010). Due to the competitive characteristics of Palmer amaranth, this weed has become one of the most competitive weeds of crop production (Klingaman and Oliver 1994), as evidenced by soybean yield reductions of up to 68% at 10 plants per m^2 (Norsworthy et al. 2008).

Palmer amaranth is among the most herbicide resistance-prone dicots, with resistance now confirmed to herbicide mechanisms of action in the U.S. including: dinitroanilines, ALS-inhibitors, photosystem II inhibitors, glycines, and hydroxyphenylpyruvate dioxygenase (HPPD) inhibitors (Norsworthy et al. 2008; Gossett et al. 1992; Gaeddert et al. 1997; Culpepper et al. 2006; Thompson et al. 2012; Heap 2013). Palmer amaranth populations exhibiting multiple-resistance to glycine and ALS-inhibiting herbicides have been confirmed in Mississippi and Georgia (Nandula et al. 2012; Sosnoskie et al. 2011). Glyphosate has historically been very efficacious on Palmer amaranth (Corbett et al. 2004; Culpepper and York 1998; Parker et al. 2005; Whitaker et al. 2010). However, applying glyphosate alone over wide areas on highly variable prolific weeds made the evolution of resistant weeds inevitable (Owen 2001; Thill and Lemerle 2001; Green 2009).

With the widespread distribution of GR Palmer amaranth in soybean, alternative control options are needed. As such, Monsanto Company, the developer of glyphosate-resistant crops, has added dicamba resistance to the Genuity® Roundup Ready 2 Yield® platform which will be marketed as Genuity® Roundup Ready 2 Yield® Xtend (Monsanto Company, St. Louis, MO). Dicamba-resistant soybean could potentially offer a new herbicide mechanism-of-action to manage Palmer amaranth and other troublesome weeds (Behrens et al. 2007; Subramanian et al. 1997). Soybean is usually very sensitive to dicamba, as evidenced by 37% injury from a postemergence application at V3 of dicamba at 0.56 kg ae ha^{-1} 2 weeks after treatment (Kelley et al. 2005). Another study by Feng et al. (2010) evaluated injury of conventional soybean and dicamba-resistant soybean at 28 days after a preemergence and/or postemergence application of dicamba at various rates; results from this particular study indicate complete death of conventional soybean treated with dicamba at 0.55 kg ha^{-1} and little to no injury on dicamba-resistant soybean, even at the highest rate used (5.0 kg ha^{-1}). Dicamba resistance is conferred by a bacterial *O*-demethylase enzyme that is able to metabolically inactivate dicamba within the plant. (Herman et al. 2005). This enzyme was derived from a dicamba monooxygenase (DMO) and was isolated from a soil bacterium, *Pseudomonas maltophilia*, which was introduced into the plant through *Agrobacterium*-mediated gene transfer to create dicamba-resistant soybean (Behrens et al. 2007). Krueger et al. (1989) first reported the isolation of microorganisms capable of degrading dicamba from soil and water samples which were obtained from a dicamba manufacturing plant.

Dicamba was commercialized in the 1960's, and current commercial formulations include Clarity® and Banvel® (BASF, Florham Park, NJ), which are labeled for use in soybean, cotton, and corn (Feng et al. 2010). Clarity® may be applied preemergence at 15 to 30 days prior to planting cotton and soybean but only after 2.5 cm of accumulated rainfall or irrigation at rates of 0.27 to 0.55 kg ha^{-1}. Similar rates of Clarity® may be applied preemergence or early postemergence in corn but crop injury is possible depending on growth stage, germplasm, use rates, and environmental conditions (Feng et al. 2010).

Dicamba is a synthetic auxin herbicide which is readily absorbed by plants via shoot and root uptake, is translocated through the plants system by both symplastic (including phloem) and apoplastic (including xylem) pathways, and accumulates in areas of active growth (WSSA 2007; Ashton and Crafts 1981). Auxinic herbicides are structurally similar to plant hormones often referred to as auxins or indole-3-acetic acid (IAA). IAA is vital to regulate cell division and elongation and long-range signaling for systemic communication among various plant organs (Mithila et al. 2011; Grossman 2010; Went 1926). Dicamba mimics the natural plant hormone IAA, leading to an epinastic response in broadleaf weed species, eventually leading to chlorosis and necrosis (WSSA 2007). These herbicides generally regulate cell division and elongation and developmental processes including vascular tissue and floral meristem differentiation, leaf initiation, phyllotaxy, senescence, apical dominance and root formation (Grossman 2010). Recent research has led to new theories of auxin carrier-mediated transfer within plants. Chapman and Estelle (2009) indicates that when auxin concentrations are low in plant tissues, auxin responsive genes are not expressed due to the presence of Aux/IAA repressor proteins that bind to the promoters of auxin-responsive genes. As auxin concentrations increase and promote gene expression by ubiquitin-mediated degradation of transcriptional repressors (Aux/IAA), thereby activating gene expression by a novel "release from repression" mechanism (Mithila et al. 2011). Auxins accomplish this by binding to the bottom of the T1R1 pocket and acting as "molecule glue" that stabilizes the interaction between the auxin reception protein homologs and its substrates in an auxin dependent manner (Guilfoyle 2007; Tan et al. 2007; Mithilia et al 2011).

