Antagonism of Barnyardgrass (Echinochloa Crus-Galli) Control with Graminicides by Glufosinate in Libertylink Soybeans (Glycine Max)

Amber Nicole Eytcheson

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Antagonism of barnyardgrass \((Echinochloa crus-galli)\) control with graminicides by glufosinate in LibertyLink soybeans \((Glycine max)\)

By

Amber Nicole Eytcheson

A Dissertation
Submitted to the Faculty of
Mississippi State University
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in Agriculture
in the Department of Plant and Soil Sciences

Mississippi State, Mississippi

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Antagonism of barnyardgrass (*Echinochloa crus-galli*) control with graminicides by glufosinate in LibertyLink soybeans (*Glycine max*).

By

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Field and greenhouse experiments were conducted to determine barnyardgrass control as affected by glufosinate and graminicide tank-mixtures, application timing of tank-mixtures of graminicides plus glufosinate and application time of day of tank-mixtures of glufosinate and clethodim. When increased rates of graminicide were tank-mixed with glufosinate, barnyardgrass control was unaffected by quizalofop-P plus glufosinate; however, clethodim plus glufosinate control in the field indicated the potential for reduced barnyardgrass control. When evaluating increasing glufosinate rates tank-mixed with graminicides, barnyardgrass control was not negatively affected by the combination of glufosinate and graminicides. The difference in soybean yield among the graminicides may indicate that the cyclohexanedione herbicides had a slight yield advantage over the aryloxyphenoxypropionate herbicides due to potential increased levels of barnyardgrass control. Applications of glufosinate alone provide variable control throughout the growing season in both field and greenhouse experiments. Although barnyardgrass control in the field was not affected by glufosinate application timing, data from the greenhouse indicates potential exists for reduced control if
glufosinate is applied 1 or 3 d before graminicides. Clethodim was unaffected by application time of day; however, glufosinate applications at midnight reduced barnyardgrass control compared to applications made at noon and 6 P.M. Applications at 6 A.M. also reduced barnyardgrass efficacy compared to applications at 6 P.M. Environmental factors such as temperature and light at the time of application are likely responsible for the time of day effects observed in these studies. For maximum benefit from incorporating graminicides into a glufosinate weed control system, fluazifop-P, quizalofop-P, clethodim and sethoxydim should be applied with glufosinate at 594 or 890 g ai ha\(^{-1}\). Sequential treatments of glufosinate should be applied 7 d prior to a graminicide application or 1, 3 or 7 d after a graminicide application. To optimize barnyardgrass efficacy with tank mixtures of glufosinate and clethodim, applications should be made at noon or early evening to avoid potential time of day effects.
DEDICATION

I would like to dedicate this work to my Lord and Savior, Jesus Christ. You have blessed me with a wonderful husband, supportive and loving family and the opportunity to continue my education. I have enjoyed the journey that you have laid before me and am looking forward to what lies ahead.

“Have I not commanded you? Be strong and of good courage; be not frightened, neither be dismayed; for the Lord your God is with you wherever you go.” Joshua 1:9.

I would also like to dedicate this research to my husband Ryan. You have sacrificed more than anyone in our journey. You have encouraged me to push through difficult times and persevere, you are my rock. I would also like to dedicate this work to my late-grandfather, Herman George Brewe, Jr., my uncle, Carl Brewe and my father, Maurice Brewe. I hope to carry on the legacy my grandfather left behind and strive to continue our family’s agricultural traditions another generation.

“Thy word is a lamp unto my feet, and a light unto my path.”

Palms 119:105.
ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to the faculty and staff of the Department of Plant and Soil Science at Mississippi State University, especially the Weed Science faculty for your guidance throughout this research. Most importantly, I’d like to thank my major professor, Dr. Dan Reynolds for allowing me the opportunity to be a part of his program. His instruction, patience, support and hospitality has nurtured and refined my professional capabilities for the future. I would also like to thank the members of my graduate committee, Dr.’s John Byrd, Thomas Eubank, Trent Irby and Angus Catchot for their guidance throughout this degree. I am grateful for their willingness to answer questions and encouragement to reach my full potential.

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TABLE OF CONTENTS

DEDICATION........................................................................................................................................ ii

ACKNOWLEDGEMENTS..................................................................................................................... iii

LIST OF TABLES.................................................................................................................................. vi

LIST OF FIGURES ............................................................................................................................. vii

CHAPTER

I. INTRODUCTION ...............................................................................................................................1

Literature Cited.....................................................................................................................................10

II. THE EFFECT OF GLUFOSINATE AND GRAMINICIDE TANK-MIX RATES ON BARNYARDGRASS CONTROL .................................................................16

Abstract...............................................................................................................................................16

Introduction........................................................................................................................................17

Materials and Method .......................................................................................................................20

Increasing rate of graminicide ........................................................................................................20

Field experiments..............................................................................................................................20

Greenhouse experiments..................................................................................................................22

Increasing rate of glufosinate.............................................................................................................24

Field experiments..............................................................................................................................24

Greenhouse experiments..................................................................................................................25

Results and Discussion ..................................................................................................................27

Increasing rate of graminicide ........................................................................................................27

Field experiments..............................................................................................................................27

Greenhouse experiments..................................................................................................................30

Increasing rate of glufosinate.............................................................................................................32

Field experiments..............................................................................................................................32

Greenhouse experiments..................................................................................................................35

Literature Cited......................................................................................................................................45

III. BARNYARDGRASS CONTROL AS AFFECTED BY APPLICATION TIMING OF GLUFOSINATE APPLIED ALONE OR TANK-MIXED WITH GRAMINICIDES ..................................................................................48
Abstract..........................................................................................................................48
Introduction..........................................................................................................................49
Materials and Method ........................................................................................................53
  Field Experiments ...........................................................................................................53
  Greenhouse Experiments ..............................................................................................56
Results and Discussion .......................................................................................................57
  Field Experiments ...........................................................................................................57
  Greenhouse Experiments ..............................................................................................61
Literature Cited ...................................................................................................................73

IV. APPLICATION TIME OF DAY EFFECT ON GLUFOSINATE WHEN TANK-MIXED WITH CLETHODIM ON BARNYARDGRASS EFFICACY .............................................................77

Abstract..........................................................................................................................77
Introduction.........................................................................................................................78
Materials and Method .......................................................................................................82
Results and Discussion .....................................................................................................83
Literature Cited ...................................................................................................................93
# LIST OF TABLES

2.1 Field experiments evaluating the effect of barnyardgrass control with increasing graminicide rates tank-mixed with glufosinate..........................37

2.2 Greenhouse experiments evaluating the effect of barnyardgrass control with increasing graminicide rates tank-mixed with glufosinate..............39

2.3 Field experiments evaluating barnyardgrass control as affected by increasing glufosinate rates tank-mixed with graminicides....................40

2.4 Greenhouse experiments evaluating barnyardgrass control as affected by increasing glufosinate rate tank-mixed with graminicides.................44

3.1 Barnyardgrass height and growth stage at the time of application for field experiments in 2013 and 2014

3.2 Barnyardgrass control as affected by application timing of glufosinate when applied alone or tank-mixed with clethodim

3.3 Barnyardgrass biomass as affected by application timing of glufosinate when applied alone or tank-mixed with clethodim

3.4 Barnyardgrass height and growth stage at the time of application for greenhouse experiments in 2013 and 2014

3.5 Barnyardgrass control as affected by application timing of glufosinate when applied alone or tank-mixed with fluazifop-P, quizalofop-P or clethodim

3.6 Barnyardgrass biomass as affected by application timing of glufosinate when applied alone or tank-mixed with fluazifop-P, quizalofop-P or clethodim

4.1 Environmental data at the time of the glufosinate application..................89

4.2 Barnyardgrass control as affected by clethodim and glufosinate interaction pooled over time of day............................90

4.3 Barnyardgrass control as affected by glufosinate and time of day interaction pooled over clethodim rates..........................90
LIST OF FIGURES

2.1 2014 Soybean yield as affected by glufosinate rate, pooled over all graminicide and graminicide rates. ..........................................................38

2.2 Barnyardgrass biomass as affected by graminicide main effect, pooled over glufosinate rates. ..........................................................41

2.3 Field experiments evaluating barnyardgrass biomass as affected by glufosinate rate main effect, pooled over graminicides. ..................42

2.4 Soybean yield as affected by graminicide main effect, pooled over glufosinate rates..........................................................43
CHAPTER I
INTRODUCTION

Genetically modified (GM) crops with tolerance to non-selective herbicides have been rapidly adopted in the United States due to the higher crop yield, lower pesticide costs as well as their simplicity and flexibility (Fernandez-Cornejo et al. 2005; Fernandez-Cornejo et al. 2014). The introduction and adoption of crops resistant to glyphosate in the Roundup Ready® system enabled producers to reduce production costs associated with herbicide purchases, applications, tillage, hand weeding and is more environmentally benign than the soil tillage and herbicides it has replaced; some researchers consider glyphosate to be a “Once in a Century Herbicide” (Duke and Powles 2008; Gianessi 2005). The intensive use of glyphosate has contributed to the evolution of glyphosate-resistant (GR) weeds, leaving many producers seeking alternative weed control technologies to prevent absolute crop failure. The widespread infestation of GR Palmer amaranth (Amaranthus palmeri S. Wats.) in soybean (Glycine max Merr.) is a major contributor to the greater adoption of LibertyLink® (LL) soybean in the Midsouthern United States (Riar et al. 2013a; Riar et al. 2013b).

