CONTROL OF AMARANTHUS SPECIES USING DICAMBA AS A PRE- AND POST- HERBICIDE IN MISSOURI

A Thesis
Presented to
The Faculty of the Graduate School
At the University of Missouri

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science, Plant, Insect and Microbial Sciences

By
ASHLEY A. SCHLICHENMAYER
Dr. Reid J. Smeda, Thesis Supervisor

JULY 2013
The undersigned, appointed by the dean of the Graduate School, have examined the Thesis entitled

CONTROL OF AMARANTHUS SPECIES USING DICAMBA AS A PRE- AND POST- HERBICIDE IN MISSOURI

Presented by Ashley A. Schlichenmayer
A candidate for the degree of
Master of Science, Plant, Insect and Microbial Sciences
And hereby certify that, in their opinion, it is worthy of acceptance.

________________________
Reid J. Smeda
Professor

________________________
Kevin W. Bradley
Associate Professor

________________________
Robert J. Kremer
Adjunct Professor
I would first and foremost like to express my undying gratitude, appreciation and love for God, for with Him, all things are possible. From the bottom of my heart, I thank Joseph Kamphoefner for the indescribable ways he has shown support through the trials and tribulations of these past years. Additionally, I thank my family for always believing in me and showing so much encouragement throughout my entire life. I say ‘thank you’ to my friends, for showing me the light at the end of the tunnel and constantly proving to me that I surround myself with great people.

Furthermore, I owe a huge thank you to my lab partners, Tye Shauck and Spencer Riley for their contributions to every aspect of my projects. Thank you to Tim Reinbott, Jim Wait, Ray Glendening, and Jason Weirich for support at the farm and use of equipment, and to the undergraduate staff, especially Jonny Davis, for daily assistance in the field. Finally, I would like to thank my advisor, Dr. Reid Smeda, for allowing me the opportunity to attend graduate school, as well as my committee members, Dr. Kevin Bradley and Dr. Robert Kremer, for all of their contributions. Thank you!
TABLE OF CONTENTS

Acknowledgements ........................................................................................................... ii

List of Tables ...................................................................................................................... v

List of Figures ..................................................................................................................... vi

List of Appendices .............................................................................................................. xi

Justification and Objectives ............................................................................................ xii

   Residual Study. ............................................................................................................... xii

   Growth Stage Study ....................................................................................................... xii

Chapter 1: Literature Review .......................................................................................... 1

   Introduction ................................................................................................................... 1

   Plant Growth Regulators (PGRs) ................................................................................. 1

      Definition. .................................................................................................................. 1

      History. ..................................................................................................................... 2

      Mode of Action. ......................................................................................................... 4

      Herbicide Resistance ............................................................................................... 6

   Dicamba ......................................................................................................................... 7

   Herbicide Resistant Crops ......................................................................................... 10

   Amaranthus .................................................................................................................. 13

   Purpose of Research .................................................................................................... 17

   Literature Cited ............................................................................................................. 18
Chapter 2: Influence of soil residual dicamba on the emergence of common waterhemp (*Amaranthus rudis*) ................................. 26

Abstract .................................................................................................................. 26
Introduction ............................................................................................................ 28
Materials and Methods .......................................................................................... 31
Results and Discussion .......................................................................................... 33
Literature Cited ....................................................................................................... 40

Chapter 3: Impact of Palmer amaranth (*Amaranthus palmeri*) and common waterhemp (*Amaranthus rudis*) plant height on the response to dicamba .......... 61

Abstract .................................................................................................................. 61
Introduction ............................................................................................................ 63
Materials and Methods .......................................................................................... 67
   Field Trials .......................................................................................................... 67
   Greenhouse Trials ................................................................................................. 70
Results and Discussion .......................................................................................... 71
   Field Trials .......................................................................................................... 71
   Greenhouse Trials ................................................................................................. 75
Literature Cited ....................................................................................................... 80
APPENDIX .............................................................................................................. 100
## List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chapter 2:</strong></td>
<td></td>
</tr>
<tr>
<td>2.1. List of herbicide treatments for residual control of common waterhemp (<em>Amaranthus rudis</em>).</td>
<td>42</td>
</tr>
<tr>
<td>2.2. Weekly average temperatures and total precipitation for residual control of common waterhemp experimental areas in 2011 and 2012. Weather data were recorded for weather stations based at the University of Missouri farms at New Franklin and Columbia, Missouri.</td>
<td>43</td>
</tr>
<tr>
<td><strong>Chapter 3:</strong></td>
<td></td>
</tr>
<tr>
<td>3.1. Soybean planting specifications and herbicide applications at three locations (Bradford, Portageville, and Novelty) in Missouri in 2011 and 2012.</td>
<td>84</td>
</tr>
<tr>
<td>3.2. Average air temperature and total precipitation for common waterhemp (<em>Amaranthus rudis</em>) and Palmer amaranth (<em>Amaranthus palmeri</em>) field sites in 2011. Data were recorded weekly at Portageville and Columbia, MO from the time of soybean planting through <em>Amaranthus</em> harvest.</td>
<td>85</td>
</tr>
<tr>
<td>3.3. Average air temperature and total precipitation for common waterhemp (<em>Amaranthus rudis</em>) and Palmer amaranth (<em>Amaranthus palmeri</em>) field sites in 2012. Data were recorded weekly at Portageville, Columbia, and Novelty, MO from the time of soybean planting through <em>Amaranthus</em> harvest.</td>
<td>86</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Chapter 2:</strong></td>
<td></td>
</tr>
<tr>
<td>2.1.</td>
<td>Representative arrangement of PVC rings (20.3 x 7.6 cm) in 0.9 x 1.5 m plot area for dicamba residual trial.</td>
</tr>
<tr>
<td>2.2.</td>
<td>Means of emerged waterhemp plants by treatment, averaged over site year (HARC 2011 A, Bradford 2011 A, Bradford 2012 A and Bradford 2012 B) and seeding date at 24 days after seeding. Means followed by the same letter are not significantly different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor.</td>
</tr>
<tr>
<td>2.3.</td>
<td>Total biomass of waterhemp by treatment, averaged over site year (HARC 2011 A, Bradford 2011 A, Bradford 2012 A and Bradford 2012 B) and seeding date at 24 days after seeding. Means followed by the same letter are not significantly different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor.</td>
</tr>
<tr>
<td>2.4.</td>
<td>Means of emerged waterhemp plants (24 days after seeding) at Bradford 2011 A. Means followed by the same letter within a treatment are not significantly different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor; NS, not significant.</td>
</tr>
<tr>
<td>2.5.</td>
<td>Means of emerged waterhemp plants (24 days after seeding) at HARC 2011 A. Means followed by the same letter within a treatment are not significantly different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor; NS, not significant.</td>
</tr>
<tr>
<td>2.6.</td>
<td>Means of emerged waterhemp plants (24 days after seeding) at Bradford 2012 A. Means followed by the same letter within a treatment are not significantly different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor; NS, not significant.</td>
</tr>
</tbody>
</table>
2.7. Means of emerged waterhemp plants (24 days after seeding) at Bradford 2012 B. Means followed by the same letter within a treatment are not significantly different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor; NS, not significant. .......................................................... 50

2.8. Means of emerged waterhemp plants (24 days after seeding) at Bradford 2011 A. Means followed by the same letter within a seeding date are not significantly different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor; NS, not significant. .......................................................... 51

2.9. Means of emerged waterhemp plants (24 days after seeding) at HARC 2011 A. Means followed by the same letter within seeding date are not significantly different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor. .......................................................... 52

2.10. Means of emerged waterhemp plants (24 days after seeding) at Bradford 2012 A. Means followed by the same letter within seeding timing are not significantly different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor; NS, not significant. .......................................................... 53

2.11. Means of emerged waterhemp plants (24 days after seeding) at Bradford 2012 B. Means followed by the same letter within seeding timing are not significantly different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor; NS, not significant. .......................................................... 54

2.12. Total biomass of waterhemp by treatment, averaged over site years (HARC 2011 A, Bradford 2011 A, Bradford 2012 A and Bradford 2012 B) at 24 days after seeding. Means followed by the same letter within treatment are not significantly different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor; NS, not significant. ....................... 55

2.13. Total biomass of waterhemp by seeding date, averaged over site years (HARC 2011 A, Bradford 2011 A, Bradford 2012 A and Bradford 2012 B) at 24 days after seeding. Means followed by the same letter within seeding date are not significantly different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor. .......................................................... 56
2.14. Biomass of waterhemp plants at Bradford 2011 A. Means followed by the same letter within seeding date are not significantly different using Fisher’s Protected LSD at $P=0.05$. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor; NS, not significant. ................................................................. 57

2.15. Biomass of waterhemp plants at HARC 2011 A. Means followed by the same letter within seeding date are not significantly different using Fisher’s Protected LSD at $P=0.05$. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor. ................................. 58

2.16. Biomass of waterhemp plants at Bradford 2012 A. Means followed by the same letter within seeding date are not significantly different using Fisher’s Protected LSD at $P=0.05$. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor; NS, not significant. ................................................................. 59

2.17. Biomass of waterhemp plants at Bradford 2012 B. Means followed by the same letter within seeding date are not significantly different using Fisher’s Protected LSD at $P=0.05$. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor. ................................. 60

Chapter 3:

3.1. Visible response of Palmer amaranth to growth regulators at Portageville in 2012, 14 days after treatment (DAT). Applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm) within each plot. Means with the same letter within plant size are not significantly different using Fisher’s Protected LSD at $P=0.05$. Means without letters are not significantly different within a plant size. Vertical bars indicate standard error of the means................................................................. 87

3.2. Visible response of Palmer amaranth to growth regulators at Portageville in 2012, 28 days after treatment (DAT). Applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm) within a plot. Means with the same letter within plant size are not statistically different using Fisher’s Protected LSD at $P=0.05$. Means without letters are not significantly different within a plant size. Vertical bars indicate standard error of the means. ................................................................. 88
3.3. Visible response of common waterhemp to growth regulators at Bradford in 2012, 14 days after treatment (DAT). Applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm) within a plot. Means with the same letter within plant size are not statistically different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. 

3.4. Visible response of common waterhemp to growth regulators at Novelty in 2012, 14 days after treatment (DAT). Applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm) within a plot. Means with the same letter within plant size are not statistically different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. 

3.5. Visible response of common waterhemp to growth regulators at Bradford in 2012, 28 days after treatment (DAT). Applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm) within a plot. Means with the same letter within plant size are not statistically different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. 

3.6. Visible response of common waterhemp to growth regulators at Novelty in 2012, 28 days after treatment (DAT). Applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm) within a plot. Means with the same letter within plant size are not statistically different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. 

3.7. Mean biomass of Palmer amaranth, 28 days after treatment (DAT) with growth regulators at Portageville in 2012. Applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm). Means with the same letter within plant size are not statistically different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. 

3.8. Mean biomass of common waterhemp, 28 days after treatment (DAT) with growth regulators at Bradford in 2012. Applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm). Means with the same letter within plant size are not statistically different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means.
3.9. Mean biomass of common waterhemp, 28 days after treatment (DAT) with growth regulators at Novelty in 2012. Applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm). Means with the same letter within plant size are not statistically different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. ................................................................. 95

3.10. Visible response of Palmer amaranth, 28 days after herbicide application in a greenhouse environment. Data were averaged over two trials and applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm). Means with the same letter within plant size are not statistically different using Fisher’s Protected LSD at P=0.05. Means without letters are not significantly different within a plant size. Vertical bars indicate standard error of the means. ................................................................. 96

3.11. Visible response of common waterhemp, 28 days after herbicide application in a greenhouse environment. Data were averaged over two trials and applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm). Means with the same letter within plant size are not statistically different using Fisher’s Protected LSD at P=0.05. Means without letters are not significantly different within a plant size. Vertical bars indicate standard error of the means. ................................................................. 97

3.12. Mean Palmer amaranth biomass, 28 days after herbicide application in a greenhouse environment. Data were averaged over two trials and applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm). Means with the same letter within plant size are not statistically different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. ................................................................. 98

3.13. Mean common waterhemp biomass, 28 days after herbicide application in a greenhouse environment. Data were averaged over two trials and applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm). Means without an asterisk within plant size are not statistically different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. ................................................................. 99
LIST OF APPENDICES

Table

A.1. Visible ratings (0= no control, 100= plant death) for Palmer amaranth, 14 and 28 days after treatment (DAT), at Portageville, MO in 2011. Plant sizes at treatment were in four groups: 5 to 10, 12 to 18, 20 to 25, and 28 to 35 cm. .......................................................................... 101

A.2. Visible ratings (0= no control, 100= plant death) for common waterhemp, 14 and 28 days after treatment (DAT), at Columbia, MO in 2011. Plant sizes at treatment were in four groups: 5 to 10, 12 to 18, 20 to 25, and 28 to 35 cm. .......................................................................... 102

A.3. Dry weight per plant for common waterhemp at Columbia, MO and Palmer amaranth at Portageville, MO, 28 days after treatment in 2011. Plant sizes at treatment were in four groups: 5 to 10, 12 to 18, 20 to 25, and 28 to 36 cm. .......................................................................... 103
JUSTIFICATION AND OBJECTIVES

Residual Study. Soil residual activity of dicamba on waterhemp is not well documented, and could be beneficial for early season weed control. With a dicamba resistant soybean event nearing commercial release, best management practices for weeds using preemergence (PRE) and post emergence (POST) herbicide programs is ongoing. Research is needed to evaluate the persistence of dicamba activity in soil. The objective of this study is to determine the impact of dicamba as a residual herbicide for control of waterhemp.

Growth Stage Study. Amaranthus species are increasingly difficult to control in agronomic cropping systems in Missouri, especially with the spread of populations expressing resistance to multiple herbicide modes of action. In a dicamba resistant soybean system, dicamba represents a new mode of action in soybean for POST control of these difficult species. Research is needed to determine the most effective field use rate of dicamba at multiple growth stages to control Amaranthus species using POST applications.
CHAPTER 1: LITERATURE REVIEW

Introduction

Plant Growth Regulators (PGRs)

Definition. Hormones are chemical messengers that are produced in plants and animals to regulate cellular processes. Plant function is controlled by six primary types of hormones, which are often referred to as plant growth regulators: auxins, gibberellins, cytokinins, ethylene, abscisic acid, and brassinosteroids. Auxins were the first plant hormones to be studied and are the most abundant in plants. Auxins are classified as having an aromatic ring, a net positive charge, and a carboxyl group which is negatively charged (Taiz and Zeiger 2006).