The auxin herbicides are often classified intro four groups, depending on structural and chemical properties: phenoxyalkanoic acids (eg. 2,4-D), benzoic acids (eg. dicamba), pyridines (eg. picloram), and quinolinecarboxylic acids (e.g. quinclorac) (Mithila et al. 2005). Physiological activity of these herbicides depends largely on the resemblance of their structure to those of endogenous auxins, and their persistence in the plant (Coupland 1994). These herbicides often exhibit selectivity to various weeds due to decarboxylation, side chain degradation, and side chain elongation, as a result of rapid conversion of parent molecules from aryl hydroxylation, and glycoside conjugate formation (Coupland 1994; Owen 1991; Hagin et al. 1970; Broadhurst et al. 1966). Dicamba offers control of many annual broadleaf weeds including *Amaranthus* species (WSSA 2007). Norsworthy et al. (2008) indicated 97 to 100% control of six-leaf GR Palmer amaranth with dicamba applied at 0.28 kg ha^{-1}.

Auxinic herbicides 2,4-D and MCPA were the first truly selective herbicides, and their discovery was revolutionary for agriculture (Coupland 1994). Since the independent discovery of these compounds by English and American researchers during the 1940's, 30 weeds have evolved resistance to auxinic herbicides (Heap 2013; Mithila et al. 2011). Dicamba was commercialized for agricultural use for over 50 years ago, and during this time five weed species have been reported as dicamba-resistant: common hempnettle (*Galeopsis tetrahit* L.), kochia (*Kochia scoparia* L.), wild mustard (*Sinapis arvensis* L.), common lambsquarters (*Chenopodium album* L.) and prickly lettuce (*Lactuca serriola* L.) (Heap 2013). In 1990 the first documented case of dicamba-resistance occurred in wild mustard in fields near Minto, Manitoba (Jasieniuk et al. 1995; Heap and Morrison 1992). The most recently documented dicamba-resistant weed, prickly lettuce, was located adjacent to a research farm near Pullman, Washington in 2007; this population of prickly lettuce was also confirmed to be cross resistant with dicamba, 2,4-D, and MCPA (Burke et al. 2009).

Despite long-term use of these herbicides, the incidence of auxin-resistance has remained low, as compared to glyphosate usage and resistance issues since GR crops were introduced (Jasieniuk et al. 1995). Coupland (1994) indicates that it has been difficult to resolve the mechanism-of-action of auxinic herbicides due to the multiplicity of biochemical effects within the cell and this may play a role in the evolution of resistance. However, Preston et al. (2009) reports that resistance to dicamba in kochia is likely conferred by a single allele with a high degree of dominance.

The overall objective of this research is to determine the optimum utilization of dicamba-resistant soybean technology to manage troublesome weed species in Mississippi. Specific objectives of this research include (1) determine residual activity of field-applied dicamba on Palmer amaranth emergence, (2) evaluate various rates of dicamba to determine the most efficacious rates and timings for the postemergence control of GR Palmer amaranth and (3) greenhouse confirmation of optimum dicamba rates for control of Palmer amaranth.

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CHAPTER II

PREEMERGENCE AND POSTEMERGENCE EFFICACY OF DICAMBA ON GLYPHOSATE RESISTANT PALMER AMARANTH (*Amaranthus palmeri* S. Wats.) AND OPTIMUM RATE FOR CONTROL

Abstract

A two year experiment was conducted in the Mississippi Delta in 2011 and 2012 to determine the most efficacious rates and timings for the preemergence and postemergence control of glyphosate-resistant (GR) Palmer amaranth with dicamba. In addition, a greenhouse experiment was conducted to confirm the optimum rate for control of Palmer amaranth with a new formulation of dicamba (BAS 18322H). Preemergence field experiments included dicamba at 0, 0.28, 0.56, and 1.1 kg ae ha^{-1} and were compared to 0.07 kg ae ha^{-1} flumioxazin. These treatments were applied at 30, 15, and 0 days prior to planting. Postemergence field experiments included dicamba at 0.28, 0.56, and 1.1 kg ae ha^{-1} applied with and without 0.84 kg ae ha^{-1} glyphosate to 5, 10, and 15 cm Palmer amaranth. In the greenhouse, dicamba at 0.14, 0.28, 0.56, 1.1, and 2.2 kg ha^{-1} was applied to 5, 10, and 15 cm Palmer amaranth.

Introduction

The extensive adoption of glyphosate-resistant (GR) technology from the 1990's through the mid 2000's led to a reduction in the use of herbicides other than glyphosate (Young 2006; Whitaker et al. 2010). During that time many growers relied only on glyphosate for weed control (Foresman and Glasgow 2008; Gustafson 2008; Green 2009). This has led to evolution of GR biotypes, which has reduced or eliminated the viability of glyphosate-only herbicide systems (Whitaker et al. 2010). Of the weeds that have evolved GR, Palmer amaranth (*Amaranthus pameri* S. Wats.) has become the most problematic in the southeastern United States (Steckel 2007). In addition, Palmer amaranth populations have also been confirmed to exhibit multiple-resistance to glycine and ALS-inhibiting herbicides in Mississippi and Georgia (Nandula et al. 2012; Sosnoskie et al. 2011).The development of dicamba/glyphosate-resistance in soybean and cotton could provide an alternative mechanism-of-action (MOA) to GR cropping systems to control Palmer amaranth (Behrens et al. 2007; Subramanian et al. 1997).

Auxinic herbicides 2,4-D and MCPA were the first truly selective herbicides, and their discovery was revolutionary for agriculture (Coupland 1994). Dicamba, also an auxinic herbicide, was commercialized in the 1960's, and commercial formulations include Clarity® and Banvel® (BASF, Florham Park, NJ), which are labeled for use in soybean, cotton, and corn (Feng et al. 2010). Clarity®[1] may be applied preemergence 15 to 30 days prior to planting cotton and soybean at rates of 0.27 to 0.55 kg ae ha^{-1} but after 2.5 cm of accumulated rainfall or irrigation. Similar rates of Clarity may be applied preemergence or early postemergence in corn.