The LL system utilizes the GM crop resistance to the herbicide glufosinate. Glufosinate is a non-selective, non-residual POST herbicide used in GM crops including canola (Brassica napus L.), corn (Zea mays L.), cotton (Gossypium hirsutum L.) and soybeans (Anonymous 2011a and Senesman 2007). Phosphinothricin [homoalanin-4-yl-
(methyl)phosphic acid, the active portion of the glufosinate molecule, inhibits glutamine synthetase, the enzyme that converts ammonia and glutamate to glutamine (Coetzer and Al-Khatib 2001; Devine et al. 1993; Hess 2000). The accumulation of ammonia and stomatal closure in the plant directly inhibits photosystem I and II reactions by reducing the pH gradient across cell membranes which uncouples photophosphorylation, leading to rapid cell destruction and eventually, plant death (Coetzer and Al-Khatib 2001; Senesman 2007).

Glufosinate controls a broad spectrum of annual and perennial grass and broadleaf weeds (Anonymous 2011a and Senesman 2007). Additionally, glufosinate can control weeds that are difficult to control with glyphosate such as the Ipomoea spp. and hemp sesbania [Sesbania herbacea (P. Mill.) McVaugh], as well as GR weeds such as horseweed [Coneza canadensis (L.) Cronq.], and Amaranthus spp (Culpepper et al. 2000; Green and Owen 2011; Whitaker et al. 2011). Shurley et al. (2010) reported in areas of prevalent GR Palmer amaranth, especially in non-irrigated conservation tillage, a glufosinate-based system is the most efficacious and cost effective tool to manage GR Palmer amaranth. However, grass weed control with glufosinate may be inadequate and may require additional management inputs (Beyers et al. 2002; Burke et al. 2005; Gardner et al. 2006; Koger et al. 2007; Steckel et al. 1997). Ritter and Menbere (2001) reported that early POST applications of glufosinate at 400 g ai ha$^{-1}$ did not adequately control giant foxtail (Setaria faber) in a glufosinate tolerant soybean system. Similarly, Culpepper and York (1999) reported glufosinate at 400 g ai ha$^{-1}$ applied POST only provided 81 to 94% and 64% season-long control of fall panicum (Panicum dichotomiflorum Michx.) and goosegrass [Eleusine indica (L.) Gaertn.], respectively.
Culpepper et al. (2000) reported glufosinate at 400 g ai ha⁻¹ provided 77 and 83% control of broadleaf signalgrass \([Urochloa platyphlla\ (Nash)\ R.D.\ Webster]\) and goosegrass, respectively. A sequential application of glufosinate at 290 g ai ha⁻¹ improved control only 13 and 5%, respectively, compared to a single application of glufosinate (Culpepper et al. 2000). Stephenson and Scroggs (2009) reported that two applications of glufosinate at 880 g ai ha⁻¹ resulted in less than 90% barnyardgrass \([Echinochloa crus-galli\ (L.)\ Beauv.]\) control at season-end. Due to limited translocation of glufosinate, application timing in regard to plant size at time of application is critical for season long weed control. Glufosinate applied late postemergence compared to earlier applications was ineffective on larger goosegrass (Culpepper et al. 2000) and barnyardgrass (Craigmyle et al. 2013) due to plant regrowth and escapes. When treated at 15 cm plant height, giant foxtail, common lambsquarters \((Chenopodium\ album\ L.)\), common cocklebur \((Xanthium\ strumarium\ L.)\), and Pennsylvania smartweed \((Polygonum\ pensylvanicum\ L.)\) control was 45% less than when the weed species were treated at 10 cm plant height with glufosinate at 420 g ai ha⁻¹ (Steckel et al. 1997).

A recent survey of soybean consultants in the Midsouthern United States concluded that 35% of the total scouted LL acres were treated solely with glufosinate (Riar et al. 2013b). However, glufosinate applied alone may provide less than adequate summer annual grass control compared to glyphosate (Culpepper et al. 2000). Therefore, producers may need to tank-mix herbicides to broaden the spectrum of weeds controlled and reduce application cost (Beyers et al. 2002; Corkern et al. 1998; Green 1989; Kim et al. 2005; Vidrine 1989; Vidrine et al. 1995; Zhang et al. 1995).
Producers that utilize the LL soybean cropping system can combine glufosinate, a non-selective herbicide and a graminicide herbicide for enhanced grass weed control. The arloxyphenoxypropionate (FOP) and cyclohexanedione (DIM) herbicide families, commonly known as the graminicide herbicide group, are utilized for POST annual and perennial grass control without causing injury to dicotyledonous weeds or crops (Devine et al. 1993; Senesman 2007). The FOP herbicides fluazifop-P and quizalofop-P and the DIM herbicides clethodim and sethoxydim are labeled for use in soybeans (Anonymous 2010a; Anonymous 2010b; Anonymous 2010c; Anonymous 2011b). The FOP and DIM herbicide families are both inhibitors of fatty acid biosynthesis. The primary mode of action is the inhibition of the de novo fatty acid biosynthesis at the acetyl-CoA (ACCase) enzyme, located in the stroma of plastids (Anderson 1996; Devine et al. 1993; Senseman 2007). Plant growth ceases soon after application, initially affecting the actively growing tissues, followed by destruction of the intercalary meristem within 1 to 3 wks after application (Anderson 1996; Senseman 2007). Older leaves often turn orange, purple or red before turning necrotic (Anderson 1996; Senseman 2007).

However, combinations of FOP and DIM herbicides with herbicides used to control broadleaves typically result in antagonism (Barnes and Oliver 2004; Burke et al. 2005; Burke et al. 2002; Gardner et al. 2006; Jordan 1995; Kim et al. 2005; Vidrine 1989; Vidrine 1995). Barnes and Oliver (2004) reported cloransulam tank-mixed with fluazifop-P plus fenoxaprop or quizalofop-P antagonized broadleaf signalgrass and barnyardgrass control compared to the graminicides applied alone. Kim et al. (2005) reported bromoxynil tank-mixed with quizalofop-P antagonized seedling maize control, and the magnitude of antagonism increased as the rate of bromoxynil increased. The
antagonism of graminicides by broadleaf herbicides applied with graminicides may sometimes be reduced or alleviated by increasing the rate of the graminicide and/or sequential herbicide applications (Green 1989). However, there have been conflicting reports of antagonism caused by glufosinate when graminicide herbicides are applied at normal use rates as tank-mixed or sequential applications. Beyers et al. (2002) reported that glufosinate plus quizalofop reduced giant foxtail biomass 87% compared to the untreated and had 20% greater biomass reduction than glufosinate alone. Johnson et al. (2014) and Wright et al. (2006) reported that glufosinate tank-mixed with clethodim, sethoxydim, or fluazifop-P, applied at labeled rates had no evidence of antagonism and controlled GR johnsongrass ([Sorghum halepense (L.) Pers.], and barnyardgrass 81 to 98% and 100%, respectively. However, Burke et al. (2005), Gardner et al. (2006) and Irby et al. (2007) reported glufosinate tank-mixed or applied sequentially with clethodim, sethoxydim, fluazifop-P or quizalofop-P caused antagonized control of broadleaf signalgrass, fall panicum, goosegrass, johnsongrass and large crabgrass ([Digitaria sanguinalis (L.) Scop.]).

The recent trend in increasing farm size and reliance on non-selective POST herbicides for weed control have forced pesticide applicators to make POST applications over a broader application interval (Anonymous 2014; Sellers et al. 2004). Additionally, wind velocity is often times lower near sunrise and sunset, thus reducing the potential for herbicide drift to non-target plants. Reduced efficacy of herbicides applied near or after sunset is referred to as time of day effect (Sellers et al. 2004). Several POST herbicides, including glufosinate have been reported to be sensitive to application time of day (Anderson et al. 1993a; Martinson, et al. 2005; Sellers et al. 2003; Sellers et al. 2004;
Stewart et al. 2009; Stopps et al. 2013; Waltz et al. 2004). Several environmental factors may influence herbicide efficacy throughout the day. High wind speeds impact POST herbicide applications by allowing drift onto non-target crops (Duke 2005). Therefore, producers will apply herbicides in the morning hours, or late in the evening when wind speeds are lowest (Waltz et al. 2004); however, herbicide efficacy may be reduced at these times of day. The presence of dew on leaf surfaces at these times may interfere with herbicide absorption and increase herbicide loss through runoff (Anderson 1996; Fausey and Renner 2001; Kogan and Zungia 2001; Waltz et al. 2004). To avoid the interaction with dew POST herbicides can be applied during the day, after the dew has evaporated from the leaf surface. Increased relative humidity and air temperature during this time frame may also improve POST herbicide efficacy (Anderson 1996; Anderson et al. 1993a; Coetzer et al. 2001; Fausey and Renner 2001; Friesen and Wall 1991; Kumaratilake and Preston 2005; Martinson et al. 2005; Peterson and Hurle 2001; Stopps et al. 2013; Waltz et al. 2004). Giant foxtail control was less than 50% when fluazifop-P plus bromoxynil were applied in temperatures less than 25°C, regardless of the time of day applied (Friesen and Wall 1991). Uptake and translocation of radiolabeled glyphosate was significantly greater in Florida beggarweed [Desmodium tortuosum (Sw.) DC.] at 95% relative humidity than 45 and 70% (Sharma and Singh 2001). Differential herbicide response due to diurnal leaf movement may also contribute to the time of day effect. Sellers et al. (2003) reported that diurnal leaf movements of velvetleaf (Abutilon theophrasti Medik.) contributed to reduced glufosinate efficacy when applications were made near sundown. However, diurnal leaf movement is not known to exist in grass
species; therefore, reduced grass efficacy following a herbicide application due to diurnal fluctuations can likely be eliminated as a contributing factor to the time of day effect.