At levels exceeding normal expression, plant growth regulators (PGRs) can induce herbicidal effects when introduced to plants. A common group of PGRs used as herbicides are often referred to as the synthetic auxins. They are classified into families based on the carboxylic moieties of each herbicide around their aromatic rings (Gleason et al. 2011). Four families of synthetic auxins comprise the herbicidal PGRs: phenoxy carboxylic acids (e.g. 2,4-D), benzoic acids (e.g. dicamba), pyridine carboxylic acids (e.g. clopyralid), and quinolone carboxylic acids (e.g. quinclorac) (Anonymous 2011a).

Plant growth regulator herbicides (with the exception of quinclorac) are selectively most active on broadleaf plants. Monocot species detoxify and translocate dicamba metabolites, however, sensitive broadleaf species cannot (Chang and Vanden
When used properly, monocot plants such as corn, sorghum, cereals, and turf exhibit minimal effects following dicamba application. Synthetic auxins are also used under specific conditions such as pre-plant burndown applications prior to planting soybeans or other broadleaf crops, especially in no-till situations. In addition to cropped areas, synthetic auxins are frequently used in pastures, fallow ground, and non-crop situations (Anonymous 2010).

Most synthetic auxins are formulated as either salts or esters; the ester formulation exhibits greater efficacy, but the potential for off-target movement by volatilization is also higher (Breeze and van Rensburg 1992). Herbicide ionic liquids are a new technology which has potential to increase efficacy and reduce environmental impact (water solubility and high volatility) of synthetic auxin salts over commercially available free acid formulations (Cojocaru et al. 2013).

**History.** In 1880, Charles Darwin noted that plants bend toward a light source. He believed this resulted from some recognition signal in the tip of plant, which was then transmitted to the lower portion of the plant (Peterson 1967). Research following Darwin’s observations led to the discovery of a hormone, concentrated in the apical meristem, which controlled aspects of plant growth and was light-sensitive. By 1926, the reported hormone was extracted from a plant (Went 1926). Further studies resulted in Zimmerman and Hitchcock’s description of plant responses to phenoxyacetic acids and benzoic acids in 1942, and led to the understanding that they were synthetic compounds similar to the hormone Darwin had described (Zimmerman and Hitchcock 1942; Zimmerman and Hitchcock 1948). In 1943, John F. Lontz received a patent for the
use of 2,4-D as a “Plant Regulant Composition” (Peterson 1967). In 1944, Mitchell and
Hammer, after working extensively with 2,4-D as a biological warfare agent, suggested
its use as an agricultural herbicide. The selectivity for weed control was considered a
major advantage for farming operations (Marth and Mitchell 1944; Mitchell and
Hammer 1944). On December 11, 1945, Franklin D. Jones was issued a US patent for
“Methods and Compositions for Killing Weeds,” listing 2,4-D and its derivatives as a new
tool for killing plants (Anonymous 2005). As an herbicide, 2,4-D was released for

The popularity of 2,4-D increased due to several factors. From 1944 to 1950, the
cost of a pound of 2,4-D dropped from $12.50 (US dollars) to $0.50 (Peterson 1967),
making this herbicide very inexpensive to apply. Also, 2,4-D controlled a broad
spectrum of broadleaf weeds, especially troublesome perennials, such as field bindweed
(Convolvulus arvensis) and thistles (Cirsium species). Through time, 2,4-D was applied to
an increasing number of acres. By 1970, Iowa producers were applying 2,4-D to nearly
all their corn acres and most of their acreage in soybeans and pastures as well
(Anderson 2005). The use of 2,4-D and other newly developed herbicides resulted in
decreased labor and fuel costs, as producers reduced cultivation and devoted fewer
hours to mechanical hand-removal. Removing weeds from crop plants resulted in
higher crop yields. Cardwell (1982) estimated that the use of herbicides increased corn
yields in Minnesota by 23% between the 1930s and the 1980s. Similarly, Warren (1998)
found that herbicides were a major influence in the increased productivity of all major
crops in the US.
Dicamba is an herbicide similar to 2,4-D; it is a derivative of benzoic acid. It is thought that benzoic acid was discovered by Nostradamus in 1556. Antifungal properties of benzoic acid were described in 1875 (Krebs et al. 1983; Salkowski 1875). Even today, benzoic acid derivatives are used as antifungal topical ointments and in acidic foods to prevent molding. Dicamba, also known as 3,6-dichloro-2-methoxybenzoic acid, or 3,6-dichloro-o-anisic acid, was first registered as a commercial herbicide in 1967 (Erickson et al. 2006). Dicamba is used non-selectively for the removal of broadleaf weeds prior to planting broadleaf crops, as well as pre-plant or post emergence (POST) on grass crops such as corn or wheat (Anonymous 2010). Selectivity is based upon the ability of monocot plants to metabolize dicamba into 5-hydroxy-2-methoxy-3,6-dichlorobenzoic acid (5-hydroxy) and 3,6-dichlorosalicylic acid (DCSA), whereas broadleaf species are less likely to detoxify the herbicide (Chang and Vanden Born 1971). Current use includes: asparagus, barley, corn, cotton, oats, proso millet, rye, sorghum, soybeans, sugarcane and wheat, as well as pastures, fallow, golf courses, and residential lawns (Anonymous 2010). Dicamba controls a broad spectrum of annual, biennial and perennial broadleaf weed species. Several formulations of dicamba are registered for application: dimethylamine salt (DMA), diglycolamine salt (DGA), isopropylamine salt (IPA), sodium salt, potassium salt, and as an acid (Erickson et al. 2006).

**Mode of Action.** Plant growth regulators appear to mimic the natural plant hormone indole-3-acetic acid (IAA), commonly referred to as auxin (Taiz and Zeiger 2006). Although the exact mechanism of action is not well understood, Grossman (2010) has
summarized the mechanism of action as occurring in three phases. The first phase, referred to as the stimulation phase, is initiated in sensitive species within minutes of application. The overdose of IAA (from $10^{-9}$ to $10^{-2}$ pg) in the plant stimulates biosynthesis of ethylene in shoot tissue within 2 hours, which uncouples growth regulation. Within 3 to 4 hours, visible symptoms in affected plants include: leaf-cupping, epinasty of the stems, and callous formation. Additionally, membrane pumps located in the plasmalemma efflux protons, resulting in acidification of intercellular spaces, which is thought to induce cell elongation. Additionally, PGR application stimulates accumulation of ABA (abscisic acid), which can be detected in plant tissues 5 to 8 hours after application. The second phase, observed within 24 hours following PGR exposure, is characterized by inhibition of growth in both root and shoot meristems. This is associated with the closing of stomates and reduced transpiration. Finally, overproduction of reactive oxygen species is accompanied by reduced carbon fixation and starch assimilation. The third phase is the net plant response following the first two phases. Progressive chlorosis, senescence of plant tissue, and destruction of vascular integrity limit transport of water, nutrients and carbohydrates, resulting in death of sensitive plant species (Grossman 2010).

In addition to morphological changes, auxin alters gene expression during the stimulation phase (Gleason et al. 2011). For Arabidopsis mutants exposed to dicamba, the influx of auxin into cells causes an up-regulation of some genes and concurrent down-regulation of others (Gleason et al. 2011). Other genes indicative of plants under stress will also be induced, including ABA-responsive genes, and several genes involved
in transcription. Dicamba application to *Arabidopsis* mutants repressed cell wall biosynthesis, IAA catabolism, and multiple transport proteins (Gleason et al. 2011). The activity of auxin in plants is complex and not entirely understood; however, interactions between auxin and auxin protein receptors have been studied a great deal in recent years (Dharmasiri et al. 2005a; Dharmasiri et al. 2005b; Guilfoyle and Hagen 2007; Kelley and Riechers 2007; Kepinski and Leyser 2005) which could eventually lead to a full realization of auxin activity, transport, herbicide mode of action, and weed resistance.

**Herbicide Resistance.** The herbicides 2,4-D and dicamba consistently rank in the top ten most widely used herbicides in the United States (Todd and Suter 2001). Despite long-term use, widespread resistance to auxinic herbicides has not been reported compared to other widely used herbicides with single modes of action; 30 species have been selected resistant to synthetic auxin herbicides worldwide (Heap 2013). Researchers suggest that the importance of auxins in controlling plant growth and the close mimicking to natural auxin limits the number of resistant species (Wright et al. 2010). Auxin plays a role in nearly every aspect of the growth and development of plants; therefore, plants have many auxin receptors. Resistance mechanisms in multiple auxin receptors may be necessary to impart resistance in plants (Gressel and Segel 1982).

Extensive research regarding heritability of resistance to synthetic auxins has generated mixed results. While resistance to picloram and 2,4-D in wild mustard (*Sinapis arvensis* L.) was inherited by a single dominant allele, resistance to picloram and clopyralid in yellow starthistle (*Centaurea solstitialis* L.) was the result of a single recessive allele (Mithila et al. 2005; Sabba et al. 2003). Similar discrepancies have been
noted with the dicamba resistant weed, *Kochia scoparia*. While some research suggests a single, dominant allele (Preston et al. 2009), other research indicates that dicamba resistance must be quantitative (Cranston et al. 2001). Mixed results regarding inheritance of resistance to dicamba and other auxinic herbicides indicates a complex mechanism of action for auxinic herbicides, and further substantiates the relatively low potential for selecting resistant weed species with this chemistry.

**Dicamba**

Dicamba has a unique set of chemical properties. Though an acid, dicamba is formulated into various salts for use in field applications, as they are more readily absorbed into plants. Once through the cuticle, the salt forms of dicamba rapidly disassociate to the acid form (Erickson et al. 2006). Under normal conditions, dicamba photodegrades slowly in air and water, with a half-life of 269 days (Senseman 2007).

Environmental and soil parameters influence the longevity of dicamba. Dicamba has a negative charge at a range of pH levels (Burnside and Lavy 1966) and is soluble in water, not readily binding to soil colloids. Soils high in kaolinite clay may adsorb dicamba molecules due to its high anion adsorption capacity (Burnside and Lavy 1966). Donaldson and Foy (1965) found that ED\textsubscript{50} values (effective dose to kill 50% of plants) of dicamba were ten times higher in a peaty muck soil than in sandy or sandy loam soils. This reflects the high adsorption properties of the peaty muck soil.
Due to the high mobility of dicamba in soils, leaching can occur and low concentrations have been detected in groundwater (Hallberg 1989). The National Water Quality Assessment study between 1992 and 1996 found that dicamba was detected in 0.13% of over 2,300 sites, with the maximum concentration at 0.21 µg/L (Kolpin et al. 2000). The Environmental Protection Agency does not specifically set a maximum contaminant level (MCL) for dicamba, but the equivalent MCL for 2,4-D is 70 µg/L, well above the maximum level of dicamba detected (Anonymous 2009). Leaching of dicamba, possibly caused by negative adsorption properties or anion repulsion capacity, may be reduced with higher soil organic matter content. Organic matter adsorbs both positively and negatively charged herbicides (Burnside and Lavy 1966). Likewise, dicamba was shown to move faster through soil columns containing sand and traveled more slowly with increased clay and organic matter (Donaldson and Foy 1965).

Reduction of dicamba activity in soil occurs primarily by microbial metabolism (Fogarty and Tuovinen 1995; Smith 1974). Primary metabolites are 3,6-dichlorosalicylic acid (DCSA) and 2,5-dihydroxy-3,6-dichlorosalicylic acid (5-hydroxy) (Senseman 2007). Soil microorganisms degrade a wide spectrum of synthetic compounds and may develop new mechanisms of degradation over time (Kellogg et al. 1981). Three pure bacterial cultures are capable of degrading dicamba, two species of *Pseudomonas* and one species of *Moraxella* (Fogarty and Tuovinen 1995; Krueger et al. 1989). The three bacterial strains were isolated from collected water and soil samples near a dicamba manufacturing facility in Beaumont, Texas, indicating that these microbes may have evolved dicamba-degrading capabilities due to selection pressure over time (Krueger et
al. 1989). Additionally, these three strains were able to breakdown dicamba at a range of pH levels (Krueger et al. 1989).

Conditions favorable to microbial activity result in more rapid dissipation of dicamba. Fogarty and Tuovinen (1995) reported that dicamba degradation is enhanced by increased temperature, with an optimum of 30 C. With a soil moisture of only 13%, little to no detoxification of dicamba occurred four months after application to soils under growth chamber conditions; only 30% of the dicamba had dissipated after 9 months (Burnside and Lavy 1966). In a laboratory study using mineral salts media, up to 2000 mg/L of dicamba were completely degraded by both a pure culture of *Pseudomonas paucimobilis* and a soil consortium within 104 hours (Fogarty and Tuovinen 1995). Dicamba degradation is also pH dependent. Fogarty and Tuovinen (1995) demonstrated that optimal activity of a pure culture of *P. paucimobilis* occurs at neutral pH, whereas a mixed culture provides optimum dicamba degradation at a pH from 6.5 to 7.0.

Persistence of dicamba in soils has been highly variable across soil types, rainfall conditions and ground cover. Under field conditions in Nebraska, dicamba did not harm crops planted two years after application, even when treatments were applied at 22 kg ha\(^{-1}\) (Burnside et al. 1971). However, 0.59 kg ha\(^{-1}\) of dicamba resulted in almost a total loss of tartary buckwheat (*Fagopyrum tataricum*) bioassayed 12 weeks after application in two soil types from Canada. Plants were also severely damaged where only 0.29 kg ha\(^{-1}\) were applied (Friesen 1965). In autoclaved soils, all buckwheat plants were killed at both the 0.29 and 0.59 kg ha\(^{-1}\) rates when planted 12 weeks after dicamba application,
demonstrating the importance of microbial breakdown of dicamba (Friesen 1965). In soils collected in Oklahoma, the half-life of dicamba ranged from 17 to 32 days, depending upon the vegetative cover of the soil prior to sampling (Altom and Stritzke 1973). In greenhouse studies using snap pea bioassays, dicamba at a concentration as low as 0.5 ppmw (parts per million weight) resulted in little reduction in plant biomass when peas were seeded 16 weeks after application. However, higher dicamba concentrations and plantings at 0, 4, or 8 weeks after application resulted in moderate to severe injury or plant death (Sheets et al. 1968).

In anaerobic conditions, dicamba exhibited a half-life of 21.7 to 27.9 days in three Chinese soils at 25 C (Gu et al. 2003). However, at 15 C, the half-life of dicamba ranged from 29 to 161.2 days in the same three soils. Furthermore, 90% of dicamba was degraded within 14 days in an enrichment culture at 25 C (Gu et al. 2003). In anaerobic soils, the half-life of dicamba is 141 days (Erickson et al. 2006).