[1] Clarity®, BASF Agricultural Products, Research Triangle Park, NC 27709.

Dicamba, which has been used in row crops for many years, has proved to provide control of many annual broadleaf weeds including *Amaranthus* species (WSSA 2007). Dicamba has been proven to control *Amaranthus* species, as evidenced by 97 to 100% control of GR Palmer amaranth at the six-leaf stage with dicamba applied at 0.28 kg ha^{-1} (Norsworthy et al. 2008).

Due to the evolution of GR weeds, interest in the utility of dicamba for an alternative control option is increasing. Dicamba has become a common herbicide for early preplant applications in the spring and has been shown to provide greater than 86% control of GR horseweed (*Conyza canadensis* L. Cronq.) (Owen et al. 2009). Another experiment by Eubank et al. (2008) found that the addition of 2,4-D and dicamba to paraquat improved control of GR horseweed (78 to 89%). However, crop injury can be expected on soybean if the dicamba label is not closely followed.

A study by Feng et al. (2010) evaluated injury of conventional soybean and dicamba-resistant soybean 28 days after a preemergence and postemergence application of dicamba at various rates; results from this particular study indicate complete death of conventional soybean treated with dicamba at 0.55 kg ha^{-1} with little to no injury on dicamba-resistant soybean, even at the highest rate observed (5.0 kg ha^{-1}). Thompson et al. (2007) reported soybean sensitivity to preemergence applications of dicamba applied within 14 days of planting. However, dicamba and other auxinic herbicides vary in soil persistence, depending on environmental conditions such as soil moisture (Cheng and Lehmann 1985). Other research by Altom and Stritzke (1973) indicates that dicamba is persistent and has a half-life in various soils that vary from 7 to 32 days.

Auxinic herbicides do not affect a single target site and they do not have long-term residual activity, which has led to the belief that these compounds are "low-risk" for resistance development (Coupland 1994). Despite commercialization of dicamba in agriculture over 50 years ago, the incidence of resistance has remained low, compared to glyphosate usage and resistance issues since GR crops were introduced (Jasieniuk et al. 1995). According to Heap (2013), five weed species have been reported as dicamba-resistant in cropland: common hempnettle (*Galeopsis tetrahit* L.), kochia (*Kochia scoparia* L.), wild mustard (*Sinapis arvensis* L.), common lambsquarters (*Chenopodium album* L.) and prickly lettuce (*Lactuca serriola* L.).

Dicamba is more specifically classified as a synthetic auxin herbicide, which is readily absorbed by shoot and root uptake and is translocated through the plants system by both phloem and xylem pathways accumulating in areas of active growth (WSSA 2007; Ashton and Crafts 1981). The auxinic herbicides are structurally similar to plant hormones indole-3-acetic acid (IAA), often referred to as auxins. The plant hormone IAA is vital to regulate cell division and elongation along with long-range signaling for systemic communication among various plant organs (Mithila et al. 2011; Grossman 2010; Went 1926). These herbicides generally regulate the functions of IAA in vascular tissue and floral meristem differentiation, leaf initiation, phyllotaxy, senescence, apical dominance and root formation (Grossman 2010). Dicamba mimics the natural plant hormone IAA, resulting in epinastic response in broadleaf weed species, eventually leading to chlorosis and necrosis (WSSA 2007).

The auxin herbicides exhibit selectivity to various weeds and are often classified intro four groups, depending on structural and chemical properties: phenoxyalkanoic acids (e.g. 2,4-D), benzoic acids (e.g. dicamba), pyridines (e.g. picloram), and quinolinecarboxylic acids (e.g. quinclorac) (Mithila et al. 2005). Selectivity of these herbicides depends largely on the resemblance of their structure to endogenous auxins within the plant (Coupland 1994). Selectivity is due to decarboxylation, side chain degradation, and side chain elongation, as a result of rapid conversion of parent molecules from aryl hydroxylation, and glycoside conjugate formation (Coupland 1994; Owen 1991; Hagin et al. 1970; Broadhurst et al. 1966).

A new technology in the pipeline for commercialization is dicamba-resistant soybean, which will be marketed as Genuity® Roundup Ready 2 Yield® Xtend (Monsanto Company, St. Louis, MO). Along with this new technology are new formulations of a traditional chemistry. Monsanto Company and BASF Corporation are collaborating together to bring the dicamba-resistant soybean technology to market with intentions to develop individual formulations of dicamba to be used for this cropping system. BASF will introduce BAS 18322H, a new low volatile formulation of dicamba. The dicamba-resistant soybean system will allow producers the option of applying dicamba as an additional MOA in-season and prior to planting for control of GR Palmer amaranth along with other broadleaf weeds. Research is needed to evaluate the level of efficacy that can be obtained with new dicamba formulations.

The overall objective of this research is to determine the optimum utilization of dicamba-resistant soybean technology to manage troublesome weed species in Mississippi. The specific objectives include (1) to determine residual activity of field-applied dicamba on Palmer amaranth emergence, (2) field experiments to evaluate various rates of dicamba to determine the most efficacious rates and timings for the postemergence control of GR Palmer amaranth and (3) greenhouse experiments to evaluate and confirm the optimum rate for control of Palmer amaranth with the new BAS 18322H formulation of dicamba.