Previous research has shown that glufosinate is sensitive to many factors contributing to the time of day effect. Glufosinate applications made at 95% relative humidity had greater control of giant foxtail, compared to applications made at 40% (Anderson et al. 1993a). Kumaratilake and Preston (2005) reported that absorption of glufosinate was not affected by temperature; however, translocation of glufosinate to the meristematic regions of wild radish (*Raphanus raphanistrum* L.) increased in warm temperatures as compared to translocation of glufosinate to the shoot tips in cold temperatures. A semi-systemic herbicide like glufosinate has very little translocation, thus an increase in herbicide translocation to meristematic regions may result in increased efficacy. Anderson et al. (1993b) reported greater ammonia accumulation and visual injury of giant foxtail when glufosinate was applied at the end of the photoperiod, rather than at the beginning. Sellers et al. (2004) reported that radiolabeled glufosinate applied at 10 P.M. had greater translocation than when applied at 2 P.M.; however, less glutamine synthetase inhibition and ammonia accumulation occurred at the 10 P.M. application. It is theorized that during the light period, glutamine synthetase is active and glufosinate is translocated to the chloroplast, acting as a sink for glufosinate (Sellers et al. 2004). However, during the dark period, glufosinate absorption is initially higher but glutamine synthetase is not as active; therefore, the chloroplast is no longer a sink for glufosinate (Sellers et al. 2004). This allows for greater translocation of glufosinate during dark period. Sellers et al. (2004) hypothesized that the glufosinate molecules are being translocated and sequestered into the vacuole, making them unavailable for glutamine
synthetase in the following light period. The difference in glutamine synthetase inhibition and ammonia accumulation between the application times may explain the differences in the time of day effect with glufosinate (Sauer et al. 1987; Sellers et al. 2004; Wild et al. 1987).

Barnyardgrass is one of the most troublesome grasses in soybean production in the Midsouth. As one of the top 10 most common and troublesome weeds in the southern U. S., it can produce up to 39,000 seed per plant (Bagavathiannan et al. 2012; Webster 2013). Barnyardgrass exhibits prolific seed dormancy, prolonged emergence period, ability to grow rapidly and flower in a range of photoperiod and environmental conditions (Bagavathiannan et al. 2011; Maun and Barrett 1986; Mitch 1990; Potvin 1986). Although barnyardgrass has the ability to germinate from soil depths as great as 12.7 cm, the primary emergence depth is 1.27 to 3.8 cm (Dawson and Bruns 1962). Barnyardgrass densities of 0 to 500 per m of row reduced soybean yield 0 to 78%, with an average yield reduction of 0.25% for each barnyardgrass plant per m of soybean row (Vail and Oliver 1993). A common rotational crop with rice (*Oryza sativa* L.) in the Midsouth is soybeans. In rice production systems, barnyardgrass is the most problematic weed species, including populations with multiple herbicide resistance to fenoxaprop-P-ethyl, imazamox, imazethapyr, propanil and quinclorac (Heap 2015; Norsworthy et al. 2013). As a major pest of rice and soybean production systems, barnyardgrass control is critical in order to prevent yield loss, reduce the number of seeds entering the soil seedbank and prevent alternative host sites for insect and disease pests.

Limited data are available on the effect of combinations of glufosinate and graminicides on barnyardgrass control in a LL soybean system. Producers utilizing the
LL soybean system would benefit from appropriate management strategies to reduce or alleviate potential graminicide antagonism. Therefore, the objectives of this research were to determine barnyardgrass control as affected by glufosinate and graminicide tank-mixture rates, application timing, and application time of day to optimize barnyardgrass efficacy.
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CHAPTER II
THE EFFECT OF GLUFOSINATE AND GRAMINICIDE TANK-MIX RATES ON BARNYARDGRASS CONTROL

Abstract

Field and greenhouse experiments were conducted to evaluate antagonism-potential of glufosinate-graminicide mixtures on barnyardgrass control. Barnyardgrass antagonism did not occur when graminicide or glufosinate rates were increased when tank-mixed with glufosinate or graminicides. When increased rates of graminicide were tank-mixed with glufosinate, barnyardgrass control was unaffected by the mixture of quizalofop-P and glufosinate; however, clethodim plus glufosinate control in the field indicated potential for reduced barnyardgrass control may exist. When glufosinate was tank-mixed with the graminicides, soybean yield increased 14% compared to the graminicides applied alone. When evaluating increasing glufosinate rates tank-mixed with graminicides, barnyardgrass control was unaffected. Biomass reductions were greater with glufosinate at 1 and 1.5X compared to glufosinate at 0.5X. Soybean yield increased 7% when clethodim and sethoxydim were included in the tank-mix compared to no graminicide; however, soybean yield as affected by fluazifop-P and quizalofop-P were not different from no graminicide. The difference in soybean yield among the graminicides may indicate that the DIM herbicides had a slight yield advantage over the FOP herbicides due to potential increased levels of barnyardgrass control. In this
research, antagonism did not occur; however, reduced levels of control did occur and may indicate that if conditions are favorable, barnyardgrass antagonism may occur when clethodim is applied with glufosinate.

**Nomenclature:** Clethodim; fluazifop-P; glufosinate; quizalofop-P; sethoxydim; barnyardgrass, *Echinochloa crus-galli* (L.) Beauv. ECHCG; soybean, *Glycine max* L.

**Key words:** Antagonism, tank mixture, interaction, crop oil concentrate.

**Introduction**

Genetically modified (GM) crops with tolerance to non-selective herbicides have been rapidly adopted in the United States due to their higher crop yield, lower pesticide costs as well as simplicity and flexibility of the technology (Fernandez-Cornejo et al. 2005; Fernandez-Cornejo et al. 2014). The introduction and adoption of crops resistant to glyphosate in the Roundup Ready® system enabled producers to reduce production costs associated with herbicide purchases, applications, tillage, hand weeding and is environmentally harmless compared to the the soil tillage and herbicides it has replaced; some researchers consider glyphosate to be a “Once in a Century Herbicide” (Duke and Powels 2008; Gianessi 2005). The intensive use of glyphosate has contributed to the evolution of glyphosate-resistant (GR) weeds, leaving many producers seeking alternative technologies for weed control to prevent absolute crop failures. The widespread infestation of GR Palmer amaranth (*Amaranthus palmeri* S. Wats.) in soybean (*Glycine max* Merr.) has been a major contributor to increased adoption of LibertyLink® (LL) soybean in the Midsouthern United States (Riar et al. 2013a; Riar et al. 2013b).
The LL system utilizes the GM crop resistance to the herbicide glufosinate.

Glufosinate is a non-selective, non-residual POST herbicide used in GM crops including canola (*Brassica napus* L.), corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.) and soybeans (Anonymous 2011a; Senseman 2007). Glufosinate controls weeds that are difficult to control with glyphosate such as the *Ipomoea* spp. and hemp sesbania [*Sesbania herbacea* (P. Mill.) McVaugh], as well as GR weeds such as horseweed [*Conyza canadensis* (L.) Cronq.], and *Amaranthus* spp (Culpepper et al. 2000; Green and Owen 2011; Whitaker et al. 2011). Shurley et al. (2010) reported in areas of prevalent GR Palmer amaranth, especially in non-irrigated conservation tillage, a glufosinate-based system is the most efficacious and cost effective tool to manage GR Palmer amaranth. However, grass weed control with glufosinate may be inadequate and may require additional management inputs (Beyers et al. 2002; Burke et al. 2005; Gardner et al. 2006; Koger et al. 2007; Steckel et al. 1997). Culpepper et al. (2000) reported glufosinate at 400 g ai ha\(^{-1}\) provided 77 and 83% control of broadleaf signalgrass [*Urochloa platyphlla* (Nash) R.D. Webster] and goosegrass, respectively. A sequential application of glufosinate at 290 g ai ha\(^{-1}\) improved control only 13 and 5%, respectively. Stephenson and Scroggs (2009) reported that two applications of glufosinate at 880 g ai ha\(^{-1}\) resulted in less than 90% barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] control by season-end.

A recent survey of soybean consultants in the Midsouthern United States concluded that 35% of the total scouted LL acres were treated solely with glufosinate (Riar et al. 2013b). Compared to glyphosate, glufosinate applied alone may provide less than adequate summer annual grass control; thus, an additional herbicide will be

The arloxyphenoxypropionates (FOP) and cyclohexanediones (DIM) herbicide families, commonly known as the graminicide herbicide group, are utilized for POST annual and perennial grass control without causing injury to dicotyledonous weed or crops (Devine et al. 1993; Senesman 2007). The FOP herbicides fluazifop-P and quizalofop-P and the DIM herbicides clethodim and sethoxydim are labeled for use in soybeans (Anonymous 2010a; Anonymous 2010b; Anonymous 2010c; Anonymous 2011b).