**Herbicide Resistant Crops**

A decline in the development of new selective herbicides in the 1990s (Duke 2012) contributed to genetic manipulation of crops for expanding the use of effective, non-selective herbicides. A prime example is the development of glyphosate-resistant (GR) crops, released in 1996. By 1998, 40% of US soybeans and more than 80% of soybeans planted in Argentina were glyphosate-resistant (Shaner 2000).

**Weed Resistance.** Rapid and widespread adoption of GR crops led to dramatic increases in the application of glyphosate in the US, from 2.5 million kg/yr in 1995 to 30
million kg/yr in 2002 (Young 2006). Shaner (2000) reported an increase in the use of glyphosate as well as a decrease in the application of other herbicide modes of action. Glyphosate is active on a broad spectrum of weed species, and other herbicide modes of action were not needed necessarily for adequate weed control. Thus, producers reduced chemical input costs while maintaining or improving weed control. The rapid onset of glyphosate-resistant crops resulted in large areas repeatedly treated with a single herbicide mode of action; often multiple applications of glyphosate were made in a single season. Reliance upon a single mode of action for weed control has been shown to shift the weed spectrum in crop fields toward tolerant species and select for resistance among existing populations (Bauman 2010; Culpepper 2006; Owen 2008).

The Weed Science Society of America defines herbicide tolerance as “the inherent ability of a species to survive and reproduce after herbicide treatment. This implies that there was no selection or genetic manipulation to make the plant tolerant; it is naturally tolerant,” likewise, herbicide resistance is defined as “the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type. In a plant, herbicide resistance may occur naturally or may be induced by genetic engineering or selection of variants produced by tissue culture or mutagenesis” (Anonymous 2011b). As tolerant species or resistant biotypes become more populous, additional measures of control become necessary to reduce weed competition and maintain crop yield.

To date, 24 species worldwide and 14 species in the US have been selected for resistance to glyphosate (Heap 2013). Along with Ambrosia trifida L, Conyza canadensis...
L, and other species, *Amaranthus* species have been named some of the most economically troublesome glyphosate-resistant species, especially in the Midwest and the south (Culpepper 2006; Hager and Sprague 2002; Johnson and Gibson 2006; Nandula et al. 2005; Owen 2008). In 2005, Zelaya and Owen reported common waterhemp populations were insensitive to nearly 15-fold the rate of glyphosate required to kill glyphosate-sensitive plants after three cycles of recurrent selection. Glyphosate-resistant weeds are prominent in recent literature (Pline-Srnic 2006; Preston and Wakelin 2008; Salas et al. 2012; Shaner 2009), indicating that finding methods of control are of utmost importance.

Development of crops with resistance to PGRs is one method to control glyphosate-resistant weeds. *Pseudomonas maltophilia* is a soil bacterium which has the ability to detoxify dicamba. Research scientists have isolated the dicamba monooxygenase gene from *P. maltophilia* which encodes for the enzyme that degrades dicamba. When transformed into broadleaf crops, plants are able to detoxify dicamba (Behrens et al. 2007). Resistance to dicamba will be combined with existing glyphosate resistance to control problematic weeds (Anonymous 2013). Incorporating additional modes of action, such as dicamba, into existing weed management programs, will reduce selection pressure on glyphosate and extend the usefulness of those herbicides (Shaner et al. 2012). For existing glyphosate resistant weeds, the use of an effective residual herbicide with a PGR herbicide is an effective strategy to preclude selection of PGR resistant weeds. Proper resistance management and prevention strategies should include tank combinations of multiple modes of action as well as applications of both
preemergence (PRE) and post-emergence (POST) herbicides (Norsworthy et al. 2012). Any herbicide, used alone for weed control, is subject to resistance selection. Therefore, education and intense management are necessary to maintain current and increasing yield demands (Duke and Powles 2008).

**Amaranthus**

Weed competition for water, sunlight and nutrients is a significant factor that reduces crop yield. Natural populations of weeds could potentially cause up to 90% reduction in crop yield (Gianessi and Sankula 2003). Palmer amaranth (*Amaranthus palmeri*) and common waterhemp (*Amaranthus rudis*) have been shown to decrease soybean yield as much 79 and 56%, respectively, when only 8 plants m$^{-1}$ were present (Bensch et al. 2003). Corn yield was decreased 74% when common waterhemp was allowed to compete season-long (Steckel and Sprague 2004).

*Amaranthus* species are difficult to control in the Midwest (Hager and Sprague 2002) due to several factors: high seed production, rapid growth rate, genetic variability and ability to evolve resistance to herbicides (Ward et al. 2013). Members of this genus are small-seeded, summer annual weeds which exhibit high fecundity. Several *Amaranthus* species produce over 250,000 seeds per plant (Sellers et al. 2003), which have a hard seed coat that allows the seeds to remain viable in the soil seed bank for at least 4 years (Buhler and Hartzler 2001). Menges (1987) found that Palmer amaranth seed persisted at 18 million seed ha$^{-1}$ even after 6 years of intense weed management and after a soil seed bank reduction of 98% compared to nontreated plots. Common
waterhemp emerges season-long (Hartzler et al. 1999) and Palmer amaranth has been shown to emerge as early as March and as late as October in California (Keeley et al. 1987). The extended germination pattern for common waterhemp and Palmer amaranth complicates proper herbicide application timing for effective weed control. Additionally, common waterhemp and Palmer amaranth are characterized by rapid growth (Horak and Loughin 2000). Palmer amaranth and common waterhemp were shown to have a height increase of up to a 0.21 and 0.16 centimeters per growing degree day, respectively (Horak and Loughin 2000). Sellers (2003) reported that Palmer amaranth biomass was up to 65% greater than other *Amaranthus* species just two weeks after planting. Likewise, Steckel et al. (2003) identified common waterhemp plants to weigh as much as 720 g at maturity, while Palmer amaranth has been reported to weigh nearly 7100 g (Keeley et al. 1987). Rapid growth of these two species results in a smaller time frame of herbicide application to ensure adequate control compared to other slower growing summer annuals (Horak and Loughin 2000).

Common waterhemp and Palmer amaranth, two members of this genus, are dioecious (Sauer 1957). The dioecious nature of common waterhemp and Palmer amaranth results in genetically diverse progeny (Tranel et al. 2009). Combined with the prolific nature of the genus and over exposure to glyphosate, both species have evolved resistance to glyphosate. Palmer amaranth was first confirmed to be resistant to glyphosate in Georgia in 2006 (Culpepper et al. 2006). Waterhemp was reported with reduced sensitivity to glyphosate in greenhouse studies in Illinois in 2002 (Patzoldt et al. 2002) and confirmed to be resistant in field trials in Missouri in 2008 (Legleiter and
Bradley 2008). As *Amaranthus* species are often identified as one of the most problematic species in the Midwest, biotypes resistant to glyphosate are a significant economic threat to corn and soybean producers (Hager and Sprague 2002; Hager et al. 1997; Legleiter et al. 2009).

In addition to glyphosate resistance, many populations exhibit resistance to other herbicide modes of action, including: acetolactate synthase inhibitors, photosystem II inhibitors, dinitroanilines, p-hydroxyphenylpyruvate dioxygenase inhibitors and protoporphyrinogen oxidase inhibitors. However, *Amaranthus* species have not developed resistance to dicamba, which may effectively control resistant biotypes. In 1997, a biotype of common waterhemp was reported to be cross-resistant to a number of ALS-inhibitors in the sulfonylurea family (Sprague et al. 1997). However, the resistant waterhemp was controlled by a tank combination of flumetsulam and metolachlor, or atrazine and dicamba (Hager et al. 2000; Sprague et al. 1997). At least 8 *Amaranthus* species have been reported as having biotypes resistant to triazines, four of which are in the United States (LeBaron and MacFarland 1990). Studies have shown that adding dicamba to tank mixes for PRE or early POST applications consistently results in greater than 80 and 90% control of triazine resistant *Amaranthus* species, respectively (Birschbach et al. 1993; Fuerst et al. 1986; Ritter et al. 1985). Soltani et al. (2009) also showed that a POST application of dicamba alone resulted in greater than 92% control of waterhemp in corn. Furthermore, greater than 95% control of waterhemp was achieved when PRE applications of isoxaflutole plus atrazine were followed by dicamba alone or with diflufenzopyr or atrazine (Soltani et al. 2009).
Dicamba may aid in control of *Amaranthus* plants at small sizes. When applied to triazine resistant *Amaranthus* plants ≤2.5 cm, dicamba at 0.28 kg ha\(^{-1}\) resulted in ≥94% control (Fuerst et al. 1986). Dicamba applied POST to 5 to 10 cm waterhemp at a rate of 0.6 kg ha\(^{-1}\) resulted in 91 to 98% control 70 days after treatment (DAT) and reduced plant density and biomass ≥94 and ≥98%, respectively (Soltani et al. 2009). When dicamba was applied to 8 to 12 cm waterhemp at a rate of 0.54 kg ai ha\(^{-1}\) with 1.03 kg ai ha\(^{-1}\) atarazine, visible control was 98% for both susceptible and triazine resistant biotypes (Sprague et al. 1997). Field applications of growth regulators often include *Amaranthus* plants of varying sizes due to the extended germination pattern of these species. Though dicamba successfully controls small plants, little research has been conducted to evaluate the effectiveness of multiple rates of dicamba on larger *Amaranthus* plants, which would also be present in the field at the time of application.

The ineffectiveness of glyphosate and other POST herbicides on resistant *Amaranthus* species means that innovative solutions for weed control are needed. The use of dicamba in dicamba resistant soybean systems will offer producers an additional option for weed control. Johnson et al. (2010) performed the most comprehensive weed control evaluation with dicamba in dicamba resistant soybeans to date. Studies were conducted at 19 site years and included applications made on 3 to 5, 3 to 8, and 8 to 16 inch weeds. They also included rates of dicamba from 0.14 to 1.69 kg ha\(^{-1}\) and rates of glyphosate from 0.84 to 1.69 kg ha\(^{-1}\). Across multiple years and locations, the research determined that control of glyphosate susceptible waterhemp and Palmer amaranth was 95% or greater for all treatments which included both glyphosate and...
dicamba in some combination in dicamba resistant soybeans. For glyphosate resistant Palmer amaranth, control increased from 60 to 100% when dicamba was applied POST compared to glyphosate alone. Likewise, control of glyphosate resistant waterhemp increased from 30 to 95% with dicamba plus glyphosate POST. All applications which included dicamba POST increased control from glyphosate alone POST applications (Johnson et al. 2010).

**Purpose of Research**

Though synthetic auxin herbicides have been used in crop production systems for decades, dicamba resistant soybeans will alter the use of dicamba; namely, in-crop use for weed control. Research on the residual activity of dicamba on waterhemp is lacking. The objective of the residual study is to determine the impact of soil applied dicamba on the suppression of waterhemp from seed. In addition, POST application of dicamba at multiple rates on waterhemp and Palmer amaranth must be evaluated at different growth stages because these species grow rapidly early in the growing season and narrow the time frame for labeled herbicide application.
Literature Cited


CHAPTER 2: INFLUENCE OF SOIL RESIDUAL DICAMBA ON THE EMERGENCE OF COMMON WATERHEMP (AMARANTHUS RUDIS)

ASHLEY A. SCHLICHENMAYER & REID J. SMEDA*

Abstract

Dicamba resistant soybean (Glycine max L. Merr.) is an emerging technology that will offer an additional option for postemergence (POST) control of difficult weeds such as waterhemp (Amaranthus rudis Sauer). An additional benefit of dicamba may include residual suppression of target weeds. Field studies were established at two sites in central Missouri in 2011 and 2012 to evaluate the influence of dicamba rate on the suppression of waterhemp from seed. In 0.9 by 1.5 m plots, 6 polyvinyl chloride (PVC) pipe rings were established in an “X” pattern. Dicamba was soil applied at 0.14, 0.28, and 0.56 kg ae ha⁻¹, 2,4-D at 0.56 kg ae ha⁻¹, acetochlor at 1.05 kg ai ha⁻¹, and acetochlor plus dicamba at 1.05 kg ai ha⁻¹ + 0.28 kg ae ha⁻¹; an nontreated control was also included. Immediately after treatment (0 days after treatment; DAT) and at 2, 4, 7, 10 and 14 DAT, 200 seeds of waterhemp were scattered on the soil surface in targeted PVC rings within each plot. At 24 days after seeding (DAS), 0.56 kg ha⁻¹ dicamba and 2,4-D reduced waterhemp emergence by 37 and 41%, respectively, compared to the

*Authors: Graduate Research Assistant, Professor, Division of Plant Sciences, University of Missouri, 108 Waters Hall, Columbia, MO 65211. Corresponding author’s E-mail: aaskv9@mail.missouri.edu
nontreated control. Dicamba exhibits residual activity from 0 to 7 days after application across site years. Treatments containing acetochlor reduced waterhemp emergence ≥80%; addition of dicamba to acetochlor did not further suppress waterhemp emergence. Across all site years, treatments with acetochlor reduced total biomass at 35 DAS 77% greater than growth regulator treatments alone. Dicamba and 2,4-D performed similarly at the same rate, but should not be considered a substitute for conventional residual herbicides such as acetochlor.

**Nomenclature:** acetochlor; dicamba; 2,4-D; common waterhemp, *Amaranthus rudis* AMATA.

**Keywords:** Glyphosate-resistance.
Introduction

The herbicide dicamba mimics auxin and is utilized for selective control of broadleaf weed species such as common waterhemp. Traditional use involves applications prior to planting (PRE) broadleaf crops in no-till situations, usage postemergence (POST) in monocot cropping systems, or applications in non-crop situations such as land in the conservation reserve program (CRP) (Anonymous 2010).

Increased reliance on glyphosate for POST weed control has selected for weed biotypes which are resistant to glyphosate; six species currently exhibit glyphosate resistance in Missouri (Heap 2013). Because of the rapid spread of glyphosate-resistant waterhemp in Midwest soybean production systems (Powles 2008), the utility of a plant growth regulator herbicide provides a new tool for effective management of waterhemp (Johnson et al. 2010). Glyphosate resistant common waterhemp was confirmed in Missouri in 2008 (Legleiter and Bradley 2008). According to a recent survey, 41 Missouri counties contain glyphosate resistant populations (Rosenbaum and Bradley 2013).