Materials and Methods

Field experiments were conducted in 2011 and 2012 at on-farm locations in the Mississippi Delta. In 2011, two on-farm locations were used to conduct field experiments. Location One (34°34'N, 90°46'W) near Greenville, Mississippi consisted of Commerce very fine sandy loam soil and more specifically classified as an Inceptisol, with a pH of 5.9, an organic matter of 0.96%, and a cation exchange capacity (CEC) of 9.6. Location Two (33°35'N, 91°07'W) near Jonestown, Mississippi consisted of Dubbs and Dundee very fine sandy loam soil which was classified as Alfisols, with a pH of 6.2, an organic matter of 0.72% and a CEC of 12.3. In 2012, field experiments were only conducted at the Greenville, Mississippi location. Both locations were naturally infested with established populations of GR Palmer amaranth. These on-farm locations have been in row crop production for many years with the Greenville location mostly devoted to GR soybean production and the Jonestown location having rotations of GR corn (*Zea mays* L.) in 2010 and GR cotton (*Gossypium hirsutum* L.) in 2009 prior to this research.

Treatments at the Greenville location were applied with a tractor-mounted sprayer calibrated to deliver 140 L ha^{-1} at a pressure of 248 kPa. Treatments at the Jonestown location were applied with a CO_2 pressurized backpack sprayer which was also calibrated to deliver 140 L ha^{-1} at a pressure of 262 kPa. Tee Jet®[2] flat fan nozzles were used for all applications.

The preemergence experiment was a factorial arrangement of treatments in a randomized complete block design. Factor One included four rates of dicamba[3] at 0, 0.28, 0.56, and 1.1 kg ae ha^{-1}, Factor Two being application timings of 30, 15, and 0 days prior to planting. Flumioxazin[4] at 0.07 kg ae ha^{-1} was applied as a comparison treatment of residual activity. All treatments contained paraquat[5] at 0.75 kg ae ha^{-1} and NIS[6] (non-ionic surfactant) at 0.25% v/v.

Treatments were visually rated at 7, 14, 21, and 28 days after treatment (DAT). Visual ratings were based on a scale from 0 to 100%, with 0 representing no residual control and 100% representing no emergence of plants within a plot. At 28 DAT, two 1-m^2 areas of each plot were hand harvested to collect plant density counts and above-ground biomass for Palmer amaranth. Plant biomass samples were oven-dried for 7 days at 66 C. These two areas were averaged and plant density and biomass was calculated as a percent reduction based on the nontreated plot of each replication (Equation 2.1).

Percent reduction = (Plant density or biomass of nontreated - plant density or biomass of treatment)/plant density or density of nontreated x100 [2.1]

In 2011, preemergence applications were made on March 29, April 11, and April 21. Daytime temperatures during this time frame ranged from 16 to 27 C. Overall rainfall accumulations at both locations were sufficient for activation of residual activity. In

[2] Tee Jet®, Spraying Systems Co., Wheaton, IL 60189.
[3] Dicamba, Clarity®, BASF Agricultural Products, Research Triangle Park, NC 27709.
[4] Flumioxazin, Valor SX®, Valent U.S.A. Corporation, Walnut Creek, CA 94596.
[5] Paraquat, Gramoxone SL®, Syngenta, Greensboro, NC 24719.
[6] Non-Ionic Sufactant, Induce®, Helena Chemical Company, Collierville, TN 38017

2012, applications were made on April 23, May 8, and May 23. Daytime temperatures in 2012 ranged from 21 to 32 C, which was slightly warmer than the prior year. Rainfall in 2012 was almost half the amount received 2011, which did not provide residual activation at several application timings.

Data were analyzed in ANOVA, and means were separated using Fisher's protected LSD at $p \leq 0.05$ through SAS[7] PROC MIXED v.9.2. Locations were analyzed as site-years and were included as a random statement with DAT and herbicide treatment as main effects.

The postemergence experiment was a factorial arrangement of treatments in a randomized complete block design. Factor One included three rates of dicamba at 0.28, 0.56, and 1.1 kg ae ha^{-1}, Factor Two was two rates of glyphosate[8] at 0 and 0.84 kg ae ha^{-1} and Factor Three being plant heights of 5, 10, and 15 cm Palmer amaranth. Visual ratings were taken 7, 14, 21, and 28 DAT. Visual ratings were made on a scale from 0 to 100%, with 100% being completely controlled and 0% representing no visual effects. Plant density counts and above-ground biomass for Palmer amaranth were collected 28 DAT from the average of two 1-m^2 areas of each plot. Plant biomass samples were oven-dried for 7 days at 66 C. Plant biomass were calculated as a percent reduction based on the nontreated plot of each replication (Equation 2.1).

Data were analyzed in ANOVA, and means were separated using Fisher's protected LSD at $p \leq 0.05$ through SAS PROC GLIMMIX v.9.2. Locations were

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[7] SAS, Version 9.2, SAS Institute, Inc., SAS Campus Dr., Cary, NC 27513.
[8] Glyphosate, Roundup PowerMax®, Monsanto Company, St. Louis, MO 63167.

analyzed as site-years and were included as a random statement with plant height, biomass, and herbicide treatment as main effects.

A greenhouse experiment was conducted in 2012 at the R.R. Foil Research Center in Starkville, Mississippi for confirmation of the optimum rate of dicamba for control of GR Palmer amaranth. The experiment was a factorial arrangement of treatments in a randomized complete block design. Factor One included five rates of dicamba (BAS 18322H) at 0.14, 0.28, 0.56, 1.1, and 2.24 kg ae ha^{-1} and Factor Two was plant heights of 5, 10, and 15 cm Palmer amaranth.