Producers that utilize the LL soybean cropping system can combine glufosinate, a non-selective herbicide and a graminicide herbicide for enhanced grass weed control. There have been conflicting reports of antagonism caused when graminicide herbicides are applied at normal use rates with glufosinate. Burke et al. (2005) reported decreased goosegrass [*Eleusine indica* (L.) Gaertn.] control when clethodim was applied with glufosinate. Gardner et al. (2006) reported reduced control of annual grasses when glufosinate was included in mixture with clethodim, fluazifop-P, quizalofop-P and sethoxydim. However, Beyers et al. (2002) reported adequate giant foxtail (*Setaria faberi* Herrm.) control when quizalofop-P was tank-mixed with glufosinate. GR johnsongrass [*Sorghum halepense* (L.) Pers.] control was greater when herbicide programs included clethodim compared to glufosinate applied alone (Johnson et al. 2014).
Barnyardgrass is one of the most troublesome grasses in soybean production areas of the Midsouth (Webster 2013). Barnyardgrass exhibits prolific seed dormancy, a prolonged emergence period, the ability to grow rapidly and flower in a range of photoperiod and environmental conditions (Bagavathiannan et al. 2011; Maun and Barrett 1986; Mitch 1990; Potvin 1986). Barnyardgrass densities of 0 to 500 per m of row reduced soybean yield 0 to 78%, with an average yield reduction of 0.25% for each barnyardgrass plant per m of soybean row (Vail and Oliver 1993). A common rotational crop with rice (*Oryza sativa* L.) in the Midsouth is soybeans. As a major pest of rice and soybean production systems, barnyardgrass control is critical in order to prevent yield loss and reduce the number of seeds entering the soil seedbank.

The antagonism of graminicides by broadleaf herbicides may be reduced or alleviated by increasing the rate of the more active herbicide or by decreasing the rate of the less active herbicide (Green 1989). Limited data are available on the effect of glufosinate and graminicides combinations on barnyardgrass control in a LL soybean system. Producers utilizing the LL soybean system would benefit from appropriate management strategies to prevent potential graminicide antagonism. Therefore, the objective of this research was to determine barnyardgrass control as affected by glufosinate and graminicide tank-mixture rates.

**Materials and Method**

**Increasing rate of graminicide**

*Field experiments*

Field studies were conducted in 2013 and 2014 to evaluate the antagonism-potential of glufosinate-graminicide mixtures on barnyardgrass control. Experiments
were conducted at the Black Belt Branch Experiment Station in Brooksville, MS on an Okolona silty clay (Fine, smectitic, thermic Oxyaquic Hapluderts) with 8% sand, 51% silt, 41% clay, 2% organic matter and pH of 6.8 and a Brooksville silty clay (Fine, smectitic, thermic Aquic Hapluderts) with 7% sand, 48% silt, 45% clay, 1.8% organic matter and pH of 6.0 in the respective years. Experiments were conducted in fields naturally infested with populations of barnyardgrass. Barnyardgrass density averaged 1,205 and 269 plants m\(^{-2}\) in 2013 and 2014, respectively. In 2013, the experiment was conducted in a fallowed field, not planted to soybean. Plot size in the fallowed area was 2.8 by 9.4 m. Pioneer 95L01 soybeans (Pioneer 95L01 soybean, Pioneer Hi-Bred International, INC., PO Box 1000, Johnston, IA) were planted May 19, 2014 with a target population of 271,930 plants ha\(^{-1}\). Plots were three rows (0.96 m) by 9.4 m long.

Herbicide treatments consisted of quizalofop-P (Assure II\(^{®}\), 105 g ai l\(^{-1}\), Du Pont de Nemours and Co., 1007 Market Street, Wilmington, DE 19898) at 0, 28, 56 or 84 g ai ha\(^{-1}\) and clethodim (Select Max \(^{®}\), 116 g ai l\(^{-1}\), Valent U. S. A. Co., PO Box 8025, Walnut Creek, CA 94596) at 0, 38, 76 or 114 g ai ha\(^{-1}\) applied with glufosinate (Liberty\(^{®}\) 280 SL, 280 g ai l\(^{-1}\), Bayer CropScience LP, PO Box 12014, 2 T.W. Alexander Drive, Research Triangle Park, NC 27709) at 0 or 594 g ai ha\(^{-1}\). The graminicide rates represent 0X, 0.5X, 1X or 1.5X rates, respectively. Crop oil concentrate (Agri-dex\(^{®}\), Helena Chemical Company, 225 Schilling Blvd., Suite 300, Collierville, TN 38017) at 1.0% v v\(^{-1}\) was included with all graminicide treatments. No adjuvant was included when glufosinate was applied alone. Herbicide treatments were applied with a CO\(_2\)-pressurized backpack sprayer equipped with XR8002 flat-fan nozzle (TeeJet Technologies, PO Box 7900, Wheaton, IL 60187) at an application volume of 140 l ha\(^{-1}\) and a pressure of 220 kPa.
Herbicide treatments were applied when barnyardgrass plants had three to four fully expanded leaves. Soybeans were 15 to 17 cm tall at the V3 growth stage at the time of application. Visual estimates of barnyardgrass control were recorded 7, 14, 21, 28 and 56 days after treatment (DAT), using a scale of 0 to 100%, where 0 = no control and 100 = complete control. Chlorosis, height reductions and regrowth were visually evaluated to estimate control. Barnyardgrass biomass was collected 56 DAT, using a 1 m quadrat and plants were separated to only include barnyardgrass plants that were present at the time of application. Samples were oven dried at 65°C for 1 wk to determine barnyardgrass biomass on a dry matter basis. Soybeans were machine harvested and yield was recorded.

The experimental design was a randomized complete block with a factorial arrangement of treatments: Factor A was graminicide, Factor B was graminicide rate nested within graminicide herbicide and Factor C was glufosinate rate. Four replications for each treatment were used in each experiment. Barnyardgrass control data were pooled across years because experimental replication was considered a random variable. Untransformed and arcsine square root transformed data were subjected to analysis of variance, but interpretations were similar to untransformed data; therefore, untransformed data were used for analysis. Data were subjected to ANOVA and means were separated using Fischer’s protected LSD test at P = 0.05.

**Greenhouse experiments**

Treatments described in the field studies were also evaluated in a greenhouse environment. Barnyardgrass seed were planted approximately 2.5 cm deep in 40-cm³ plastic conetainers (D40 Deepot Cell, Stuewe and Sons, Inc., 2290 SE Kiger Island Dr.,
Corvallis, OR 97333) containing commercial potting soil mix (Metro-Mix 360, Sungro Horticulture, 770 Silver Street, Agawam, MA 01001) and placed into a column module. Containers were surface irrigated after planting with tap water and were subirrigated for the duration of the experiment. Plants were thinned to three plants per container within 1 wk after emergence, and grown at 35/30°C night/day temperature. Natural light was supplemented with light from sodium vapor lamps (General Electric Sodium Vapor Lamps, Lucalox LU 400, General Electric Consumer and Industrial Lighting, 1975 Noble Rd., Nela Park, Cleveland, OH 44112) to provide a 16-h photoperiod (Dodds et al. 2007).

Approximately 1 wk after thinning, when plants had fully expanded three to four leaves, herbicide treatments were applied using a compressed air spray chamber equipped with a single 80015EV flat-fan nozzle (TeeJet Technologies, PO Box 7900, Wheaton, IL 60187) at an application volume of 140 l ha⁻¹ and a pressure of 240 kPa.

Barnyardgrass control was visually estimated 7, 14, 21 and 28 DAT, using a scale of 0 to 100%, where 0 = no control and 100 = complete control. Chlorosis, height reductions and regrowth were visually evaluated to estimate control. Barnyardgrass biomass was collected 28 DAT, and oven dried at 65°C for 1 wk to determine barnyardgrass biomass on a dry matter basis.

Four replications for each treatment were used in each experiment and the experiment was replicated in time. Data were pooled across experimental replications because experimental replication was considered a random variable. Untransformed and square root transformed data were subjected to analysis of variance, but interpretations were similar to untransformed data; therefore, untransformed data were used for analysis.
Data were subjected to ANOVA and means were separated using Fischer’s protected LSD test at $P = 0.05$. 

**Increasing rate of glufosinate**

*Field experiments*

Field studies were conducted in 2013 and 2014 to evaluate antagonism-potential of glufosinate-graminicide mixtures on barnyardgrass control. Experiments were conducted at the Black Belt Branch Experiment Station in Brooksville, MS on a Brooksville silty clay (Fine, smectitic, thermic Aquic Hapluderts) with 7% sand, 48% silt, 45% clay, 1.8% organic matter and pH of 6.0. Experiments were conducted in a field naturally infested with populations of barnyardgrass. Barnyardgrass density was approximately 269 plants m$^{-2}$ in 2013 and 2014. In 2013, the experiment was conducted in a fallowed field, not planted to soybean. Plot size in the fallowed area was 2.8 by 9.4 m. Pioneer 95L01 soybeans were planted May 19, 2014 with a target population of 271,930 plants ha$^{-1}$. Plots were three rows (0.96 m) by 9.4 m long.