Besides resistance to herbicides, there are several other factors that contribute to the difficulty in controlling *Amaranthus* species. Members of this genus are small-seeded, summer annual weeds which exhibit high fecundity. Several *Amaranthus* species produce over 250,000 seeds per plant (Sellers et al. 2003). Seeds of *Amaranthus* species possess a hard seed coat, which allows seeds to remain viable in the soil seed bank for up to 4 years (Buhler and Hartzler 2001). Common waterhemp emerges over a long period during the growing season compared to other summer annual species (Hartzler et al. 1999); control practices are necessary over an extensive part of the
growing season to preclude increases in the soil seed bank. Although a number of PRE herbicides can effectively suppress waterhemp emergence, in-season applications are necessary to control later emerging plants.

Dicamba resistance is an emerging technology that would permit the use of dicamba in broadleaf crops such as soybean. Little research has evaluated dicamba as a PRE herbicide. Johnson et al. (2010) observed that soil applications of 0.28 kg ha\(^{-1}\) dicamba resulted in >90% control of common lambsquarters (\textit{Chenopodium album}) and horseweed (\textit{Conyza canadensis}), but less than 10% control of giant ragweed (\textit{Ambrosia trifida}). Control of common waterhemp with dicamba applied PRE was <60%, but only a single rate was evaluated. Dicamba demonstrates potential residual activity on small seeded broadleaf weeds, and should be further investigated with multiple rates.

Dicamba persists in soils and can result in injury to emerging plants. In greenhouse studies, 0.5 ppmw of dicamba had minimal impact (<4% reduction) on snap bean (\textit{Phaseolus vulgaris} L.) biomass when beans were planted 16 weeks after herbicide application. However, at higher dicamba concentrations (2 or 8 ppmw) and at a shorter duration of bean establishment after application of dicamba (0, 4, or 8 weeks), moderate injury to plant death was observed (Sheets et al. 1968). In Nebraska, no residual activity of dicamba was measured, as treatments up to 22 kg ha\(^{-1}\) did not impact soybean (\textit{Glycine max} L. Merr.) or field bean (\textit{Phaseolus vulgaris} L.) seed yields two years after application (Burnside et al. 1971). In growth chamber studies, the half-life of dicamba ranged from 17 to 32 days, with variation dependent on the vegetative cover of the Oklahoma soil prior to sampling (Altom and Stritzke 1973).
The duration of dicamba activity is related to soil microbial activity. Decreased soil activity of dicamba occurs primarily by microbial metabolism (Fogarty and Tuovinen 1995; Smith 1974). In greenhouse studies, 70 to 100% of applied dicamba was present in the soil nine months after application when soil moisture was low (13% soil capacity), but was non-detectible when soil moisture was 80% field capacity (Burnside and Lavy 1966). Fogarty and Tuovinen (1995) reported that a pure culture of *Pseudomonas paucimobilis* degraded dicamba efficiently at pH 7.0, whereas a mixed culture provided optimum dicamba degradation at a pH from 6.5 to 7.0. Likewise, Krueger et al. (1989) observed a 23 to 35% increase in dicamba breakdown when pH was increased from 6.0 to 7.0 for two strains of *Pseudomonas*. Dicamba degradation was enhanced with increasing temperature, reaching an optimum at 30°C (Fogarty and Tuovinen 1995). In two Canadian soils, 0.59 kg ha\(^{-1}\) of dicamba resulted in death of nearly all Tartary buckwheat plants (*Fagopyrum tataricum*) assayed 12 weeks after application (Friesen 1965). Severe damage to buckwheat plants occurred where only 0.29 kg ha\(^{-1}\) was applied (Friesen 1965). However, in autoclaved soils (devoid of microbial activity), all buckwheat plants were killed at both rates. Friesen (1965) suggested that microbial breakdown of dicamba is important in the loss of soil activity.

Residual activity of dicamba may extend efficacy on emerging waterhemp following POST applications. However, little research has explored the residual activity of dicamba. Therefore, the objective of this research was to determine the residual activity of multiple rates of dicamba on common waterhemp emergence under field conditions.
Materials and Methods

Field trials were established in 2011 and 2012 at two locations in central Missouri: the Bradford Research and Extension Center (Bradford) near Columbia, and the Horticulture and Agroforestry Research Center (HARC) near New Franklin. The soil type at Bradford was a Mexico silt loam (Fine, smectitic, mesic Vertic Epiaqualfs) with 2.2% organic matter and a pH of 5.8, while the soil type at HARC was a Menfro silt loam (Fine-silty, mixed, superactive, mesic Typic Hapludalfs) with 2.6% organic matter and a pH of 5.9. In 2010, the trial area at Bradford was planted to corn and regional fertilizer and weed management recommendations were practiced. At HARC, the experimental area was an established stand of tall fescue (*Festuca arundinacea*). The area was cleared of vegetation using a disk harrow in the spring.

Prior to establishment, field areas were tilled to a depth of approximately 15 cm using a Bush Hog RTH72 rotary tiller (Bushhog, Selma, AL). Within a 0.9 x 1.5 m area (considered a plot), 6 pieces of 20.3 cm diameter x 7.6 cm deep polyvinyl chloride (PVC) were arranged in an “X” pattern; rings were pressed into the ground to prevent movement of waterhemp seed outside the target area (Figure 2.1). Herbicide treatments were applied to the entire 0.9 x 1.5 m plot area, over the top of the established rings. Herbicide treatments were randomized within each replication. Within individual herbicide treatments, seeding date was randomized among the 6 established rings. Each ring comprised 52 cm$^{-2}$ and was considered the target area for data collections.
Treatments were initiated in May and June; herbicide treatments are listed in Table 2.1. At a speed of 4.8 km h\(^{-1}\), herbicides were applied with a CO\(_2\) pressurized backpack sprayer equipped with XR8002 TeeJet (TeeJet\(^{\circledR}\) Spraying Systems, Wheaton, IL) flat fan nozzle tips calibrated to deliver 140 L ha\(^{-1}\) at 117 kPa. Herbicides were applied at Bradford on June 2 and June 22, 2011 for the first (referred to as the A timing) and second (referred to as the B timing) timings, respectively, and at HARC on June 3 and June 23, 2011 for the A and B timings, respectively. Bradford treatments for the A and B timings in 2012 were made on May 14 and May 31, respectively. At HARC in 2012, treatment applications were made on May 15 and May 30, for the A and B timings, respectively. Immediately after herbicide application, considered 0 days after treatment (DAT), as well as at 2, 4, 7, 10 and 14 DAT, approximately 200 seeds of waterhemp (source was Mokane, MO; approximately 30% germination in lab tests) were scattered randomly on the soil surface within a single PVC piece in each plot.

Data collected included waterhemp emergence and above ground waterhemp biomass. Waterhemp seedlings were considered emerged when cotyledons were fully expanded. Emerging seedlings of species other than waterhemp were manually removed at the soil surface within each ring as necessary. Cumulative waterhemp emergence was recorded through 24 days after seeding (DAS) with no additional emergence observed thereafter. Therefore, the emergence estimates of waterhemp varied based upon seeding date, but each estimate occurred 24 DAS. At 35 DAS, all waterhemp plants in each PVC piece were harvested at soil level. Plants were dried at 49 C for 3 days and dry weight biomass recorded. Plots were replicated 5 times in a
split plot design, where the main plot factor was herbicide treatment and the sub-plot factor was time of seeding of waterhemp. The experiment was repeated two times at each location (in distinct areas) for both years (total of 8 site years).

Weather conditions varied widely between site years. Due to drought conditions, trial areas at Bradford were irrigated. Approximately 2.54 cm of water were applied every 10 to 12 days beginning June 5 in 2012. Table 2.2 shows the mean temperature and total rainfall for trial areas. Low waterhemp emergence due to drought precluded the use of the second timing of the trials at both locations in 2011 (Bradford B and HARC B), and both timings at HARC in 2012. The remaining four studies (Bradford 2011 A, HARC 2011 A, Bradford 2012 A, and Bradford 2012 B) were subjected to statistical analysis.

Data were subjected to an ANOVA using PROC GLM in SAS 9.3 (SAS Institute Incorporated, Cary, NC). Due to non-normal distribution, dry weights were subjected to a log transformation and emergence data were subjected to a square root transformation prior to ANOVA. Untransformed data are presented for simplicity, while statistical separations are based on transformed means. Due to significant location and year effects, site years were analyzed separately. Differences among means were separated using Fisher’s Protected LSD at P=0.05.

**Results and Discussion**

Averaged over site years and seeding date, all treatments significantly reduced the emergence of common waterhemp compared to the nontreated control (Figure
2.2). Overall, emergence was reduced by 14 to 81%. Treatments including acetochlor resulted in greater than 80% reduction of emergence compared to the nontreated control. Results with the highest rate of dicamba (0.56 kg ha\(^{-1}\)) and the equivalent rate of 2,4-D were similar, reducing emergence by 37 and 41%, respectively. The lowest rates of dicamba (0.14 and 0.28 kg ha\(^{-1}\)) reduced waterhemp emergence by 15 and 21%, respectively.

Total biomass for growth regulator treatments was similar to the nontreated control (Figure 2.3). Treatments including acetochlor resulted in 74 to 82% reduction in biomass compared to the nontreated control. Addition of dicamba at 0.28 kg ha\(^{-1}\) did not enhance suppression of waterhemp biomass compared to acetochlor alone. Biomass data was collected at 35 DAS, which ranged from 35 to 49 DAT. By 35 DAS, seedlings in treatments with high emergence (nontreated control, 0.14 and 0.28 kg ha\(^{-1}\) dicamba) were in competition for limited resources contained in the 52 cm\(^2\) area. Conversely, seedlings which had emerged in growth regulator treatments with low waterhemp densities (0.56 kg ha\(^{-1}\) dicamba and 2,4-D) had more resources available per plant and were able to accumulate greater biomass than seedlings emerged in higher density areas.

Waterhemp emergence was influenced by herbicide rate and seeding timing at each site year (Figures 2.4 to 2.7). At Bradford 2011 A, up to 10 waterhemp seedlings emerged in the nontreated control (Figure 2.4). With treatment, up to a 69% increase in emergence was observed at the 10 and 14 DAT seeding timings compared to the 0 to 7 DAT seeding timings. Waterhemp emergence at the 10 and 14 DAT seeding timings in
response to dicamba was similar or greater than emergence in the nontreated control. This indicates that waterhemp suppression with dicamba may only be rate dependent for a short period. Waterhemp emergence was 46% greater for 0.56 kg ha\(^{-1}\) 2,4-D compared to 0.56 kg ha\(^{-1}\) dicamba at Bradford 2011 A, but was similar for the other site years. Overall, waterhemp emergence declined as herbicide rate increased for HARC 2011 A, Bradford 2012 A and Bradford 2012 B with emergence highest in the nontreated control for each seeding date (Figures 2.5 to 2.7). Maximum emergence in the nontreated control was 48, 63, and 67 seedlings for HARC 2011 A, Bradford 2012 A and Bradford 2012 B, respectively. At two site years, HARC 2011 A and Bradford 2012 B, waterhemp emergence ranged from 39 to 48 plants 52 cm\(^{-2}\) at 0 DAT for the nontreated control. By the 14 DAT seeding timing, emergence declined 68% in the nontreated control. A similar trend was seen in several of the treatments and was likely influenced by limited soil moisture in both 2011 and 2012, despite irrigation at Bradford in 2012 (Table 2.2).

Limited rainfall in both 2011 and 2012 restricted waterhemp emergence (Table 2.2). In all four site years, emergence was overall lower than expected; 30% germination potential would have resulted in approximately 60 seedlings per treatment and seeding date. In 2011, less than 20 cm of rain was recorded for the time period in which the trials were conducted; maximum germination in these site years was less than 50 plants. In 2012, drought conditions were much worse; both site years received less than 5 cm rain from May 13 to July 15. Application of supplemental irrigation every 10 to 12 days resulted in approximately 11.6 and 16.8 cm of water for Bradford 2012 A and
Bradford 2012 B, respectively. Waterhemp emergence was therefore overall greater in 2012 than in 2011; with the maximum emergence in the nontreated control around 67 plants.

Within seeding date, waterhemp emergence varied across herbicide treatment (Figures 2.8 to 2.11). At Bradford 2011 A, the effect of herbicide rate was not significant for the 7, 10 and 14 DAT seeding timings, suggesting that the influence of herbicide on emergence declined (Figure 2.8). Emergence of waterhemp seeded between 0 and 7 DAT was similar to the nontreated control for rates of dicamba up to 0.28 kg ha\(^{-1}\). Compared to the nontreated control, waterhemp emergence decreased 51% for the 0 to 7 DAT seeding timings with 0.56 kg ha\(^{-1}\) dicamba, while waterhemp emergence increased 38% at the same rate of 2,4-D. For treatments including acetochlor, waterhemp emergence was reduced 66 to 87% from the nontreated control for the 0 to 7 DAT seeding timings. At HARC 2011 A and Bradford 2012 B, differences in waterhemp emergence were more distinguishable between herbicide rates for the 0, 2 and 4 DAT seeding timings (Figure 2.9 and 2.11). For HARC 2011 A and Bradford 2012 B as well as Bradford 2012 A, waterhemp emergence followed a similar pattern, with an overall decrease as dicamba rates increased. However, greater differences in emergence among herbicide rate were observed at the 10 and 14 DAT seeding timings for Bradford 2012 A compared to HARC 2011 A and Bradford 2012 B. The activity of dicamba plus acetochlor versus acetochlor alone varied across site year and seeding timing. Averaged across all site years and seeding dates, acetochlor plus dicamba reduced emergence an
additional 7% over acetochlor alone, and was most noticeable at Bradford 2012 A (Figure 2.10).

Overall, seeding date had little impact on accumulation of waterhemp biomass when averaged across site years. Total biomass of waterhemp was not significantly different between seeding dates within treatment (Figure 2.12). At 0 and 2 DAT, waterhemp biomass was up to 33% lower for dicamba treatments compared to the nontreated control. By 10 and 14 DAT, biomass accumulated for dicamba and 2,4-D treatments exceeded biomass accumulated by nontreated control plants.

Total biomass was impacted by herbicide treatment within seeding date (Figure 2.13). At 0 DAT, biomass was reduced up to 33% with increasing rates of dicamba, although not significantly different from the nontreated control. The addition of acetochlor reduced waterhemp biomass up to 86%. For seeding dates between 0 and 10 DAT, growth regulator treatments were similar to the nontreated control; only treatments containing acetochlor significantly reduced biomass. By 14 DAT, residual activity by herbicide treatments became more variable.