Confirmed GR Palmer amaranth seed was collected from prior field experiment plots and grown in flats to be transplanted at the seedling stage into individual 10 by 10 cm pots. Each pot was filled with a commercial potting mix[9] and contained one plant. Plants were fertilized and sub-irrigated as needed. Treatments were made in a spray chamber calibrated to deliver 140 L ha^{-1} with a Tee Jet® flat fan spray tip at 400 kPa.

Visual ratings were made at 7, 14, 21 and 28 DAT. Visual ratings were based on a scale from 0 to 100%, with 0% representing no visual effects and 100% representing complete control. At 28 DAT, Palmer amaranth plants were hand harvested to collect plant density and above-ground biomass. Plant biomass was calculated as a percent reduction based on the nontreated plot of each replication (Equation 2.1).

Data were analyzed in ANOVA, and means were separated using Fisher's protected LSD at $p \leq 0.05$ through SAS PROC GLIMMIX v.9.2. Trials were repeated in time and included as a random statement with plant height, biomass, and herbicide treatment as main effects.

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[9] Metro-Mix 360, Sun Gro Horticulture, Vancouver, British Columbia.

Results and Discussion

Preemergence experiment

There were no interactions between rating intervals and herbicide treatments; however, they were independently significant ($p \leq 0.05$). Application timings were not significant and data were pooled across the three timings accordingly. Data will be discussed as herbicide treatments pooled across rating intervals and also as rating intervals pooled across all herbicide treatments.

Flumioxazin controlled Palmer amaranth 95% and was similar to 0.56 and 1.1 kg ha^{-1} dicamba at 75 and 85%, respectively (Table 2.1). However, control of Palmer amaranth was greater with flumioxazin compared to the lowest rate of dicamba at 0.28 kg ha^{-1} which controlled only 66%. All treatments resulted in greater control at the 14 day rating by controlling Palmer amaranth 87% (Table 2.2). All treatments at 21 and 28 day rating intervals significantly declined and controlled Palmer amaranth 81 and 72%, respectively.

There was no significant interaction between herbicide rate and application timing for plant density and biomass reductions of Palmer amaranth. Therefore, data were pooled over application timings and discussed according to herbicide treatments. Flumioxazin reduced Palmer amaranth plant density by 88%, which was greater than 0.28 kg ha^{-1} dicamba which reduced plant density 16% compared to the nontreated (Table 2.3). Dicamba at 0.56 and 1.1 kg ha^{-1} and flumioxazin reduced plant biomass of Palmer amaranth between 75 and 92%. Dicamba at 0.28 kg ha^{-1} only reduced plant biomass 25%.

Over the length of this study, application timings between March 29 and May 23 did not affect residual activity and persistence of dicamba or flumioxazin on Palmer amaranth. Residual activity of herbicide treatments on Palmer amaranth was greatest at the 14 day rating interval and declined at each rating interval thereafter. These results indicate that dicamba applied preemergence at 0.56 kg ha^{-1} or higher offers residual control of Palmer amaranth comparable to flumioxazin, the standard residual herbicide used in this experiment. However, residual control of dicamba will not persist as long as flumioxazin, as seen during the wet conditions in 2011. In drier years, as in 2012, dicamba can be very persistent in the soil (Altom and Stritzke 1973). Dicamba should be evaluated in combination with residual herbicides such as flumioxazin to provide consistent residual control of Palmer amaranth. The improved residual control of dicamba during dry conditions or environments is only a benefit of dicamba persistence and should not be solely relied on for preemergence control of Palmer amaranth. Future research should include various rates of dicamba in combination with residual herbicides to determine if dicamba provides additional control.

Postemergence experiment

At 14 and 28 DAT, significant interaction was present between herbicide treatments and plant height. For the purpose of this paper, only the 14 and 28 DAT efficacy ratings will be discussed. Glyphosate alone at 0.84 kg ha^{-1} controlled 5 cm Palmer amaranth 39 and 30% 14 and 28 DAT, respectively (Table 2.1). All treatments containing dicamba, regardless of rate, improved control of 5 cm Palmer amaranth over glyphosate alone at both 14 and 28 DAT. Dicamba alone at 0.56 and 1.1 kg ha^{-1} were comparable and controlled 5 cm Palmer amaranth between 81 and 88% 14 DAT and between 90 and 95% 28 DAT, respectively. The lowest rate of dicamba, at 0.28 kg ha^{-1}, controlled 5 cm Palmer amaranth between 76 and 82% 14 and 28 DAT, respectively. The addition of glyphosate to dicamba did not significantly improve control of 5 cm Palmer amaranth over dicamba alone treatments 14 and 28 DAT.

As weed size increased to 10 cm, glyphosate alone controlled Palmer amaranth only 28 and 17% 14 and 28 DAT, respectively (Table 2.1). Dicamba alone at 0.28, 0.56, and 1.1 kg ha^{-1} controlled 10 cm Palmer amaranth 60, 70, and 80%, respectively, 14 DAT. Dicamba alone at 0.28, 0.56, and 1.1 kg ha^{-1} controlled 10 cm Palmer amaranth 61, 75, and 87%, respectively, 28 DAT. Glyphosate, when used in combination with all rates of dicamba, did not improve control of 10 cm Palmer amaranth compared to dicamba alone 28 DAT. However, 14 DAT glyphosate used in combination with dicamba at 0.56 and 1.1 kg ha^{-1} controlled 10 cm Palmer amaranth between 78 and 83%.