Herbicide treatments consisted of quizalofop-P at 56 g ai ha$^{-1}$, fluazifop-P (Fusilade DX®, 240 g ai l$^{-1}$, Syngenta Crop Protection, LLC., PO Box 18300, Greensboro, NC 27419) at 210 g ai ha$^{-1}$, clethodim at 76 g ai ha$^{-1}$, sethoxydim (Poast Plus®, 120 g ai l$^{-1}$, BASF Corporation, 26 Davis Drive, Research Triangle Park, NC 27709) at 210 g ai ha$^{-1}$ or none, applied with glufosinate at 0, 297, 594 or 890 g ai ha$^{-1}$. Glufosinate rates represent 0X, 0.5X, 1X or 1.5X rates, respectively. Crop oil concentrate at 1.0% V V$^{-1}$ was included with all graminicide treatments. No adjuvant was included when glufosinate was applied alone. Herbicide treatments were applied with a CO$_2$-pressurized backpack sprayer equipped with XR8002 flat-fan nozzle (TeeJet
Technologies, PO Box 7900, Wheaton, IL 60187) at an application volume of 140 l ha⁻¹ and a pressure of 220 kPa when barnyardgrass plants had three to four fully expanded leaves. Soybeans were 15 to 17 cm tall at the V3 growth stage at the time of application. Visual estimates of barnyardgrass control were recorded at 7, 14, 21, 28 and 56 DAT, using a scale of 0 to 100%, where 0 = no control and 100 = complete control. Chlorosis, height reductions and regrowth were visually evaluated to estimate control. Barnyardgrass biomass was collected 56 DAT, using a 1 m quadrat and plants were separated to only include barnyardgrass plants that were present at the time of application. Samples were oven dried at 65°C for 1 wk to determine barnyardgrass biomass on a dry matter basis. Soybeans were machine harvested and yield was recorded.

The experimental design was a randomized complete block with a factorial arrangement of treatments: Factor A was graminicide and Factor B was glufosinate rate. Four replications for each treatment were used in each experiment. Barnyardgrass control data were pooled across years because experimental replication was considered a random variable. Untransformed and square root transformed data were subjected to analysis of variance, but interpretations were similar to untransformed data; therefore, untransformed data were used for analysis. Data were subjected to ANOVA and means were separated using Fischer’s protected LSD test at P = 0.05.

**Greenhouse experiments**

Treatments described in the field studies were also evaluated in the greenhouse. Barnyardgrass seed were planted approximately 2.5 cm deep in 40-cm³ plastic conetainers containing commercial potting soil mix and placed into a column module.
Conetainers were surface irrigated after planting with tap water and were subirrigated for the duration of the experiment. Plants were thinned to three plants per conetainer within 1 wk of emergence, and grown at 35/30° C night/day temperature. Natural light was supplemented with light from sodium vapor lamps to provide a 16-h photoperiod (Dodds et al. 2007).

Approximately 1 wk after thinning, when plants had three to four fully expanded true leaves, herbicide treatments were applied with a compressed air spray chamber equipped with a single 80015EVS flat-fan nozzle at an application volume of 140 l ha⁻¹ and a pressure of 240 kPa. Barnyardgrass control was visually estimated 7, 14, 21 and 28 DAT, using a scale of 0 to 100%, where 0 = no control and 100 = complete control. Chlorosis, height reductions and regrowth were visually evaluated to estimate control. Barnyardgrass biomass was collected 28 DAT, and oven dried at 65°C for 1 wk to determine barnyardgrass biomass on a dry matter basis.

Four replications for each treatment were used in each experiment and the experiment was repeated in time. Experimental replication was considered a random variable; therefore, data were pooled across experimental replication. Untransformed and square root transformed data were subjected to analysis of variance, but interpretations were similar to untransformed data; therefore, untransformed data were used for analysis. Data were subjected to ANOVA and means were separated using Fischer’s protected LSD test at P = 0.05.
Results and Discussion

Increasing rate of graminicide

Field experiments

The interaction of graminicide and graminicide rate by glufosinate rate was significant for all data evaluations. Barnyardgrass control 7 DAT by quizalofop-P at 1X applied alone was similar to glufosinate and quizalofop-P at 1X plus glufosinate (Table 2.1). Quizalofop-P at 0.5X controled barnyardgrass 83%, but control increased to 94% with the addition of glufosinate. Similarly, control increased from 88 to 95% when glufosinate was added to quizalofop-P at 1.5X. Clethodim at 1.5X, glufosinate alone and clethodim at 1.5X plus glufosinate controlled barnyardgrass 92 to 95%. Clethodim at 0.5X and 1X resulted in 80 and 85% control, respectively; however, the addition of glufosinate increased barnyardgrass control to 95 and 96%, respectively.

At 14 DAT, quizalofop-P at 1 and 1.5X controlled barnyardgrass 95 to 97%, the addition of glufosinate did not improve control (Table 2.1). However, the addition of glufosinate to quizalofop-P at 0.5X increased barnyardgrass control from 90 to 95%. The addition of glufosinate to clethodim at all rates improved barnyardgrass control to 96% with all clethodim tank mixes. The tank mix of clethodim plus glufosinate at all rates had greater barnyardgrass control than glufosinate applied alone. These results are consistent with previous research where clethodim and quizalofop-P applied alone or mixed with glufosinate provided adequate control of annual grasses 14 DAT (Gardner et al. 2006). In contrast to these results, Burke et al. (2005) reported goosegrass control was antagonized 14 DAT when clethodim at 105 and 140 g ai ha⁻¹ was mixed with glufosinate, compared to the control of glufosinate and clethodim applied alone.
Glufosinate applied alone and quizalofop-P at 0.5X with and without glufosinate provided less control of barnyardgrass than quizalofop-P at 1X, 21 DAT (Table 2.1). Barnyardgrass control did not increase with the addition of glufosinate to quizalofop-P at 1X nor by increasing the rate to 1.5X. All rates of clethodim applied with or without glufosinate provided 91 to 95% barnyardgrass control, and were not different from glufosinate applied alone. Quizalofop-P at 1X provided greater barnyardgrass control compared to glufosinate alone and quizalofop-P at 0.5X plus glufosinate, 28 DAT (Table 2.1). Quizalofop-P at 1X provided 94% barnyardgrass control; there was no effect on barnyardgrass control by including glufosinate and increasing the rate of quizalofop-P. Clethodim at 0.5X applied with and without glufosinate provided similar control to glufosinate applied alone. Glufosinate plus clethodim at 1X reduced barnyardgrass control compared to clethodim at 1X alone. Clethodim at 1.5X applied with or without glufosinate had no effect on barnyardgrass control compared to the control of clethodim alone at 1X. These results contradict previous research. Gardner et al. (2006) observed antagonized control of annual grasses when glufosinate was mixed with graminicides 28 DAT. However, Beyers et al. (2002) reported 91% control of giant foxtail 28 DAT by glufosinate plus quizalofop-P. By 56 DAT, regardless of quizalofop-P and glufosinate rate, barnyardgrass control ranged from 87 to 93% (Table 2.1). Clethodim at 0.5X and 1X alone had 95 and 96% barnyardgrass control, respectively, compared with 84 and 85% control by clethodim at 0.5X and 1X applied with glufosinate, respectively. Clethodim at 1.5X with or without glufosinate had 90 to 92% barnyardgrass control, respectively. Quizalofop-P applied with or without glufosinate did not adversely affect barnyardgrass biomass, with yielded 10 to 17 g and was not different from glufosinate
applied alone (Table 2.1). Clethodim at 1.5X plus glufosinate yielded more biomass than clethodim at 0.5 and 1X applied alone. Barnyardgrass biomass was not adversely affected when glufosinate was applied with clethodim at 0.5, 1 or 1.5X.

Soybean yield was unaffected by the interaction of graminicide and graminicide rate by glufosinate; however the glufosinate rate main effect was significant. Therefore, yield data are presented pooled over all graminicides and graminicide rates. When glufosinate was included with graminicide applications, soybean yield increased 14% compared to the graminicides applied alone (Figure 2.1). The increase in yield may be due to differences in barnyardgrass necrosis between glufosinate and the graminicides after application. Glufosinate takes 3 to 5 days to achieve complete necrosis; whereas the graminicides take 7 to 14 days to achieve plant death (Senseman 2007). The difference in barnyardgrass interference with soybean in regards to the time it took for barnyardgrass death to occur with glufosinate and graminicides may be responsible for the yield differences. In our experiment, the untreated barnyardgrass yielded 40 to 53 g. Vail and Oliver (1993) reported that 40 and 110 g of barnyardgrass biomass per m of row resulted in 10 and 25% soybean yield reduction, respectively.

In field experiments, barnyardgrass antagonism did not occur when evaluating barnyardgrass control with increasing graminicide rates tank-mixed with glufosinate. However, barnyardgrass control depended on the graminicide tank-mixed with glufosinate. Barnyardgrass control was not affected by quizalofop-P tank-mixed with glufosinate. Throughout the growing season, clethodim at 0.5X and 1X tank-mixed with glufosinate controlled barnyardgrass greater than clethodim at 0.5X and 1X alone; however, by 56 DAT control was less with the tank-mix than clethodim applied alone.
due to barnyardgrass regrowth from the crown. Therefore, the potential for reduced control exists with clethodim plus glufosinate. When glufosinate was applied with the graminicides, there was a 14% increase in yield compared to the graminicides alone, even though there was no increase in control when glufosinate was tank-mixed with clethodim and quizalofop-P. The lack of graminicide by graminicide rate interaction indicate that soybean yield was independent of graminicide and graminicide rate.