At each site year, total waterhemp biomass was variable for the nontreated control (Figures 2.14 to 2.17) and reflected variable emergence. Differences among chemical treatments were significant within seeding date. At HARC 2011 A (Figure 2.15) and Bradford 2012 B (Figure 2.17), treatments including acetochlor resulted in an 82% reduction in biomass at all seeding dates compared to treatments with dicamba alone. For three of four site years, biomass was similar across growth regulator treatments for the 0 and 2 DAT seeding dates, but variable for the 4 to 14 DAT seeding timings.
Acetochlor alone and acetochlor plus dicamba were not significantly different; exceptions were 14 DAT at Bradford 2011 A and 10 DAT at Bradford 2012 B.

There is limited research with dicamba use as a preemergence herbicide, primarily due to concerns of residual injury on planted broadleaf crops. With conventional PRE herbicides tank mixed with dicamba, increases in broadleaf control have been observed. Birschbach et al. (1993) reported 81% visible control (31 to 43 DAT) of triazine-resistant *Amaranthus hybridus* when 2.2 kg ha\(^{-1}\) metolachlor plus 0.56 kg ha\(^{-1}\) dicamba were applied PRE, compared to 16% control with metolachlor alone. Myers and Harvey (1993) observed up to 97% visible control (43 to 44 DAT) of *Chenopodium album* for applications of 2.2 kg ha\(^{-1}\) metolachlor plus 0.56 kg ha\(^{-1}\) dicamba, while metolachlor alone resulted in a maximum of 43% control. This research found 1.05 kg ha\(^{-1}\) acetochlor plus 0.28 kg ha\(^{-1}\) dicamba controlled waterhemp emergence up to 100% at 38 DAT for some site years. Johnson et al. (2010) reported 60% visible control of waterhemp with 0.28 kg ha\(^{-1}\) dicamba applied PRE, 21 days after treatment. Also, Byker et al. (2013) showed that 0.60 kg ha\(^{-1}\) dicamba visually controlled *Conyza canadensis* greater than 90% when applied PRE. This research demonstrated a 15 to 21% reduction in waterhemp emergence for dicamba applied up to 0.28 kg ha\(^{-1}\) (Figure 2.2) at 24 days after seeding. An increase in dicamba rate (0.56 kg ha\(^{-1}\)) resulted in an increase in waterhemp suppression (37%) compared to the nontreated control. It appears that the rate of dicamba applied will largely impact the expression of residual activity.
Variation in environmental condition may mask residual effects. Extreme
drought may have reduced overall waterhemp germination and emergence, making it
difficult to properly define treatment effects. Likewise, residual activity of dicamba is
affected by activity of soil microbes which are also responsive to changes in
environmental condition. This research showed that changes in environmental
conditions affect residual activity of dicamba.

Over different environmental conditions and growing seasons, limited residual
activity with dicamba was observed. In most instances the residual activity was limited
to 7 days or less. For those seedlings that did emerge, biomass accumulation was
similar to the nontreated control, suggesting that the impact of dicamba is restricted to
emergence and early seedling development. With unpredictable weather conditions
following application of dicamba, conventional PRE herbicides such as acetochlor should
be included for effective management of waterhemp in soybean production systems.


Table 2.1 List of herbicide treatments for residual control of common waterhemp (*Amaranthus rudis*)

<table>
<thead>
<tr>
<th>Herbicide</th>
<th>Rate (kg ae/ai ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dicamba</td>
<td>0.14</td>
</tr>
<tr>
<td>Dicamba</td>
<td>0.28</td>
</tr>
<tr>
<td>Dicamba</td>
<td>0.56</td>
</tr>
<tr>
<td>2,4-D</td>
<td>0.56</td>
</tr>
<tr>
<td>Acetochlor</td>
<td>1.05</td>
</tr>
<tr>
<td>Acetochlor + dicamba</td>
<td>1.05 + 0.28</td>
</tr>
</tbody>
</table>
Table 2.2 Weekly average temperatures and total precipitation for residual control of common waterhemp experimental areas in 2011 and 2012. Weather data were recorded for weather stations based at the University of Missouri farms at New Franklin and Columbia, Missouri.

<table>
<thead>
<tr>
<th>Date</th>
<th>Mean Temp (C)</th>
<th>Total Precipitation (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2011</td>
<td>Bradford A</td>
</tr>
<tr>
<td>HARC A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>May 29</td>
<td>16.3</td>
<td>6.7</td>
</tr>
<tr>
<td>June 5</td>
<td>22.0</td>
<td>0.3</td>
</tr>
<tr>
<td>June 12</td>
<td>23.8</td>
<td>3.4</td>
</tr>
<tr>
<td>Jun 19</td>
<td>20.5</td>
<td>3.1</td>
</tr>
<tr>
<td>June 26</td>
<td>20.9</td>
<td>0.1</td>
</tr>
<tr>
<td>July 3</td>
<td>22.8</td>
<td>3.3</td>
</tr>
<tr>
<td>July 10</td>
<td>23.0</td>
<td>0.8</td>
</tr>
<tr>
<td>July 17</td>
<td>25.3</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bradford A</td>
</tr>
<tr>
<td>May 29</td>
<td>17.9</td>
<td>4.5</td>
</tr>
<tr>
<td>June 5</td>
<td>25.8</td>
<td>0.6</td>
</tr>
<tr>
<td>June 12</td>
<td>24.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Jun 19</td>
<td>22.4</td>
<td>2.9</td>
</tr>
<tr>
<td>June 26</td>
<td>23.0</td>
<td>0.1</td>
</tr>
<tr>
<td>July 3</td>
<td>25.4</td>
<td>7.7</td>
</tr>
<tr>
<td>July 10</td>
<td>25.4</td>
<td>1.1</td>
</tr>
<tr>
<td>July 17</td>
<td>27.6</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2012</td>
</tr>
<tr>
<td>Bradford A and B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>May 13</td>
<td>19.6</td>
<td>0.0</td>
</tr>
<tr>
<td>May 20</td>
<td>21.9</td>
<td>0.0</td>
</tr>
<tr>
<td>May 27</td>
<td>22.4</td>
<td>0.0</td>
</tr>
<tr>
<td>June 3</td>
<td>19.9</td>
<td>0.1</td>
</tr>
<tr>
<td>June 10</td>
<td>22.6</td>
<td>0.0</td>
</tr>
<tr>
<td>June 17</td>
<td>23.2</td>
<td>3.9</td>
</tr>
<tr>
<td>June 24</td>
<td>25.9</td>
<td>0.0</td>
</tr>
<tr>
<td>July 1</td>
<td>28.3</td>
<td>0.0</td>
</tr>
<tr>
<td>July 8</td>
<td>30.1</td>
<td>0.0</td>
</tr>
<tr>
<td>July 15</td>
<td>26.6</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Figure 2.1. Representative arrangement of PVC rings (20.3 x 7.6 cm) in 0.9 x 1.5 m plot area for dicamba residual trial.
Figure 2.2. Means of emerged waterhemp plants by treatment, averaged over site year (HARC 2011 A, Bradford 2011 A, Bradford 2012 A and Bradford 2012 B) and seeding date at 24 days after seeding. Means followed by the same letter are not significantly different using Fisher’s Protected LSD at $P=0.05$. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor.
Figure 2.3. Total biomass of waterhemp by treatment, averaged over site year (HARC 2011 A, Bradford 2011 A, Bradford 2012 A and Bradford 2012 B) and seeding date at 24 days after seeding. Means followed by the same letter are not significantly different using Fisher’s Protected LSD at $P=0.05$. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor.
Figure 2.4. Means of emerged waterhemp plants (24 days after seeding) at Bradford 2011 A. Means followed by the same letter within a treatment are not significantly different using Fisher’s Protected LSD at $P=0.05$. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor; NS, not significant.
Figure 2.5. Means of emerged waterhemp plants (24 days after seeding) at HARC 2011 A. Means followed by the same letter within a treatment are not significantly different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor; NS, not significant.
Figure 2.6. Means of emerged waterhemp plants (24 days after seeding) at Bradford 2012 A. Means followed by the same letter within a treatment are not significantly different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor; NS, not significant.
Figure 2.7. Means of emerged waterhemp plants (24 days after seeding) at Bradford 2012 B. Means followed by the same letter within a treatment are not significantly different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor; NS, not significant.
Figure 2.8. Means of emerged waterhemp plants (24 days after seeding) at Bradford 2011 A. Means followed by the same letter within a seeding date are not significantly different using Fisher’s Protected LSD at $P=0.05$. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor; NS, not significant.
Figure 2.9. Means of emerged waterhemp plants (24 days after seeding) at HARC 2011 A. Means followed by the same letter within seeding date are not significantly different using Fisher’s Protected LSD at $P=0.05$. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor.
Figure 2.10. Means of emerged waterhemp plants (24 days after seeding) at Bradford 2012 A. Means followed by the same letter within seeding timing are not significantly different using Fisher’s Protected LSD at \(P=0.05\). Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor; NS, not significant.
Figure 2.11. Means of emerged waterhemp plants (24 days after seeding) at Bradford 2012 B. Means followed by the same letter within seeding timing are not significantly different using Fisher’s Protected LSD at $P=0.05$. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor; NS, not significant.
Figure 2.12. Total biomass of waterhemp by treatment, averaged over site years (HARC 2011 A, Bradford 2011 A, Bradford 2012 A and Bradford 2012 B) at 24 days after seeding. Means followed by the same letter within treatment are not significantly different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor; NS, not significant.
Figure 2.13. Total biomass of waterhemp by seeding date, averaged over site years (HARC 2011 A, Bradford 2011 A, Bradford 2012 A and Bradford 2012 B) at 24 days after seeding. Means followed by the same letter within seeding date are not significantly different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor.
Figure 2.14. Biomass of waterhemp plants at Bradford 2011 A. Means followed by the same letter within seeding date are not significantly different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor; NS, not significant.
Figure 2.15. Biomass of waterhemp plants at HARC 2011 A. Means followed by the same letter within seeding date are not significantly different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor.
Figure 2.16. Biomass of waterhemp plants at Bradford 2012 A. Means followed by the same letter within seeding date are not significantly different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor; NS, not significant.
Figure 2.17. Biomass of waterhemp plants at Bradford 2012 B. Means followed by the same letter within seeding date are not significantly different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means. Abbreviations: dic, dicamba; ace, acetochlor.
CHAPTER 3: IMPACT OF PALMER AMARANTH (AMARANTHUS PALMERI) AND COMMON WATERHEMP (AMARANTHUS RUDIS) PLANT HEIGHT ON THE RESPONSE TO DICAMBA

ASHLEY A. SCHLICHENMAYER & REID J. SMEDA*

Abstract

The increasing incidence of glyphosate-resistant common waterhemp (Amaranthus rudis Sauer) and Palmer amaranth (Amaranthus palmeri S. Wats.) in Missouri soybean (Glycine max L.) fields has reached a level where alternative management approaches are needed. Developing technologies such as dicamba-resistant soybean may offer an alternative management system, but chemical rate and proper timing (plant height) on Amaranthus species for effective control is unclear. In 2012, field studies in three Missouri locations were established in the presences of waterhemp (Novelty and Columbia) or Palmer amaranth (Portageville) to determine Amaranthus response to different rates of growth regulator herbicides at multiple growth stages. Across all sites, glufosinate-tolerant soybeans were planted in early May into conventionally tilled areas. Emerging Amaranthus plants were allowed to reach four target plant sizes: 5 to 10 cm, 12 to 18 cm, 20 to 25 cm and 28 to 36 cm. Six plants of each size were treated with 0.28 to 1.12 kg ae ha⁻¹ dicamba, or 2,4-D at 0.84 or 1.12

*Authors: Graduate Research Assistant, Professor, Division of Plant Sciences, University of Missouri, 108 Waters Hall, Columbia, MO 65211. Corresponding author’s E-mail: aaskv9@mail.missouri.edu
kg ae ha\(^{-1}\); an nontreated control was also included. Averaged across plant size, waterhemp control was optimal (91%) at 0.84 kg ha\(^{-1}\) dicamba, with the same rate resulting in 79% control of Palmer amaranth. Control of both species with 2,4-D at 1.12 kg ha\(^{-1}\) was statistically equivalent to 0.84 kg ha\(^{-1}\) of dicamba. Optimal control of waterhemp resulted from 0.84 (5 to 10 cm), 0.56 (12 to 18 cm), 0.56 (20 to 25 cm), and 0.84 (28 to 35 cm) kg ha\(^{-1}\) dicamba. For Palmer amaranth, optimal control was observed with 0.42 (5 to 10 cm), 0.84 (12 to 18 cm), 1.12 (20 to 25 cm), and 0.56 (28 to 36 cm) kg ha\(^{-1}\) dicamba. The greatest reduction in Palmer amaranth biomass (87%) followed an application of 0.84 kg ha\(^{-1}\) dicamba and 1.12 kg ha\(^{-1}\) 2,4-D (78%) for plants 12 to 25 cm, compared to the nontreated control. Reductions in waterhemp biomass were greatest for plants 28 to 36 cm, with 81 and 86% reductions for 1.12 kg ha\(^{-1}\) of dicamba and 2,4-D, respectively. Both dicamba and 2,4-D can effectively manage waterhemp and Palmer amaranth, with the most uniform response evident for 5 to 10 cm plants.

**Nomenclature:** dicamba; 2,4-D; common waterhemp, *Amaranthus rudis* Sauer AMATA; Palmer amaranth, *Amaranthus palmerii* S. Wats. AMAPA; soybean, *Glycine max* L.

**Keywords:** glyphosate-resistance; growth regulator.
Introduction

*Amaranthus* species, such as common waterhemp (*Amaranthus rudis* Sauer) and Palmer amaranth (*Amaranthus palmeri* S. Wats) are troublesome and competitive weeds in crop production systems (Hager et al. 2002a). Both species decreased soybean yield by as much as 38 to 79% in the presence of 8 plants m$^{-1}$ (Bensch et al. 2003). In Arkansas, Palmer amaranth reduced soybean yields by 68% at a density of 10 plants m$^{-1}$ row (Klingaman and Oliver 1994). Soybean yield was decreased 43% when common waterhemp was present at densities of ~200 plants m$^{-2}$ and when allowed to compete for up to 10 weeks (Hager et al. 2002b).