Glyphosate controlled 15 cm Palmer amaranth only 11% 14 and 28 DAT (Table 2.1). Dicamba alone at 0.56 and 1.1 kg ha^{-1} controlled 15 cm Palmer amaranth 60 and 71% 14 DAT and 68 and 79% 28 DAT, respectively. The addition of glyphosate to 0.56 kg ha^{-1} dicamba improved control of 15 cm Palmer amaranth to 67% compared to only 60% control with dicamba alone 14 DAT. When glyphosate was used in combination with 0.56 and 1.1 kg ha^{-1} dicamba, no significant increase in control of 15 cm Palmer amaranth was provided 28 DAT. However, the addition of glyphosate applied in combination with the lowest rate of 0.28 kg ha^{-1} dicamba increased control of 15 cm Palmer amaranth 28 DAT but not at 14 DAT. Dicamba alone at 0.28 kg ha^{-1} controlled 15 cm Palmer amaranth only 52%, compared to the combination of 0.28 kg ha^{-1} dicamba plus glyphosate which controlled 60% 28 DAT.

A significant interaction between herbicide treatment and plant height occurred for plant density at the 5 and 15 cm timings, but not at the 10 cm timing. Glyphosate alone only reduced plant density of 5 cm Palmer amaranth by 24% (Table 2.2). Plant density of 5 cm Palmer amaranth was reduced with all dicamba treatments compared to glyphosate alone or the nontreated. All treatments containing dicamba reduced 5 cm plant density from 49 to 82% compared to the nontreated. At the 10 cm timing, a reduction in plant density only occurred with dicamba alone at 0.56 kg ha^{-1} and dicamba at 0.56 and 1.1 kg ha^{-1} with the combination of 0.84 kg ha^{-1} glyphosate; this reduction was not different from other treatments including glyphosate alone. The result of increased plant density at the 10 cm timing is likely due to rainfall following the application, which promoted Palmer amaranth emergence and decreased residual activity of dicamba. Glyphosate alone and dicamba alone at 0.28, 0.56 kg ha^{-1} and dicamba at 0.28 kg ha^{-1} in combination with 0.84 kg ha^{-1} glyphosate resulted in an increase in plant density compared to the nontreated. Due to rainfall after application, these treatments provided a reduction in plant competition which allowed Palmer amaranth emergence but did not provide sufficient residual activity to prevent emergence. Glyphosate alone at 0.84 kg ha^{-1} on 15 cm Palmer amaranth increased plant density above the nontreated check by 6% which is likely a result of reduced plant competition allowing emergence of Palmer amaranth. At the 15 cm timing, all treatments containing dicamba reduced plant density compared to glyphosate alone and the nontreated.

A significant interaction between herbicide treatment and plant biomass occurred at each application timing. Glyphosate applied alone reduced plant biomass of 5 cm Palmer amaranth only 4% compared to the nontreated(Table 2.2). All dicamba treatments reduced 5 cm Palmer amaranth plant biomass compared to glyphosate alone and the nontreated. Dicamba at 1.1 kg ha^{-1} with and without glyphosate reduced 5 cm plant biomass between 89 and 92%; however, these treatments only reduced plant biomass greater than glyphosate alone and dicamba at 0.28 kg ha^{-1} with 0.84 kg ha^{-1} glyphosate. Glyphosate applied alone reduced 10 cm plant biomass by 11% compared to the nontreated. All dicamba treatments, excluding dicamba at the lowest rate of 0.28 kg ha^{-1}, applied at the 10 cm timing reduced plant biomass from 64 to 89%. Glyphosate applied alone at the 15 cm timing reduced plant biomass that was not different from the nontreated. All dicamba treatments reduced plant biomass at the 15 cm timing. Dicamba at 1.1 kg ha^{-1} applied alone or in combination with 0.84 kg ha^{-1} glyphosate reduced plant biomass from 83 to 87%, which was greater than the 63% reduction with 0.28 kg ha^{-1} dicamba.

Dicamba alone at 0.56 kg ha^{-1} controlled 5, 10 and 15 cm Palmer amaranth 90, 75, and 68% 28 DAT, respectively. Dicamba at the highest rate of 1.1 kg ha^{-1} controlled 5, 10, and 15 cm Palmer amaranth 95, 87, and 79% 28 DAT, respectively. A greenhouse study by Norsworthy et al. (2008) conflicts with the findings of this study in that the control of six-leaf (5-10 cm) Palmer amaranth with 0.28 kg ha^{-1} dicamba was less than 97 to 100% control.

Plant density and biomass was reduced with all dicamba treatments at the 5 and 15 cm timing compared to glyphosate alone and the nontreated. At the 10 cm timing, no significant reductions in plant density were observed among all dicamba and glyphosate treatments compared to the nontreated. This is likely the result of wet conditions which promoted Palmer amaranth emergence and decreased the residual activity of dicamba at the 10 cm timing.

Results from this two year postemergence experiment indicate that dicamba, even at the highest rate of 1.1 kg ha^{-1} did not control 5 cm Palmer amaranth 100%. These experiments were conducted at locations with very high populations of naturally occurring GR Palmer amaranth (up to 1120 plant m^2) which may contribute to the level of efficacy observed. Dicamba provided a viable option for managing GR Palmer amaranth; however, it could not be used as a one-pass herbicide program for GR Palmer amaranth control. Dicamba will be a fundamental component of herbicide programs to manage GR Palmer amaranth in soybean and other crops but sequential applications or tank mixtures of other herbicides will be required to achieve acceptable levels of control.