Greenhouse experiments

The interaction of graminicide and graminicide rate by glufosinate rate was significant for all barnyardgrass control evaluations. Throughout the entire experiment, glufosinate applied alone provided poor barnyardgrass control (Table 2.2). At 7 DAT, quizalofop-P at 0.5X plus glufosinate had greater barnyardgrass control compared to quizalofop-P at 0.5X alone. The addition of glufosinate to quizalofop-P at 1 and 1.5X did not improve control. Alternatively, the addition of glufosinate to clethodim at 0.5 and 1X significantly improved control to 85 and 92%, respectively, compared with 61 and 80% control by clethodim at 0.5 and 1X applied alone, respectively. Glufosinate and clethodim at 1.5X provided similar control as clethodim at 1.5X applied alone. By 14 DAT, all quizalofop-P treatments with or without glufosinate effectively controlled barnyardgrass, with control ranging from 88 to 94% (Table 2.2). Barnyardgrass control was similar with clethodim at 0.5X plus glufosinate and clethodim at 0.5X applied alone. Increasing the rate of clethodim also increased barnyardgrass control.

Barnyardgrass control at 21 and 28 DAT was not different with applications of quizalofop-P with or without glufosinate, with control ranging from 94 to 99% (Table 2.2). Beyers et al. (2002) reported similar control where glufosinate plus quizalofop-P
provided 91% control of giant foxtail. Clethodim at 0.5X with or without glufosinate provided 77% and 82% barnyardgrass control 21 DAT (Table 2.2); however, clethodim at 0.5X with or without glufosinate provided the least barnyardgrass control compared to 1 and 1.5X rates of clethodim. By 28 DAT, glufosinate plus clethodim at 0.5X reduced barnyardgrass control compared to clethodim at 0.5X alone (Table 2.2). Clethodim at 1 and 1.5X applied with or without glufosinate provided 89 to 98% barnyardgrass control. In contrast to these results, Gardner et al. (2006) reported annual grass control was antagonized when glufosinate was mixed with graminicides 28 DAT, regardless of graminicide and glufosinate rate.

The interaction of graminicide and graminicide rate by glufosinate rate was significant for barnyardgrass biomass data. However, there was no difference in biomass reduction between graminicide treatments compared to the untreated check. Barnyardgrass biomass was reduced 80 to 95% (Table 2.2). These data indicate effective biomass reduction occurred regardless of the graminicide and graminicide rate. Although not statistically different, of all plots treated with quizalofop-P at 0.5, 1 and 1.5X mixed with glufosinate had the lowest barnyardgrass biomass. Similarly, of all the plots which received clethodim at 0.5X with or without glufosinate had numerically the greatest barnyardgrass biomass.

Similar to the field experiments, barnyardgrass antagonism did not occur when barnyardgrass control was evaluated with increasing graminicide rates tank-mixed with glufosinate in the greenhouse. However, a reduction in control was present, depending on the graminicide used. Barnyardgrass control was not affected by quizalofop-P tank-
mixed with glufosinate; however, the potential for reduced control exists with clethodim plus glufosinate.

**Increasing rate of glufosinate**

*Field experiments*

The interaction of graminicide by glufosinate rate was significant for all barnyardgrass control evaluations. Graminicides applied alone provided less barnyardgrass control compared to all rates of glufosinate at 7 DAT (Table 2.3). The difference in the level of control among graminicide and glufosinate treatments reflects the slow expression of symptoms by graminicides and the more rapid activity by glufosinate. At 14 DAT, glufosinate at 1.5X plus fluazifop-P or quizalofop-P increased barnyardgrass control to 96 and 97%, respectively, compared with fluazifop-P and quizalofop-P alone or mixed with glufosinate at 0.5X (Table 2.3). Glufosinate at 1X plus clethodim or sethoxydim increased barnyardgrass control compared to clethodim and sethoxydim alone or when mixed with glufosinate at 0.5X. Increasing glufosinate to 1.5X did not increase barnyardgrass control when mixed with clethodim or sethoxydim. Similar to these data, Gardner et al. (2006) reported greater goosegrass control with clethodim and fluazifop-P plus glufosinate compared to clethodim and fluazifop-P applied alone 14 DAT. However, Burke et al. (2005) reported goosegrass control was antagonized when clethodim was mixed with glufosinate at 290 and 410 g ai ha$^{-1}$, compared to clethodim and glufosinate applied alone.

Barnyardgrass control increased from 87 to 93% when fluazifop-P was applied with glufosinate regardless of rate compared with 79% control by fluazifop-P alone, 21 DAT (Table 2.3). Quizalofop-P, clethodim and sethoxydim applied alone provided 91 to
92% control and the addition of glufosinate did not increase barnyardgrass control when mixed with quizalofop-P, clethodim or sethoxydim. However, clethodim plus glufosinate at 1.5X provided better control than clethodim plus glufosinate at 0.5X. At 28 DAT, fluazifop-P plus glufosinate at 1.5X had 92% barnyardgrass control compared with 86% control with fluazifop-P alone or 87% when tank-mixed with glufosinate at 0.5X (Table 2.3). Similarly, quizalofop-P plus glufosinate at 1.5X provided 93% control compared with 86% control with quizalofop-P plus glufosinate at 0.5X. Increasing the rate of glufosinate from 0.5X to 1.5X when mixed with clethodim and sethoxydim increased barnyardgrass control from 86 to 93%. In contrast to these results, goosegrass control 28 DAT was reduced when glufosinate was applied with clethodim and fluazifop-P, compared to clethodim and fluazifop-P applied alone (Gardner et al. 2006).

Barnyardgrass regrowth from the crown had occurred by 56 DAT with all treatments, thus slightly reduced control. Fluazifop-P, quizalofop-P and sethoxydim applied alone had similar barnyardgrass control when mixed with glufosinate, regardless of glufosinate rate (Table 2.3). Clethodim plus glufosinate at 0.5X had less barnyardgrass control compared to clethodim plus glufosinate at 1 or 1.5X.

Barnyardgrass biomass as affected by the interaction of graminicide and glufosinate rate was not significant. Therefore, biomass data are presented by graminicide and glufosinate main effects. Regardless of graminicide, barnyardgrass biomass was significantly reduced compared to no graminicide, pooled over glufosinate rates, indicating similar barnyardgrass biomass reduction occurred regardless of the graminicide applied (Figure 2.2). Pooled over all graminicides, glufosinate at 1 and 1.5X reduced biomass by 48 and 49% compared to glufosinate at 0.5X, respectively (Figure
2.3). However, barnyardgrass biomass as affected by glufosinate applied at 0.5, 1 and 1.5X was not different from glufosinate at 0X, indicating that the graminicides applied alone provided similar season long control of barnyardgrass. Soybean yield as affected by the interaction of glufosinate rate and graminicide was not significant; however, the graminicide main effect was significant. Therefore, yield data are presented averaged over glufosinate rates. When pooled over glufosinate rates, clethodim and sethoxydim treatments yielded 3,076 and 3,066 kg ha⁻¹, respectively (Figure 2.4). Compared to no graminicide, soybean in spots that received clethodim and sethoxydim had a 7% increase in soybean yield, yet fluazifop-P and quizalofop-P were not different from no graminicide. The difference in soybean yield among the graminicides may indicate that the DIM herbicides controlled barnyardgrass greater than the FOP herbicides, resulting in less barnyardgrass and soybean competition.

In field experiments, antagonism did not occur when barnyardgrass control was evaluated with increasing glufosinate rates tank-mixed with graminicides. Barnyardgrass control was not affected by tank mixing graminicides with glufosinate. Averaged over graminicides, glufosinate at 1 and 1.5X had greater biomass reductions compared to glufosinate at 0.5X. In contrast to these results, Beyers et al. (2002) reported antagonized goosegrass control regardless of glufosinate rate when applied with clethodim. Pooled over all glufosinate rates, soybean yield was reduced with quizalofop-P compared to clethodim, although barnyardgrass control among the graminicides was not different. The lack of graminicide by glufosinate rate interaction indicates that soybean yield was independent of glufosinate rate.
Greenhouse experiments

The interaction of graminicide by glufosinate rate was significant for all evaluation intervals. Throughout the experiment, when glufosinate was applied alone, barnyardgrass control generally increased with an increasing rate of glufosinate and control generally decreased with time (Table 2.4). Barnyardgrass control 7 DAT varied among graminicide herbicides; however, in general, as the glufosinate rate increased so did the level of control (Table 2.4). Differences in level of control between the graminicides applied alone and glufosinate treatments reflects the slow expression of symptoms by graminicides and the more rapid activity of glufosinate. At 14 DAT, fluazifop-P alone controlled barnyardgrass less than when mixed with glufosinate at 1.5X (Table 2.4). When applied with fluazifop-P, increasing glufosinate from 0.5X to 1X increased barnyardgrass control. Quizalofop-P, clethodim and sethoxydim plus glufosinate at 1.5X improved barnyardgrass control compared to quizalofop-P, clethodim and sethoxydim applied alone.

At 21 DAT, fluazifop-P applied with glufosinate at 0.5X had less barnyardgrass control compared to fluazifop-P plus glufosinate at 1.5X (Table 2.4). Barnyardgrass control was not different when quizalofop-P, clethodim and sethoxydim were applied with or without glufosinate, with control ranging from 93 to 98%. Barnyardgrass control with fluazifop-P applied alone or mixed with glufosinate at 1.5X was greater than fluazifop-P plus glufosinate at 0.5 or 1X, 28 DAT (Table 2.4). Quizalofop-P, clethodim and sethoxydim applied with or without glufosinate at 0.5, 1 or 1.5X provided 96 to 99% barnyardgrass control.
Barnyardgrass biomass was affected by the interaction of graminicide by glufosinate rate; however, biomass was not different among the graminicides applied alone or mixed with glufosinate (Table 2.4). When glufosinate was applied alone, biomass decreased as the application rate increased from 0 to 1.5X. Compared to glufosinate at 0.5 and 1X applied alone, barnyardgrass biomass was reduced when quizalofop-P, clethodim and sethoxydim were tank-mixed with glufosinate at 0.5 and 1X. These data indicate that the addition of a graminicide to glufosinate at any rate would improve biomass reduction compared to glufosinate alone.