Control of *Amaranthus* species is challenging for producers due to several factors: high seed production; extended periods of germination; and rapid vegetative growth (Ward et al. 2013). Both common waterhemp and Palmer amaranth can produce over 250,000 seeds per plant (Sellers et al. 2003). Common waterhemp emerges from mid-May to early August in Iowa (Hartzler et al. 1999) and Palmer amaranth has been shown to emerge as early as March and as late as October in California (Keeley et al. 1987). The extended germination period for common waterhemp and Palmer amaranth complicates proper herbicide application timing for effective weed control. Additionally, these species are characterized by rapid seedling growth (Horak and Loughin 2000). In Kansas, Palmer amaranth and common waterhemp grew at a rate of up to 0.21 and 0.16 centimeters per growing degree day, respectively (Horak and Loughin 2000). Sellers et al. (2003), reported that Palmer amaranth biomass was up to 65% greater than other *Amaranthus* species just two
weeks after planting. Horak and Loughin (2000) showed that at maturity, Palmer amaranth biomass was 1.5- to 6- times greater than other *Amaranthus* species, including waterhemp. In the same study, waterhemp biomass was as much as 33% greater than *Amaranthus retroflexus*. Rapid growth of *Amaranthus* species, compared to other summer annuals, restricts the window of time when effective applications can be made (Horak and Loughin 2000).

Genetic variation within *Amaranthus* species also makes control challenging because variation contributes to the development of herbicide resistance, which is the greatest challenge crop producers face today. Much of the physiological basis for evolution of resistance results because common waterhemp and Palmer amaranth are both dioecious (Sauer 1957). This increases the genetic diversity of progeny (Tranel et al. 2009).

Many populations of waterhemp and Palmer amaranth have evolved resistance to multiple herbicides with different modes of action (MOA). In 1997, biotypes of common waterhemp and Palmer amaranth survived rates of acetolactate synthase (ALS) inhibitors (sulfonylureas) up to 100-fold higher compared to susceptible biotypes (Sprague et al. 1997). Biotypes of at least eight *Amaranthus* species exhibited resistance to triazines (LeBaron and MacFarland 1990), including both common waterhemp and Palmer amaranth (Peterson 1999). Palmer amaranth was first confirmed resistant to glyphosate in Georgia in 2006 (Culpepper et al. 2006). Waterhemp was reported with reduced sensitivity to glyphosate in greenhouse studies in Illinois in 2002 (Patzoldt et al. 2002) and confirmed resistant in field trials in Missouri.
Lee et al. (2008) reported that a novel resistance mechanism in waterhemp imparted resistance to protoporphyrinogen oxidase (PPO) inhibiting herbicides. A population of waterhemp in Illinois was recently reported to be resistant to 4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitors (Hausman et al. 2011). In Nebraska, a population of waterhemp was reported to be resistant to 2,4-D in 2012 (Bernards et al. 2012).

Although many herbicide modes of action are ineffective on waterhemp and Palmer amaranth, growth regulators, including dicamba, remain largely effective. In Illinois, ALS-resistant waterhemp was controlled by tank mixing atrazine and dicamba (Hager et al. 2000; Sprague et al. 1997). Studies have shown that adding dicamba to tank mixes for early POST applications consistently resulted in greater than 90% control of triazine-resistant *Amaranthus* species (Birschbach et al. 1993; Fuerst et al. 1986; Ritter et al. 1985). Soltani et al. (2009) also showed that a POST application of dicamba alone resulted in greater than 92% control of waterhemp in corn.

*Amaranthus* plants are effectively controlled with dicamba at small sizes. When applied to triazine-resistant *Amaranthus* plants ≤2.5 cm, dicamba at 0.28 kg ha\(^{-1}\) resulted in ≥94% control (Fuerst et al. 1986). Dicamba applied POST to 5 to 10 cm waterhemp at a rate of 0.6 kg ha\(^{-1}\) resulted in 91 to 98% control 70 days after treatment (DAT) and reduced plant density and biomass ≥94 and ≥98%, respectively (Soltani et al. 2009). When 0.54 kg ha\(^{-1}\) dicamba plus 1.03 kg ha\(^{-1}\) atrazine was applied to 8 to 12 cm waterhemp, visible control was 98% for both susceptible and triazine-resistant biotypes (Sprague et al. 1997). Field applications of growth regulators often include waterhemp
and Palmer amaranth plants of varying sizes, which results from the extended germination pattern of these species. Though dicamba successfully controls small plants, little research has been conducted to evaluate the effectiveness of multiple rates of dicamba applied to a range of sizes of waterhemp and Palmer amaranth plants, which would be present at the time of application.

Recent development of dicamba-resistant soybean will offer producers a novel method for POST control of *Amaranthus* and other broadleaf species. Johnson et al. (2010) determined that control of glyphosate-susceptible waterhemp and Palmer amaranth across 19 site years was 95% or greater with glyphosate and dicamba in dicamba-resistant soybeans. For glyphosate-resistant Palmer amaranth, control increased from 60 to 100% with dicamba compared to glyphosate alone. Likewise, control of glyphosate-resistant waterhemp increased from 30% with glyphosate alone to 95% with dicamba plus glyphosate POST (Johnson et al. 2010).

Integration of dicamba into a POST soybean management program can improve control of *Amaranthus* species which are resistant to other herbicides. However, continued emergence of waterhemp and palmer amaranth results in seedlings of variable size. Little data is available to support the efficacy of dicamba on different sizes of *Amaranthus*. The objectives of this study were to evaluate the response of common waterhemp and Palmer amaranth at four growth stages to multiple rates of dicamba and 2,4-D.
Materials and Methods

Field Trials. Field trials were established in 2011 and 2012 at three sites in Missouri. In 2011, trials were conducted at the Bradford Research and Extension Center (Bradford) near Columbia (38.89° N, 92.20°W) and at the Fisher Delta Research Center (Portageville) near Portageville (36.39° N, 89.61°W). In 2012, trials were conducted at Bradford and Portageville as well as the Greenley Memorial Research Center near Novelty (Novelty) (40.02° N, 92.16° W). Common waterhemp sites included Bradford and Novelty, while Palmer amaranth was prevalent at Portageville. The soil type at Bradford was a Mexico silt loam (Fine, smectitic, mesic Vertic Epiqualfs) with 2.2% organic matter and a pH of 5.8. At Portageville, the soil type was a Tiptonville fine sandy loam (Fine-silty, mixed, superactive, thermic Oxyaquic Argiudolls) with 1.5% organic matter and a pH of 5.5. The soil type at Novelty was a Kilwinning silt loam (Fine, smectitic, mesic Vertic Epiqualfs) with 3.1% organic matter and a pH of 5.9. Prior to experiment establishment, the trial areas at the three locations were planted to corn and respective regional recommendations for fertilization and weed management were practiced.

In experimental areas, soybeans were planted into a conventionally tilled area to provide a representative canopy. However, soybeans did not exhibit resistance to growth regulator herbicides. In 2011, glyphosate-resistant soybeans were established at Bradford (Asgrow 3803) and Portageville (Asgrow 4907) on May 12 and May 19, respectively. In 2012, glufosinate-resistant soybeans (Pioneer 93L71) were planted at all three locations between May 9 and May 17. Planting information is described in Table
3.1. Individual plots at each site were 3 m wide by 12 to 16 m long. After tillage but prior to planting (PREPLANT), an appropriate herbicide was utilized to remove unwanted vegetation when necessary. This included: 0.14 kg ai ha\(^{-1}\) fomesafen + 0.55 kg ae ha\(^{-1}\) glyphosate at Portageville in 2011, 0.07 kg ai ha\(^{-1}\) clethodim at Bradford in 2011, and 1.3 kg ae ha\(^{-1}\) glyphosate at Bradford in 2012 (Table 3.1).

To synchronize POST applications on *Amaranthus* plants of different sizes in the same plot, early emerging plants at two distinct sizes (approximately 40 per plot) were covered with plastic cups prior to application of non-selective herbicides (BURNDOWN). Burndown herbicides were applied broadcast (over the plastic cups) to all plot areas: 0.87 kg ae ha\(^{-1}\) glyphosate at Bradford in 2011; 1.26 kg ae ha\(^{-1}\) glyphosate + 0.56 kg ai ha\(^{-1}\) paraquat + 0.65 kg ai ha\(^{-1}\) glufosinate at Portageville in 2011; and 0.45 kg ai ha\(^{-1}\) glufosinate at all sites in 2012. Burndown treatments were applied at a speed of 4.8 km h\(^{-1}\) with a CO\(_2\) pressurized backpack sprayer equipped with XR8002 TeeJet (TeeJet\(^\circledR\) Spraying Systems Company, Wheaton, IL) flat fan nozzle tips, calibrated to deliver 140 L ha\(^{-1}\) at 117 kPa. In 2011 at Portageville, the burndown application was made with a tractor sprayer (Table 3.1).

Once additional waterhemp and Palmer amaranth seedlings emerged, six *Amaranthus* plants were identified (using color-coded flags) in each plot at each of four heights: 5 to 10, 12 to 18, 20 to 25 and 28 to 36 cm. POST treatments consisted of: 0.28, 0.42, 0.56, 0.84 or 1.12 kg ae ha\(^{-1}\) dicamba; 0.84 or 1.12 kg ae ha\(^{-1}\) 2,4-D; and a nontreated control. In 2011, treatments were applied at a speed of 7.2 km h\(^{-1}\) with a CO\(_2\) pressurized backpack sprayer equipped with TTI11002 Turbo TeeJet induction
nozzle tips calibrated to deliver 140 L ha$^{-1}$ at 117 kPa (Table 3.1). Equipment limitations resulted in poor coverage and droplet size distribution with TTI nozzle tips. Therefore, in 2012, treatments were applied at a speed of 4.8 km h$^{-1}$ with a CO$_2$ pressurized backpack sprayer equipped with AIXR 110015 TeeJet Air Induction nozzle tips calibrated to deliver 140 L ha$^{-1}$ at 200 kPa. In 2011, a commercially available formulation of dicamba (Clarity®, BASF Corporation, Research Triangle Park, NC) was used, but the source of dicamba in 2012 was an experimental formulation (MON100111, Monsanto Company, Saint Louis, MO). The formulation of 2,4-D used in both 2011 and 2012 was 2,4-D LoV Ester Weed Killer (Universal Crop Protection Alliance LLC., Eagan, MN).

Data collected from each site included visible control and biomass of individual common waterhemp and Palmer amaranth plants. Visible control was estimated using a scale of 0 (no injury) to 100% (plant death) at 14 and 28 days after treatment (DAT). Injury symptoms included height reduction, terminal bud kill, splitting and twisting of the stem and petioles, callous formation, and cupping of the leaves. The visible symptoms were considered and a composite injury score was recorded. At 28 DAT, individual Amaranthus plants were harvested at the soil level. Plants were dried for ~5 days at 49 C and dry weight recorded.

Field experiments were designed as a split plot. The main plot factor was chemical treatment and the sub-plot factor was plant size. Treatments were replicated four times in 2011 and five times in 2012. Individual plants of the same size in each plot were considered subsamples and averaged to generate a value for each replication. Dry weight and rating data were analyzed using PROC GLM in SAS 9.3 (SAS Institute
Incorporated, Cary, NC); dry weights were analyzed on a per plant basis. Due to non-normal distribution, dry weights were subjected to a log transformation prior to ANOVA; statistical separations were based upon transformed means, but untransformed data are presented for simplicity. Means were separated using Fisher’s Protected LSD at \( P=0.05 \). *Amaranthus* species present varied by location and differences in environmental conditions resulted in a significant location and year effect; therefore, locations were analyzed separately.

**Greenhouse Trials.** Greenhouse trials were conducted at the University of Missouri in 2012 and 2013. Individual common waterhemp and Palmer amaranth plants were established in 15 cm plastic pots filled with professional potting mix (ProMix, Hummert International, Earth City, MO). The source of common waterhemp was seed harvested from Mokane, MO; Palmer amaranth seed was purchased from Azlin Seed Service (Leland, MS). Plants were watered and fertilized as needed. Air temperatures were maintained between 24 and 37 °C. In addition to natural lighting, plants were subjected to a 15 hour photoperiod using light emitted from high pressure sodium lamps; the photosynthetic photon flux density averaged 600 μmol photon m\(^{-2}\) s\(^{-1}\).

In the greenhouse, waterhemp and Palmer amaranth seedlings were transplanted into 15 cm pots from plastic flats. As plants approached the desired sizes, four plants at each size were selected for treatment: 5 to 10; 12 to 18; 20 to 25; and 28 to 36 cm. Treatments consisted of: 0.28, 0.42, 0.56, 0.84 or 1.12 kg ae ha\(^{-1}\) dicamba; 0.84 or 1.12 kg ae ha\(^{-1}\) 2,4-D; and a nontreated control. Herbicides were applied using a
pneumatic sprayer equipped with a single AIXR 110015 TeeJet Air Induction nozzle tip calibrated to deliver 197 L ha\(^{-1}\) at 200 kPa.

Data collected included visible control and biomass of individual waterhemp and Palmer amaranth plants. Visible control was estimated using a scale of 0 (no injury) to 100% (plant death) at 28 days after treatment (DAT). Injury symptoms included height reduction, terminal bud kill, splitting and twisting of the stem and petioles, callous formation, and cupping of the leaves. The visible symptoms were considered and a composite injury score was recorded. At 28 DAT, individual *Amaranthus* plants were harvested at the soil level. Plants were dried for ~3 days at 49 C and dry biomass recorded.

Greenhouse trials were designed as completely randomized with four replications. The experiment was repeated for each *Amaranthus* species. Experimental run was not a significant factor for each species; therefore, data were combined for analysis. Data were analyzed using PROC GLM in SAS 9.3. Due to non-normal distribution, dry weights were subjected to a log transformation prior to ANOVA; statistical separations were based upon transformed means, but untransformed data are presented for simplicity. Means were separated using Fisher’s Protected LSD at P=0.05.

**Results and Discussion**

**Field Trials.** Environmental conditions precluded pooling data over years or locations.

Poor application coverage of plants in 2011 resulted in variable response of *Amaranthus*
to growth regulators. Data for 2011 were not considered further in this research and have been placed in the appendix; results and discussion are based on 2012 data.

Visible injury to common waterhemp and Palmer amaranth increased with increasing rates of growth regulator herbicides. Conversely, visual injury decreased as plant size increased. At 14 days after treatment, visible control of Palmer amaranth at Portageville ranged from 36 to 75% (Figure 3.1). For plants treated at 12 cm or greater, visible control did not exceed 62% and herbicide treatments were not statistically different within each plant size. For 5 to 10 cm tall plants, higher chemical rates (≥0.56 kg ha⁻¹ dicamba and ≥0.84 kg ha⁻¹ 2,4-D) resulted in greater control (55 to 75%) than 0.28 or 0.42 kg ha⁻¹ dicamba (41 to 50%). Injury levels with growth regulators were low, but dicamba injury has been reported to increase up to 30 DAT (Al-Khatib and Peterson 1999). Injury to Palmer amaranth plants at 28 DAT was greater than at 14 DAT (Figure 3.2). Visible control for Palmer amaranth across treatments and plant size ranged from 36 to 98%. Control of 5 to 10 cm plants was greatest, ranging from 63 to 98% across treatments. The maximum control declined as treated plant size increased: 60 to 86% (12 to 18 cm); 48 to 75% (20 to 25 cm); 36 to 70% (28 to 36 cm). At least 80% visible control of 5 to 10 cm tall plants resulted from 0.42 kg ha⁻¹ dicamba or greater as well as 1.12 kg ha⁻¹ of 2,4-D. For 12 to 25 cm plants, the rate of dicamba and 2,4-D did not influence control. For plants greater than 28 cm, control did not exceed 70%.