Greenhouse experiment

At 14 and 28 DAT, a significant interaction was present between dicamba rate and plant height and findings will be reported as herbicide treatments for each application timing 14 and 28 DAT. All rates of dicamba controlled 5 cm Palmer amaranth more than 86% 14 DAT and 91% 28 DAT (Table 2.3). Dicamba at 1.1 and 2.2 kg ha^{-1} both controlled 5 cm Palmer amaranth 99% 28 DAT. Dicamba rates of 0.14, 0.28, and 0.56 kg ha^{-1} controlled 10 cm Palmer amaranth 30, 44, and 51% 14 DAT, respectively. By 28 DAT, dicamba at 0.14, 0.28, and 0.56 kg ha^{-1} controlled 10 cm Palmer amaranth 66, 78, and 87%, respectively. The higher rates of dicamba at 1.1 and 2.2 kg ha^{-1} controlled 10 cm Palmer amaranth between 68 and 71% 14 DAT and between 96 and 98% 28 DAT. Dicamba rates of 0.14, 0.28, and 0.56 kg ha^{-1} controlled 15 cm Palmer amaranth only 25, 39, and 41% 14 DAT, respectively. By 28 DAT, efficacy increased and dicamba at 0.14, 0.28, and 0.56 kg ha^{-1} controlled 15 cm Palmer amaranth 54, 64, and 74%, respectively.

Dicamba at higher rates of 1.1 and 2.2 kg ha^{-1} controlled 15 cm Palmer amaranth between 45 and 51% 14 DAT and 84 and 91% 28 DAT.

A significant interaction occurred between dicamba rate and plant height when analyzing percent plant biomass reductions. However, when data were analyzed by plant height, there was no interaction among dicamba treatments at the 5 cm timing, unlike at the 10 and 15 cm timing where treatment interactions did occur.

All dicamba treatments provided a significant reduction of plant biomass for 5, 10 and 15 cm Palmer amaranth compared the nontreated. All rates of dicamba resulted in plant biomass reductions of 5 cm Palmer amaranth between 86 and 94% but no differences were observed among rates used (Table 2.4). Dicamba at 0.14 and 0.28 kg ha^{-1} both reduced 10 cm Palmer amaranth plant biomass 51%. Dicamba at 0.56 and 1.1 kg ha^{-1} reduced 10 cm plant biomass between 72 and 81%; dicamba at 1.1 kg ha^{-1} was not significantly lower than dicamba at 2.2 kg ha^{-1} which reduced 10 cm plant biomass 84%. Dicamba at 0.14 and 0.28 kg ha^{-1} reduced 15 cm Palmer amaranth plant biomass between 39 and 41%. Dicamba treatments at 0.56 and 1.1 kg ha^{-1} also reduced 15 cm plant biomass between 58 and 66%; however, 1.1 kg ha^{-1} dicamba was not significantly lower than dicamba at 2.2 kg ha^{-1} which reduced 15 cm plant biomass 78%.

Results from this greenhouse experiment indicate that smaller weed size is imperative when optimizing control of Palmer amaranth with dicamba, especially at rates lower than 1.1 kg ha^{-1}. Efficacy of dicamba at all rates was greater for the greenhouse experiment compared to the same treatments in the field experiment. This increase in control is likely the result of a controlled environment and not directly associated with the difference in formulations of dicamba. However, field research should be conducted to confirm if differences in control of Palmer amaranth exist with BAS 18322H compared to other formulations of dicamba. All rates of dicamba resulted in a reduction of plant biomass for 5, 10, and 15 cm Palmer amaranth. No significant differences occurred between dicamba rates for the reduction of plant biomass of 5 cm Palmer amaranth. However, dicamba treatments at 1.1 and 2.2 kg ha^{-1} provided the greatest reduction in plant biomass of 10 and 15 cm Palmer amaranth. This data suggests there is no benefit to applying dicamba at 2.2 kg ha^{-1} as opposed to 1.1 kg ha^{-1} for the control of 5, 10 and 15 cm Palmer amaranth. Dicamba applied at 1.1 kg ha^{-1}, controlled 5, 10, and 15 cm Palmer amaranth 99, 96, and 84%, respectively. However, the expected use rate will be 0.5 kg ha^{-1} of dicamba which controlled 5, 10, and 15 cm Palmer amaranth 97, 87, and 74%, respectively.

Table 2.1 Preemergence control of Palmer amaranth with dicamba and flumioxazin.

Herbicide	Rate	Control[a]
	kg ae ha^{-1}	——%——
Dicamba	0.28	66b
Dicamba	0.56	75ab
Dicamba	1.1	85ab
Flumioxazin	0.07	95a

Data are pooled over rating intervals and application timings.
[a] Means within a column followed by the same letter are not significantly different based on Fisher’s protected LSD at $p \leq 0.05$.

Table 2.2 Preemergence control of Palmer amaranth based rating intervals after initial treatment.

Rating interval[a]	Control[b]
	——%——
14 DAT	87a
21 DAT	81b
28 DAT	72c

Data are pooled over herbicide treatments and application timings.
[a] Abbreviations: DAT, days after treatment.
[b] Means within a column followed by the same letter are not significantly different based on Fisher's protected LSD at $p \leq 0.05$.

Table 2.3 Percent reduction of Palmer amaranth density and biomass 28 DAT with dicamba and flumioxazin applied preemergence[a].

		Reduction[b]	
Herbicide	Rate	Plant density	Plant biomass
	kg ae ha^{-1}	——————%——————	
Dicamba	0.28	16c	25b
Dicamba	0.56	54ab	75a
Dicamba	1.1	40bc	73a
Flumioxazin	0.07	88a	92a

Data were calculated as a percent reduction of the nontreated check.
[a] Abbreviation: DAT, days after treatment.
[b] Means within a column followed by the same letter are not significantly different based on Fisher's protected LSD at $p \leq 0.05$.