Previous research has indicated that antagonism may occur when glufosinate and graminicides are tank-mixed. Antagonism can sometimes be alleviated by either increasing the rate of the more active herbicide to override the less active one, or by decreasing the rate of the less active herbicide to a level that is physiologically inactive (Green 1989). In this research, antagonism did not occur; however, reduced levels of control was observed. Data from field and greenhouse experiments evaluating increased rates of graminicides indicate that if conditions are favorable, reduced barnyardgrass control may occur when clethodim is applied with glufosinate. Soybean yield as affected by glufosinate and graminicide rates was variable; however, combinations of glufosinate and graminicides overall provided greater control than glufosinate applied alone. To improve barnyardgrass control in a glufosinate based system, graminicides should be applied alone or tank-mixed with glufosinate compared glufosinate applied alone.
Table 2.1  Field experiments evaluating the effect of barnyardgrass control with increasing graminicide rates tank-mixed with glufosinate.

<table>
<thead>
<tr>
<th>Gramicidea</th>
<th>Graminicide Rate</th>
<th>Glufosinate rate</th>
<th>7 DAT</th>
<th>14 DAT</th>
<th>21 DAT</th>
<th>28 DAT</th>
<th>56 DAT</th>
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</tbody>
</table>

LSD (0.05)

a Crop oil concentrate at 1% v:v⁻¹ was included with graminicide treatments.
b Means within a column followed by a common letter are not different according to Fisher’s Protected LD test at P = 0.05. A numerical LSD is given for each column.
Figure 2.1 2014 Soybean yield as affected by glufosinate rate, pooled over all graminicide and graminicide rates.
Table 2.2  Greenhouse experiments evaluating the effect of barnyardgrass control with increasing graminicide rates tank-mixed with glufosinate.

<table>
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<th>Barnyardgrass control</th>
<th>Biomass&lt;sup&gt;b&lt;/sup&gt;</th>
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<td>Graminicide rate</td>
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<td></td>
<td>%</td>
<td></td>
</tr>
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<td>Quizalofop-P</td>
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<td>0</td>
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<td>0G&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>LSD (0.05)</td>
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</table>

<sup>a</sup> Crop oil concentrate at 1% v v<sup>-1</sup> was included with graminicide treatments.

<sup>b</sup> Barnyardgrass biomass was pooled over replications with a population of three plants per container.

<sup>c</sup> Means within a column followed by a common letter are not different according to Fisher’s Protected LD test at P = 0.05. A numerical LSD is given for each column.
Table 2.3  Field experiments evaluating barnyardgrass control as affected by increasing glufosinate rates tank-mixed with graminicidies.

<table>
<thead>
<tr>
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<td></td>
</tr>
<tr>
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<td></td>
</tr>
<tr>
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<td>890 1.5 92A 96AB 93ABC 92A 86A</td>
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<td>LSD (0.05)</td>
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*a Crop oil concentrate at 1% v v⁻¹ was included with graminicide treatments.

*b Means within a column followed by a common letter are not different according to Fisher’s Protected LD test at P = 0.05. A numerical LSD is given for each column.
Figure 2.2  Barnyardgrass biomass as affected by graminicide main effect, pooled over glufosinate rates.
Figure 2.3 Field experiments evaluating barnyardgrass biomass as affected by glufosinate rate main effect, pooled over graminicides.
Figure 2.4  Soybean yield as affected by graminicide main effect, pooled over glufosinate rates.
Table 2.4  Greenhouse experiments evaluating barnyardgrass control as affected by increasing glufosinate rate tank-mixed with graminicides.

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LSD (0.05)  
11  5  9  8  0.8

a Crop oil concentrate at 1% v/v was included with graminicide treatments.
b Barnyardgrass biomass was pooled over replications with a population of three plants per container.

Means within a column followed by a common letter are not different according to Fisher’s Protected LD test at P = 0.05. A numerical LSD is given for each column within each DAT rating interval.
References


Anonymous (2010a) Select Max herbicide specimen label. Walnut Creek, CA: Valent. 43 p

Anonymous (2010b) Assure II herbicide specimen label. Wilmington, DE: DuPont. 13 p


46


Vail GD, Oliver LR (1993) Barnyardgrass (Echinochloa crus-galli) interference in soybeans (Glycine max). Weed Technol 7:220-225

Vidrine PR (1989) Johnsongrass (Sorghum halepense) control in soybeans (Glycine max) with postemergence herbicides. Weed Technol 3:455-458


CHAPTER III

BARNYARDGRASS CONTROL AS AFFECTED BY APPLICATION TIMING OF GLUFOSINATE APPLIED ALONE OR TANK-MIXED WITH GRAMINICIDES

Abstract

Field and greenhouse studies were conducted to evaluate the antagonism-potential of glufosinate applied sequentially or tank-mixed with clethodim on barnyardgrass control. Applications of glufosinate alone provide variable control throughout the growing season in both field and greenhouse experiments. In the field, barnyardgrass control was not adversely effected by glufosinate and clethodim tank mix applications nor sequential applications before or after clethodim. Soybean yield was not affected by application timing or clethodim rate, with yield ranging from 1,748 to 2,733 kg ha⁻¹. In the greenhouse, glufosinate applied 1 and 3 d before graminicides generally reduced barnyardgrass control. The response with quizalofop-P was not as dramatic as the other graminicides. Although significant visual barnyardgrass control differences were detected due to application timing of glufosinate, barnyardgrass biomass with fluazifop-P and quizalofop-P did not differ between the application timings of glufosinate. However, glufosinate applied 1 and 3 days before clethodim had significantly greater biomass compared to glufosinate applied 1 and 3 days after clethodim. The differences in environmental conditions and growth stages at the time of application may have contributed to barnyardgrass control response differences between the field and
greenhouse experiments. Although barnyardgrass control in the field was not affected by glufosinate application timing, data from the greenhouse indicates potential exists for reduced control if glufosinate is applied 1 or 3 d before graminicides. For maximum benefit from incorporating graminicides into a glufosinate weed control system, glufosinate should be applied 7 d prior to a graminicide application or at least 7 d after a graminicide application.

**Nomenclature:** Clethodim; fluazifop-P; glufosinate; quizalofop-P; sethoxydim; barnyardgrass, *Echinochloa crus-galli* (L.) Beauv. ECHCG.; soybean, *Glycine max* L.

**Key words:** Antagonism, sequential applications, tank mixture, interaction, crop oil concentrate.

**Introduction**

Genetically modified (GM) crops with tolerance to non-selective herbicides have been rapidly adopted in the United States due to the higher crop yield, lower pesticide costs as well as simplicity and flexibility of the technology (Fernandez-Cornejo et al. 2005; Fernandez-Cornejo et al. 2014). The introduction and adoption of crops resistant to glyphosate in the Roundup Ready® system enabled producers to reduce production costs associated with herbicide purchases, applications, tillage, hand weeding and is more environmentally benign than the soil tillage and herbicides it has replaced; some researchers consider glyphosate to be a “Once in a Century Herbicide” (Duke and Powles 2008; Gianessi 2005). The intensive use of glyphosate has contributed to the evolution of glyphosate-resistant (GR) weeds, forcing many producers to use alternative technologies for weed control. The widespread infestation of GR Palmer amaranth (*Amaranthus palmeri* S. Wats.) in soybean (*Glycine max* Merr.) is a major contributor to the greater
adoption of LibertyLink® (LL) soybean in the Midsouthern United States (Riar et al. 2013a; Riar et al. 2013b).

The LL system utilizes the GM crop resistance to the herbicide glufosinate. Glufosinate is a non-selective, non-residual POST herbicide used in GM crops including canola (Brassica napus L.), corn (Zea mays L.), cotton (Gossypium hirsutum L.) and soybeans (Anonymous 2011a; Senseman 2007). Glufosinate controls weeds that are difficult to control with glyphosate such as the Ipomoea spp. and hemp sesbania [Sesbania herbacea (P. Mill.) McVaugh], as well as GR weed such as horseweed [Cynya canadensis (L.) Cronq.], and Amaranthus spp (Culpepper et al. 2000; Green and Owen 2011; Whitaker et al. 2011). Shurley et al. (2010) reported in areas of prevalent GR Palmer amaranth, especially in non-irrigated conservation tillage, a glufosinate-based system is the most efficacious and cost effective tool to manage GR Palmer amaranth. However, grass weed control with glufosinate may be inadequate and may require additional management inputs (Beyers et al. 2002; Burke et al. 2005; Gardner et al. 2006; Koger et al. 2007; Steckel et al. 1997). Culpepper and York (1999) reported glufosinate (400 g ai ha⁻¹) applied POST only provided 81 to 94% and 64% season-long control of fall panicum (Panicum dichotomiflorum Michx.) and goosegrass [Eleusine indica (L.) Gaertn.], respectively. Culpepper et al. (2000) reported glufosinate at 400 g ai/ha provided 77 and 83% control of broadleaf signalgrass [Urochloa platyphylla (Nash) R.D. Webster] and goosegrass. A sequential application of glufosinate at 290 g ai ha⁻¹ improved control by only 13 and 5%, respectively. Stephenson and Scroggs (2009) reported that two applications of glufosinate at 880 g ai ha⁻¹ resulted in less than 90% control of barnyardgrass [Echinochloa crus-galli (L.) Beauv.].
Due to limited translocation of glufosinate, plant size at time of application is critical for season long weed control. Glufosinate applied late postemergence compared to earlier applications was ineffective on larger goosegrass (Culpepper et al. 2000) and barnyardgrass (Craigmyle et al. 2013) due to plant regrowth and escapes. When treated at 15 cm plant height, giant foxtail (Setaria faberi Herrm.), common lambsquarters (Chenopodium album L.), common cocklebur (Xanthium strumarium L.), and Pennsylvania smartweed (Polygonum pensylvanicum L.) control was 45% less than when the weed species were treated at 10 cm plant height with glufosinate applied at 420 g ai ha⁻¹ (Steckel et al. 1997).