Waterhemp was more sensitive to higher rates of dicamba and 2,4-D than Palmer amaranth (Figures 3.3 to 3.6). At 14 DAT, visible control of waterhemp at Bradford ranged from 35 to 90% (Figure 3.3) and ranged from 46 to 87% at Novelty
(Figure 3.4). Unlike Palmer amaranth, variation within plant size and between treatments was significant. For all treatments, control of plants 12 cm or greater did not exceed 87% at either location; control did not exceed 82% for plants greater than 20 cm.

For plants up to 18 cm in height at Bradford, higher chemical rates (≥0.56 kg ha$^{-1}$ dicamba and ≥0.84 kg ha$^{-1}$ 2,4-D) resulted in greater control (71 to 90%) than 0.28 or 0.42 kg ha$^{-1}$ dicamba (43 to 46%) (Figure 3.3). Results at Novelty were similar, with higher chemical rates resulting in 68 to 87% control, while the lowest rates of dicamba resulted in only 49 to 62% control (Figure 3.4). Control of plants exceeding 20 cm in height was low, and >70% control required 1.12 kg ha$^{-1}$ dicamba or 2,4-D at Bradford, and 0.84 kg ha$^{-1}$ dicamba or 1.12 kg ha$^{-1}$ 2,4-D at Novelty.

At the 28 DAT evaluation for waterhemp, overall control increased at both locations for all chemical rates (Figures 3.5 and 3.6). Visible control ranged from 57 to 98% for common waterhemp at Bradford (Figure 3.5), and 75 to 99% at Novelty (Figure 3.6). At Novelty, 0.42 kg ha$^{-1}$ dicamba or greater resulted in >80% control for all plant sizes. The same level of control at Bradford was attained with ≥0.84 kg ha$^{-1}$ dicamba. Both 0.84 and 1.12 kg ha$^{-1}$ 2,4-D provided greater than 80% control for all plant sizes at both locations. Across plant sizes, 0.84 kg ha$^{-1}$ dicamba resulted in optimum control (85% or greater).

Both plant size and chemical treatment influenced biomass accumulation of Palmer amaranth (Figure 3.7). Palmer amaranth dry weight per plant increased as plant size increased for both treated and nontreated plants. Following treatment with dicamba or 2,4-D, biomass per plant was reduced up to 87 and 78%, respectively,
compared to the nontreated control. Dry weights for plants treated at 5 to 10 cm did not differ from nontreated plants. Growth regulators reduced dry weight of 12 to 25 cm plants from 43 to 87% (dicamba) and 37 to 78% (2,4-D), compared to nontreated plants. No differences among chemical treatments were noted for either 12 to 18 or 20 to 25 cm plants. For plants 28 to 36 cm in height, reductions in mean dry weight per plant were not evident above 0.42 kg ha\textsuperscript{-1} dicamba and both rates of 2,4-D (Figure 3.7).

Common waterhemp biomass was strongly influenced by growth regulators (Figures 3.8 and 3.9). Compared to the nontreated control, reductions in biomass following chemical treatment were much lower at Novelty than at Bradford. Plant biomass for all treated plant sizes was reduced only 34% at Novelty, but 70% at Bradford. Due to the lack of available precipitation, the per plant biomass of nontreated plants at Novelty were up to 80% lower than nontreated plants at Bradford. For plants up to 25 cm tall, biomass for treated plants was <5 g plant\textsuperscript{-1} at both locations. For 28 to 36 cm plants at Bradford, biomass reduction compared to the nontreated control from dicamba at 0.84 and 1.12 kg ha\textsuperscript{-1}, as well as 2,4-D at 0.84 and 1.12 kg ha\textsuperscript{-1} was 73, 81, 77, and 86%, respectively. The same treatments at Novelty resulted in 43, 26, 50, and 55% reduction in biomass. For 5 to 10 cm plants, no significant difference among herbicide treatments was observed at Novelty (Figure 3.9). Reductions in biomass were not measurable with treatments ≥0.42 kg ha\textsuperscript{-1} dicamba or either rate of 2,4-D at Bradford (Figure 3.8). Compared to the nontreated control, reductions in waterhemp biomass were optimal at 0.56 kg ha\textsuperscript{-1} dicamba (12 to 18 cm), 0.42 kg ha\textsuperscript{-1} dicamba (20 to 25 cm), and 0.84 kg ha\textsuperscript{-1} dicamba (28 to 36 cm) at Bradford (Figure 3.8). At Novelty, 0.42 kg ha\textsuperscript{-1}
dicamba (12 to 18 cm), 1.12 kg ha$^{-1}$ dicamba (20 to 25 cm) and 0.84 kg ha$^{-1}$ dicamba (28 to 36 cm) were the most effective rates (Figure 3.9).

**Greenhouse Trials.** *Amaranthus* species were more sensitive to growth regulators in the greenhouse than under field conditions. Absorbance of herbicides across the cuticle is more likely when the cuticle is thin and well hydrated (Currier and Dybing 1959), as under greenhouse conditions. Likewise, foliar absorption decreases when temperature is high and relative humidity is low (Currier and Dybing 1959), as was the case for field conditions in both 2011 and 2012 (Tables 3.2 to 3.3). For Palmer amaranth, by 28 DAT, all chemical treatments resulted in greater than 90% visible control for plants up to 25 cm (Figure 3.10). Visible control of plants greater than 25 cm was at least 80% for all treatments except 0.28 kg ha$^{-1}$ dicamba. By 28 DAT, visible control of waterhemp was similar to Palmer amaranth (Figure 3.11). Most plant growth regulator treatments resulted in greater than 90% visible control (the exceptions were 0.28 and 0.56 kg ha$^{-1}$ dicamba applied to plants greater than 28 cm). There were no significant differences between chemical rates for plants up to 25 cm for both species. Waterhemp and Palmer amaranth from 28 to 36 cm were controlled >85% with 0.84 and 1.12 kg ha$^{-1}$ of dicamba and 2,4-D.

The biomass of treated Palmer amaranth plants was reduced 64 to 99% from the nontreated control with growth regulator herbicide treatments (Figure 3.12). Biomass of 5 to 10 cm plants was reduced 97 to 99% compared to the nontreated control. For plants 12 to 18 cm, biomass reductions ranged from 82% (1.12 kg ha$^{-1}$ 2,4-D) to 96%
(1.12 kg ha\(^{-1}\) dicamba). Plant response to growth regulators was overall lower for plants 20 to 25 cm as biomass reduction ranged from 78 to 88% with 0.42 and 0.84 kg ha\(^{-1}\) dicamba treatments, respectively. For 28 to 36 cm tall plants, the greatest reductions in biomass compared to the nontreated control were 84 and 88% following applications of 1.12 kg ha\(^{-1}\) 2,4-D and dicamba, respectively.

Application of dicamba and 2,4-D to multiple sizes of common waterhemp in greenhouse studies resulted in a 57 to 96% reduction in biomass compared to the nontreated control (Figure 3.13). For plants 5 to 10 cm, biomass was not significantly reduced compared to the nontreated control. For all other plant sizes, there were significant differences compared to the nontreated control, but no significant differences between chemical treatments. Plants that were 12 to 25 cm at the time of application resulted in biomass reductions of 88 to 96% compared to the nontreated control. For 28 to 36 cm plants, the reduction in waterhemp biomass ranged from 75 to 86% compared to the nontreated control.

Differences in growth rates of Palmer amaranth and common waterhemp can influence the window of timing for application to smaller plants. Sellers et al. (2003) reported that Palmer amaranth reached a height of 10 cm within 14 days after seeding, and 20 cm by 28 days after seeding. In this research, control of Palmer amaranth plants taller than 20 cm did not exceed 75% at the highest rates of dicamba or 2,4-D at 28 DAT. Therefore, the proper timing for POST application of growth regulators as determined in this research should occur within 28 days of seeding. For waterhemp, Sellers et al. (2003) determined that plants only reached a height of 5 cm by 28 days after seeding.
This suggests that compared to Palmer amaranth, fields infested with waterhemp have a wider window for POST application of dicamba and 2,4-D.

Plant size influences the efficacy of herbicide activity on *Amaranthus* species. Hager et al. (2003) showed that delaying herbicide application to 10 cm waterhemp resulted in a 2 to 13% reduction in control from applications made to 5 cm plants. This research found similar results; a 2 to 11% reduction in control was observed as waterhemp size increased at Bradford, with the optimum control rate of 0.84 kg ha$^{-1}$ dicamba. However, at Novelty, differences in control due to size were lower, as overall control was higher (≥92%) at 28 DAT. Biomass of waterhemp was reduced up to 92% for plants <25 cm, while plants 28 to 36 cm had a maximum reduction of 85%. Reduced control of plants increasing in size is not restricted to growth regulators. Klingaman et al. (1992) determined that control of Palmer amaranth with imazethapyr was increased 3 to 30% when application height decreased from 7.2 to 3.3 cm. For Palmer amaranth, growth regulator application reduced biomass 37 to 87% for plants 12 to 25 cm, while biomass for plants 28 to 36 cm was reduced only 35 to 71% (Figure 3.7).

This research found that plant size at the time of growth regulator application is more critical with Palmer amaranth than waterhemp. If one considers 90% visible control to be the minimum for effective management, no dose of dicamba or 2,4-D could result in effective control for Palmer amaranth plants larger than 10 cm. For waterhemp, 1.12 kg ha$^{-1}$ dicamba and 2,4-D resulted in effective control of waterhemp up to 36 cm at both Bradford and Novelty. Klingaman et al. (1992) also reported that control of Palmer amaranth increased when imazethapyr rates of 0.05 and 0.07 kg ha$^{-1}$
were applied to smaller plants. However, at rates of 0.11 and 0.14 kg ha\(^{-1}\), both sizes were controlled ≥94%, indicating that response is both plant height and chemical rate dependent.

The rate of dicamba applied determines the amount of weed control. In a 20 year summary paper, Lym and Messersmith (1985) report increased control of leafy spurge (**Euphorbia esula** L.) with increased rates of spring applied dicamba. Dicamba applied at 0.6 kg ha\(^{-1}\) resulted in 47% visible control, while 79, 82, 93, and 100% control resulted from dicamba applied at 4.5, 6.7, 9.0 and 13.4 kg ha\(^{-1}\), respectively. Increasing the rate of dicamba also improved control of Canada thistle (**Cirsium arvense** L. Scop.) in Washington (Ogg 1975). When dicamba was applied at 0.3 kg ha\(^{-1}\), control of Canada thistle averaged 73 to 77%, while 0.6 kg ha\(^{-1}\) resulted in 87 to 96% control. All applications greater than 1.12 kg ha\(^{-1}\) resulted in >90% control. Managing 5 to 10 cm Palmer amaranth is most effective with 0.84 kg ha\(^{-1}\) dicamba. Above 10 cm, control was reduced to 86, 73, and 60% for 12 to 18; 20 to 25; and 28 to 36 cm plants, respectively. With waterhemp, 90% or greater control was attained on 12 to 18 cm plants with dicamba rates as low as 0.56 kg ha\(^{-1}\); optimum control was realized with 0.84 kg ha\(^{-1}\) dicamba or 1.12 kg ha\(^{-1}\) 2,4-D.

This research shows that dicamba at rates 0.84 kg ha\(^{-1}\) or higher effectively control 5 to 10 cm plants of common waterhemp and Palmer amaranth. Effective rates of dicamba or 2,4-D may be lower in a field situation where dicamba- or 2,4-D-tolerant soybeans are planted due to additional competition and shading from the crop canopy, which reduces weed interference (Teasdale 1995). Soybeans were established in the
field studies, but were not resistant to growth regulator herbicides; therefore, POST applications severely damaged crop plants and precluded competition between soybean and common waterhemp or Palmer amaranth plants.

Continuous emergence of Palmer amaranth and common waterhemp (Hartzler et al. 1999; Keeley et al. 1987) will require multiple POST applications if the timing of dicamba and 2,4-D is limited to 5 to 10 or 12 to 18 cm plants. Selection of the proper rate to control waterhemp and Palmer amaranth with dicamba or 2,4-D is critical to precluding survivors or selecting for tolerant/ resistant plants (Holt et al. 1993; Powles and Yu 2010). The overall 35 to 86% reduction in Palmer amaranth biomass and 8 to 92% reduction in waterhemp biomass indicate that treated plants may not have been competitive with soybeans. If a soybean canopy had been present, the impact of damaged *Amaranthus* on crop yield may be minimal. Preservation of dicamba- or 2,4-D tolerant soybean technology should include application of effective PRE herbicides for control of *Amaranthus* species.
Al-Khatib, K. and D. Peterson. 1999. Soybean (Glycine max) response to simulated drift from selected sulfonylurea herbicides, dicamba, glyphosate, and glufosinate. Weed Technol. 13; 264-270.


Fuerst, E. P., M. Barrett and D. Penner. 1986. Control of triazine-resistant common lambquarters (Chenopodium album) and two pigweed species (Amaranthus spp.) in corn (Zea mays). Weed Sci. 34; 440-443.


Table 3.1 Soybean planting specifications and herbicide applications at three locations (Bradford, Portageville, and Novelty) in Missouri in 2011 and 2012.