Table 2.4 Postemergence control of 5, 10, and 15 cm Palmer amaranth with dicamba and glyphosate combinations.

Application timing	Herbicide	Rate	Control[a, b] 14 DAT	Control[a, b] 28 DAT
		kg ae ha^{-1}	%	%
5 cm timing				
	Glyphosate	0.84	39c	30d
	Dicamba	0.28	76b	82c
	Dicamba	0.56	81ab	90abc
	Dicamba	1.1	88a	95ab
	Dicamba + Glyphosate	0.28 + .84	81ab	84bc
	Dicamba + Glyphosate	0.56 + .84	85ab	90abc
	Dicamba + Glyphosate	1.1 + .84	90a	96a
10 cm timing				
	Glyphosate	0.84	28d	17d
	Dicamba	0.28	60c	61c
	Dicamba	0.56	70b	75b
	Dicamba	1.1	80a	87a
	Dicamba + Glyphosate	0.28 + .84	70b	67c
	Dicamba + Glyphosate	0.56 + .84	78a	78b
	Dicamba + Glyphosate	1.1 + .84	83a	87a
15 cm timing				
	Glyphosate	0.84	11e	11e
	Dicamba	0.28	51d	52d
	Dicamba	0.56	60c	68bc
	Dicamba	1.1	71ab	79a
	Dicamba + Glyphosate	0.28 + .84	58cd	60c
	Dicamba + Glyphosate	0.56 + .84	67b	71b
	Dicamba + Glyphosate	1.1 + .84	78a	85a

[a] Abbreviation: DAT, days after treatment.

[b] Means within a column followed by the same letter are not significantly different based on Fisher's protected LSD at $p \leq 0.05$.

Table 2.5 Percent reduction of Palmer amaranth density and biomass 28 DAT with dicamba and glyphosate combinations applied postemergence[a].

Application timing	Herbicide	Rate	Reduction[b]	
			Plant density	Plant biomass
		kg ae ha^{-1}	%	
5 cm timing				
	Glyphosate	0.84	24d	4c
	Dicamba	0.28	55bc	67ab
	Dicamba	0.56	66ab	73ab
	Dicamba	1.1	82a	92a
	Dicamba + Glyphosate	0.28 + .84	49c	61b
	Dicamba + Glyphosate	0.56 + .84	68ab	81ab
	Dicamba + Glyphosate	1.1 + .84	75a	89a
10 cm timing				
	Glyphosate	0.84	-29b	11c
	Dicamba	0.28	-15ab	44bc
	Dicamba	0.56	-4ab	69ab
	Dicamba	1.1	55a	89a
	Dicamba + Glyphosate	0.28 + .84	-20b	64ab
	Dicamba + Glyphosate	0.56 + .84	10ab	78ab
	Dicamba + Glyphosate	1.1 + .84	41ab	84a
15 cm timing				
	Glyphosate	0.84	-6c	0c
	Dicamba	0.28	49b	63b
	Dicamba	0.56	61ab	75ab
	Dicamba	1.1	75ab	83a
	Dicamba + Glyphosate	0.28 + .84	49ab	59b
	Dicamba + Glyphosate	0.56 + .84	50ab	74ab
	Dicamba + Glyphosate	1.1 + .84	80a	87a

[a] Abbreviation: DAT, days after treatment.

[b] Means within a column followed by the same letter are not significantly different based on Fisher's protected LSD at $p \leq 0.05$.

Table 2.6 Confirmation of the optimum rate of dicamba (BAS 18322 H) for postemergence control of 5, 10 and 15 cm Palmer amaranth.

Application timing	Herbicide	Rate	Control[a, b] 14 DAT	28 DAT
		kg ae ha^{-1}	%	
5 cm timing				
	Dicamba	0.14	86b	94ab
	Dicamba	0.28	91ab	91b
	Dicamba	0.56	87b	97ab
	Dicamba	1.1	94ab	99a
	Dicamba	2.2	98a	99a
10 cm timing				
	Dicamba	0.14	30c	66d
	Dicamba	0.28	44b	78c
	Dicamba	0.56	51b	87b
	Dicamba	1.1	71a	96a
	Dicamba	2.2	68a	98a
15 cm timing				
	Dicamba	0.14	25c	54d
	Dicamba	0.28	39b	64c
	Dicamba	0.56	41b	74b
	Dicamba	1.1	45ab	84a
	Dicamba	2.2	51a	91a

[a] Abbreviation: DAT, days after treatment.
[b] Means within a column followed by the same letter are not significantly different based on Fisher's protected LSD at $p \leq 0.05$.

Table 2.7 Plant biomass reductions calculated as a percent reduction of biomass based on the nontreated check from 5, 10, and 15 cm Palmer amaranth 28 DAT with various rate of dicamba applied postemergence[a].

Application timing	Herbicide	Rate	Reduction[b] Plant biomass
		kg ae ha^{-1}	———%———
5 cm timing			
	Dicamba	0.14	86a
	Dicamba	0.28	87a
	Dicamba	0.56	91a
	Dicamba	1.1	95a
	Dicamba	2.2	94a
10 cm timing			
	Dicamba	0.14	51c
	Dicamba	0.28	51c
	Dicamba	0.56	72b
	Dicamba	1.1	81ab
	Dicamba	2.2	84a
15 cm timing			
	Dicamba	0.14	39c
	Dicamba	0.28	41c
	Dicamba	0.56	58b
	Dicamba	1.1	66ab
	Dicamba	2.2	78a

[a] Abbreviation: DAT, days after treatment.
[b] Means within a column followed by the same letter are not significantly different based on Fisher's protected LSD at $p \leq 0.05$.

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