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Pre-plant application (kg ai/ae ha(^{-1}))</th>
<th>Planting date</th>
<th>Variety</th>
<th>Depth (cm)</th>
<th>Population (seeds ha(^{-1}))</th>
<th>Burndown application (kg ai/ae ha(^{-1}))</th>
<th>Burndown application information</th>
<th>Treatment application date</th>
<th>Treatment application information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bradford (2011)</td>
<td></td>
<td>0.07 clethodim</td>
<td>May 12</td>
<td>Asgrow 3803</td>
<td>1.9</td>
<td>346,000</td>
<td>0.87 glyphosate</td>
<td>4.8 km h(^{-1}) XR 8002 140 L ha(^{-1}) 117 kPa</td>
<td>July 1</td>
<td>7.2 km h(^{-1}) TTI11002 140 L ha(^{-1}) 117 kPa</td>
</tr>
<tr>
<td>Portageville (2011)</td>
<td></td>
<td>0.14 fomesafen + 0.55 glyphosate</td>
<td>May 19</td>
<td>Asgrow 4907</td>
<td>3.8</td>
<td>291,000</td>
<td>1.26 glyphosate + 0.56 paraquat + 0.65 glufosinate</td>
<td>6.4 km h(^{-1}) XR 8002 94 L ha(^{-1}) 379 kPa</td>
<td>July 5</td>
<td>7.2 km h(^{-1}) TTI11002 140 L ha(^{-1}) 117 kPa</td>
</tr>
<tr>
<td>Bradford (2012)</td>
<td></td>
<td>1.3 glyphosate</td>
<td>May 11</td>
<td>Pioneer 93L71</td>
<td>1.9</td>
<td>346,000</td>
<td>0.45 glufosinate</td>
<td>4.8 km h(^{-1}) XR 8002 140 L ha(^{-1}) 117 kPa</td>
<td>June 28</td>
<td>4.8 km h(^{-1}) AIXR 110015 140 L ha(^{-1}) 200 kPa</td>
</tr>
<tr>
<td>Portageville (2012)</td>
<td></td>
<td>NA</td>
<td>May 9</td>
<td>Pioneer 93L71</td>
<td>1.3</td>
<td>173,000</td>
<td>0.45 glufosinate</td>
<td>4.8 km h(^{-1}) XR 8002 140 L ha(^{-1}) 117 kPa</td>
<td>June 26</td>
<td>4.8 km h(^{-1}) AIXR 110015 140 L ha(^{-1}) 200 kPa</td>
</tr>
<tr>
<td>Novelty (2012)</td>
<td></td>
<td>NA</td>
<td>May 17</td>
<td>Pioneer 93L71</td>
<td>1.9</td>
<td>346,000</td>
<td>0.45 glufosinate</td>
<td>4.8 km h(^{-1}) XR 8002 140 L ha(^{-1}) 117 kPa</td>
<td>June 22</td>
<td>4.8 km h(^{-1}) AIXR 110015 140 L ha(^{-1}) 200 kPa</td>
</tr>
</tbody>
</table>
Table 3.2. Average air temperature and total precipitation for common waterhemp (*Amaranthus rudis*) and Palmer amaranth (*Amaranthus palmeri*) field sites in 2011. Data were recorded weekly at Portageville and Columbia, MO from the time of soybean planting through *Amaranthus* harvest.

<table>
<thead>
<tr>
<th>Date</th>
<th>Portageville</th>
<th>Columbia</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Temp  (C)</td>
<td>Total Precipitation (cm)</td>
</tr>
<tr>
<td>May 14</td>
<td>22.8</td>
<td>2.8</td>
</tr>
<tr>
<td>May 21</td>
<td>17.3</td>
<td>1.4</td>
</tr>
<tr>
<td>May 28</td>
<td>21.5</td>
<td>2.8</td>
</tr>
<tr>
<td>June 4</td>
<td>29.0</td>
<td>0.0</td>
</tr>
<tr>
<td>June 11</td>
<td>29.6</td>
<td>0.8</td>
</tr>
<tr>
<td>June 18</td>
<td>25.8</td>
<td>4.2</td>
</tr>
<tr>
<td>June 25</td>
<td>27.2</td>
<td>0.1</td>
</tr>
<tr>
<td>July 2</td>
<td>27.3</td>
<td>0.1</td>
</tr>
<tr>
<td>July 9</td>
<td>26.7</td>
<td>2.2</td>
</tr>
<tr>
<td>July 16</td>
<td>29.3</td>
<td>0.1</td>
</tr>
<tr>
<td>July 23</td>
<td>29.5</td>
<td>0.0</td>
</tr>
<tr>
<td>July 30</td>
<td>28.6</td>
<td>0.5</td>
</tr>
<tr>
<td>August 6</td>
<td>29.2</td>
<td>2.2</td>
</tr>
</tbody>
</table>
Table 3.3. Average air temperature and total precipitation for common waterhemp (*Amaranthus rudis*) and Palmer amaranth (*Amaranthus palmeri*) field sites in 2012. Data were recorded weekly at Portageville, Columbia, and Novelty, MO from the time of soybean planting through *Amaranthus* harvest.

<table>
<thead>
<tr>
<th>Date</th>
<th>Portageville</th>
<th>Columbia</th>
<th>Novelty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Temp (C)</td>
<td>Total Precipitation (cm)</td>
<td>Mean Temp (C)</td>
</tr>
<tr>
<td>May 12</td>
<td>21.3</td>
<td>0.6</td>
<td>17.8</td>
</tr>
<tr>
<td>May 19</td>
<td>23.5</td>
<td>0.0</td>
<td>19.7</td>
</tr>
<tr>
<td>May 26</td>
<td>24.4</td>
<td>0.5</td>
<td>21.9</td>
</tr>
<tr>
<td>June 2</td>
<td>24.4</td>
<td>0.5</td>
<td>20.8</td>
</tr>
<tr>
<td>June 9</td>
<td>23.8</td>
<td>0.7</td>
<td>21.9</td>
</tr>
<tr>
<td>June 16</td>
<td>25.1</td>
<td>0.5</td>
<td>23.1</td>
</tr>
<tr>
<td>June 23</td>
<td>27.4</td>
<td>0.0</td>
<td>25.4</td>
</tr>
<tr>
<td>June 30</td>
<td>28.9</td>
<td>0.0</td>
<td>28.2</td>
</tr>
<tr>
<td>July 7</td>
<td>30.6</td>
<td>0.0</td>
<td>30.2</td>
</tr>
<tr>
<td>July 14</td>
<td>26.2</td>
<td>3.6</td>
<td>26.7</td>
</tr>
<tr>
<td>July 21</td>
<td>28.6</td>
<td>0.0</td>
<td>28.6</td>
</tr>
<tr>
<td>July 28</td>
<td>28.6</td>
<td>1.6</td>
<td>29.3</td>
</tr>
<tr>
<td>August 4</td>
<td>28.5</td>
<td>3.7</td>
<td>28.3</td>
</tr>
<tr>
<td>August</td>
<td>26.8</td>
<td>0.0</td>
<td>24.9</td>
</tr>
<tr>
<td>August</td>
<td>23.8</td>
<td>1.9</td>
<td>21.9</td>
</tr>
<tr>
<td>August</td>
<td>24.2</td>
<td>0.0</td>
<td>24.1</td>
</tr>
</tbody>
</table>
Figure 3.1. Visible response of Palmer amaranth to growth regulators at Portageville in 2012, 14 days after treatment (DAT). Applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm) within each plot. Means with the same letter within plant size are not significantly different using Fisher’s Protected LSD at P=0.05. Means without letters are not significantly different within a plant size. Vertical bars indicate standard error of the means.
Visible response of Palmer amaranth to growth regulators at Portageville in 2012, 28 days after treatment (DAT). Applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm) within a plot. Means with the same letter within plant size are not statistically different using Fisher’s Protected LSD at $P=0.05$. Means without letters are not significantly different within a plant size. Vertical bars indicate standard error of the means.
Figure 3.3. Visible response of common waterhemp to growth regulators at Bradford in 2012, 14 days after treatment (DAT). Applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm) within a plot. Means with the same letter within plant size are not statistically different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means.
Figure 3.4. Visible response of common waterhemp to growth regulators at Novelty in 2012, 14 days after treatment (DAT). Applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm) within a plot. Means with the same letter within plant size are not statistically different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means.
Figure 3.5. Visible response of common waterhemp to growth regulators at Bradford in 2012, 28 days after treatment (DAT). Applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm) within a plot. Means with the same letter within plant size are not statistically different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means.
Figure 3.6. Visible response of common waterhemp to growth regulators at Novelty in 2012, 28 days after treatment (DAT). Applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm) within a plot. Means with the same letter within plant size are not statistically different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means.
Figure 3.7. Mean biomass of Palmer amaranth, 28 days after treatment (DAT) with growth regulators at Portageville in 2012. Applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm). Means with the same letter within plant size are not statistically different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means.
Figure 3.8. Mean biomass of common waterhemp, 28 days after treatment (DAT) with growth regulators at Bradford in 2012. Applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm). Means with the same letter within plant size are not statistically different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means.
Figure 3.9. Mean biomass of common waterhemp, 28 days after treatment (DAT) with growth regulators at Novelty in 2012. Applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm). Means with the same letter within plant size are not statistically different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means.
Figure 3.10. Visible response of Palmer amaranth, 28 days after herbicide application in a greenhouse environment. Data were averaged over two trials and applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm). Means with the same letter within plant size are not statistically different using Fisher’s Protected LSD at P=0.05. Means without letters are not significantly different within a plant size. Vertical bars indicate standard error of the means.
Figure 3.11. Visible response of common waterhemp, 28 days after herbicide application in a greenhouse environment. Data were averaged over two trials and applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm). Means with the same letter within plant size are not statistically different using Fisher's Protected LSD at P=0.05. Means without letters are not significantly different within a plant size. Vertical bars indicate standard error of the means.
Figure 3.12. Mean Palmer amaranth biomass, 28 days after herbicide application in a greenhouse environment. Data were averaged over two trials and applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm). Means with the same letter within plant size are not statistically different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means.
Figure 3.13. Mean common waterhemp biomass, 28 days after herbicide application in a greenhouse environment. Data were averaged over two trials and applications were made to four plant sizes (5 to 10, 12 to 18, 20 to 25, 28 to 36 cm). Means without an asterisk within plant size are not statistically different using Fisher’s Protected LSD at P=0.05. Vertical bars indicate standard error of the means.
APPENDIX
Table A1. Visible ratings (0= no control, 100= plant death) for Palmer amaranth, 14 and 28 days after treatment (DAT), at Portageville, MO in 2011. Plant sizes at treatment were in four groups: 5 to 10, 12 to 18, 20 to 25, and 28 to 35 cm.

<table>
<thead>
<tr>
<th>Treatment (kg ae ha⁻¹)</th>
<th>14 DAT</th>
<th>Plant size at treatment (cm)</th>
<th>28 DAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 to 10</td>
<td>12 to 18</td>
<td>20 to 25</td>
</tr>
<tr>
<td>dicamba (0.28)</td>
<td>54d</td>
<td>45b</td>
<td>35d</td>
</tr>
<tr>
<td>dicamba (0.42)</td>
<td>57cd</td>
<td>59a</td>
<td>48bc</td>
</tr>
<tr>
<td>dicamba (0.56)</td>
<td>68bc</td>
<td>58ab</td>
<td>45cd</td>
</tr>
<tr>
<td>dicamba (0.84)</td>
<td>74ab</td>
<td>62a</td>
<td>63a</td>
</tr>
<tr>
<td>dicamba (1.12)</td>
<td>82a</td>
<td>69a</td>
<td>62a</td>
</tr>
<tr>
<td>2,4-D (0.84)</td>
<td>61cd</td>
<td>71a</td>
<td>55abc</td>
</tr>
<tr>
<td>2,4-D (1.12)</td>
<td>60cd</td>
<td>69a</td>
<td>61ab</td>
</tr>
</tbody>
</table>

*Means with the same letter within plant size and rating timing are not significantly different using Fisher’s Protected LSD at P=0.05.
Table A2. Visible ratings (0= no control, 100= plant death) for common waterhemp, 14 and 28 days after treatment (DAT), at Columbia, MO in 2011. Plant sizes at treatment were in four groups: 5 to 10, 12 to 18, 20 to 25, and 28 to 35 cm.

<table>
<thead>
<tr>
<th>Treatment (kg ae ha(^{-1}))</th>
<th>14 DAT</th>
<th>28 DAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plant size at treatment (cm)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 to 10(^a)</td>
<td>12 to 18</td>
</tr>
<tr>
<td>dicamba (0.28)</td>
<td>78abc</td>
<td>63c</td>
</tr>
<tr>
<td>dicamba (0.42)</td>
<td>67bc</td>
<td>82ab</td>
</tr>
<tr>
<td>dicamba (0.56)</td>
<td>56c</td>
<td>70bc</td>
</tr>
<tr>
<td>dicamba (0.84)</td>
<td>89ab</td>
<td>89a</td>
</tr>
<tr>
<td>dicamba (1.12)</td>
<td>94a</td>
<td>91a</td>
</tr>
<tr>
<td>2,4-D (0.84)</td>
<td>75abc</td>
<td>80ab</td>
</tr>
<tr>
<td>2,4-D (1.12)</td>
<td>89ab</td>
<td>88a</td>
</tr>
</tbody>
</table>

\(^a\)Means with the same letter within plant size and rating timing are not significantly different using Fisher’s Protected LSD at P=0.05.
Table A3. Dry weight per plant for common waterhemp at Columbia, MO and Palmer amaranth at Portageville, MO, 28 days after treatment in 2011. Plant sizes at treatment were in four groups: 5 to 10, 12 to 18, 20 to 25, and 28 to 36 cm.

<table>
<thead>
<tr>
<th>Treatment (kg ae ha⁻¹)</th>
<th>Plant size at treatment (cm)</th>
<th>Columbia</th>
<th>Portageville</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 to 10</td>
<td>12 to 18</td>
<td>20 to 25</td>
</tr>
<tr>
<td>Nontreated</td>
<td>7.0</td>
<td>18.6</td>
<td>14.3</td>
</tr>
<tr>
<td>dicamba (0.28)</td>
<td>6.9</td>
<td>4.8</td>
<td>5.7</td>
</tr>
<tr>
<td>dicamba (0.42)</td>
<td>3.6</td>
<td>2.6</td>
<td>2.1</td>
</tr>
<tr>
<td>dicamba (0.56)</td>
<td>6.5</td>
<td>4.0</td>
<td>7.7</td>
</tr>
<tr>
<td>dicamba (0.84)</td>
<td>3.2</td>
<td>1.7</td>
<td>5.6</td>
</tr>
<tr>
<td>dicamba (1.12)</td>
<td>1.3</td>
<td>1.1</td>
<td>2.9</td>
</tr>
<tr>
<td>2,4-D (0.84)</td>
<td>1.6</td>
<td>1.7</td>
<td>4.5</td>
</tr>
<tr>
<td>2,4-D (1.12)</td>
<td>0.6</td>
<td>1.8</td>
<td>5.6</td>
</tr>
</tbody>
</table>

*Means with the same letter within plant size and rating timing are not significantly different using Fisher’s Protected LSD at P=0.05.