A recent survey of soybean consultants in the Midsouthern United States concluded that 35% of the total scouted LL acres were treated solely with glufosinate (Riar et al. 2013b). Compared to glyphosate, glufosinate applied alone will not likely provide adequate summer annual grass control; thus, producers may choose to tank-mix herbicides to broaden and improve the spectrum of weeds controlled and reduce application cost. (Beyers et al. 2002; Corkern et al. 1998; Culpepper et al. 2000; Green 1989; Kim et al. 2005; Vidrine 1989; Vidrine et al. 1995; Zhang et al. 1995).

The arloxyphenoxypropionate (FOP) and cyclohexanedione (DIM) herbicide families, commonly known as the graminicide herbicide group, are utilized for POST annual and perennial grass control without causing injury to dicotyledonous weed or crops (Devine et al. 1993; Senesman 2007). The FOP herbicides fluazifop-P and quizalofop-P and the DIM herbicides clethodim and sethoxydim are labeled for use in soybeans (Anonymous 2010a; Anonymous 2010b; Anonymous 2010c; Anonymous 2011b).
Producers that utilize the LL soybean cropping system can combine glufosinate, a non-selective herbicide and a graminicide herbicide, for enhanced grass weed control. However, there have been conflicting reports of antagonism when graminicide herbicides are applied at normal use rates with glufosinate. Burke et al. (2005) reported decreased goosegrass \textit{[Eleusine indica (L.) Gaertn.]} control when clethodim was applied in mixture with glufosinate. Gardner et al. (2006) reported reduced control of annual grasses when glufosinate was tank-mixed with clethodim, fluazifop-P, quizalofop-P or sethoxydim. However, Beyers et al. (2002) reported adequate control of giant foxtail when quizalofop-P was tank-mixed with glufosinate. GR johnsongrass \textit{[Sorghum halepense (L.) Pers.]} control was greater when herbicide programs included clethodim compared to glufosinate applied alone (Johnson et al. 2014).

The antagonism of graminicides by broadleaf herbicides applied with graminicides may sometimes be reduced or alleviated by sequential herbicide applications (Green 1989). However, there have been conflicting reports of annual grass control antagonism from graminicides applied before or after glufosinate. Burke et al. (2005) reported antagonized goosegrass control when clethodim was applied 7 or 14 d after glufosinate. However, when glufosinate was applied 7 or 14 d after clethodim goosegrass control was equivalent to clethodim applied alone. Gardner et al. (2006) reported reduced annual grass control when graminicides were applied 1 day before, tank-mixed with or applied 1 or 3 day after glufosinate. However, annual grass control was not adversely affected when graminicides were applied 3 or 5 day before glufosinate or 5 or 7 day after glufosinate. Irby et al. (2007) reported poor barnyardgrass control when glufosinate was applied prior to graminicides. Conflicting reports of antagonism
with annual grass control may be due to the size of the grasses at the time of the glufosinate applications or that the antagonism is species specific.

Barnyardgrass is one of the most troublesome grasses in soybean production areas of the Midsouth (Webster 2013). Barnyardgrass exhibits prolific seed dormancy, prolonged emergence, rapid growth and flowers in a wide range of photoperiod and environmental conditions (Bagavathiannan et al. 2011; Maun and Barrett 1986; Mitch 1990; Potvin 1986). Barnyardgrass densities of 0 to 500 plants per m of row reduced soybean yield 0 to 78%, with an average yield reduction of 0.25% for each barnyardgrass plant per m of soybean row (Vail and Oliver 1993). A common rotational crop with rice (Oryza sativa L.) in the Midsouth is soybeans. Being that barnyardgrass is a major pest of both rice and soybean production systems, barnyardgrass control is critical in order to prevent yield loss and to reduce the number of seeds entering the soil seedbank.

Limited data are available on the effect of application timing of tank-mixtures of graminicide and glufosinate on barnyardgrass control. Producers utilizing the LL soybean system would benefit from appropriate management strategies to prevent potential graminicide antagonism. The objectives of this research were to determine the effects of sequential applications of glufosinate either before or after graminicides on barnyardgrass control.

**Materials and Method**

**Field Experiments**

Field studies were conducted in 2013 and 2014 to evaluate the potential interactions of glufosinate and clethodim for barnyardgrass control. Experiments were conducted at the Black Belt Branch Experiment Station in Brooksville, MS on an
Okolona silty clay (Fine, smectitic, thermic Oxyaquic Hapluderts) with 8% sand, 51% silt, 41% clay, 2% organic matter and pH of 6.8 and a Brooksville silty clay (Fine, smectitic, thermic Aquic Hapluderts) with 7% sand, 48% silt, 45% clay, 1.8% organic matter and pH of 6.0 in the respective years. Experiments were conducted in fields naturally infested with populations of barnyardgrass. Barnyardgrass density averaged 1,205 and 269 plants m\(^{-2}\) in 2013 and 2014, respectively. In 2013, the experiment was conducted in a fallowed field, not planted to soybean. Plot size in the fallowed area was 2.8 by 9.4 m. Pioneer 95L01 soybeans (Pioneer 95L01 soybean, Pioneer Hi-Bred International, INC., PO Box 1000, Johnston, IA) were planted May 19, 2014\(^{th}\) with a target population of 271,930 plants ha\(^{-1}\) and plots were three rows (0.96 m) by 9.4 m long.

Herbicide treatments consisted of glufosinate (Liberty® 280 SL, 280 g ai l\(^{-1}\), Bayer CropScience LP, PO Box 12014, 2 T.W. Alexander Drive, Research Triangle Park, NC 27709) at 594 g ai ha\(^{-1}\) applied 7, 3, and 1 d before, mixed with, or 1, 3 or 7 d after clethodim (Select Max ®, 116 g ai l\(^{-1}\), Valent U. S. A. Co., PO Box 8025, Walnut Creek, CA 94596) at 0 or 76 g ai ha\(^{-1}\), and clethodim applied alone at 0 or 76 g ai ha\(^{-1}\) (Corken et al. 1998). Crop oil concentrate (Agri-dex®, Helena Chemical Company, 225 Schilling Blvd., Suite 300, Collierville, TN 38017) at 1.0% v v\(^{-1}\) was included with all clethodim treatments. No adjuvant was included when glufosinate was applied alone. Graminicides were applied on d zero to eliminate differences in growth stage or environmental conditions. Herbicide treatments were applied with a CO\(_2\)-pressurized backpack sprayer equipped with XR8002 flat-fan nozzle (TeeJet Technologies, PO Box 7900, Wheaton, IL 60187) at an application volume of 140 l ha\(^{-1}\) and a pressure of 220 kPa. Herbicide
treatments were initiated when barnyardgrass plants had two to four fully expanded leaves. Barnyardgrass height and growth stages for all applications were recorded at the time of application (Table 3.1). Visual estimates of barnyardgrass control were recorded at 7, 14, 21, 28 and 56 days after the clethodim treatment (DAT), using a scale of 0 to 100%, where 0 = no control and 100 = complete control. Chlorosis, height reductions and regrowth were visually evaluated to estimate control. Barnyardgrass biomass was collected 56 DAT, using a 1 m quadrat and plants were separated to only include only the plants present at the time of application. Samples were oven dried at 65°C for 1 wk to determine biomass on a dry matter basis. Soybeans were machine harvested and yields were recorded.

The experimental design was a randomized complete block with a factorial arrangement of treatments: Factor A was glufosinate application timing relative to clethodim application and Factor B was clethodim rate. Four replications for each treatment were used in each experiment. Barnyardgrass control data were pooled across years because experimental replications were considered a random variable. Barnyardgrass control data were subjected to square root transformation, but interpretations were similar to untransformed data; therefore, untransformed data were used for analysis. Barnyardgrass biomass data were subjected to square root transformation. Interpretations of results were not similar to nontransformed data; therefore transformed data were used in the analysis with results presented in their original scale. Data were subjected to ANOVA and means were separated using Fischer’s protected LSD test at P = 0.05.
Greenhouse Experiments

Treatments described in the field studies were also evaluated in the greenhouse; however, two additional graminicides were included, fluazifop-P (Fusilade DX®, 240 g ai l⁻¹, Syngenta Crop Protection, LLC., PO Box 18300, Greensboro, NC 27419) and quizalofop-P (Assure II®, 105 g ai l⁻¹, Du Pont de Nemours and Co., 1007 Market Street, Wilmington, DE 19898). Barnyardgrass seed were planted approximately 2.5 cm deep in 40-cm³ plastic conainers (D40 Deepot Cell, Stuewe and Sons, Inc., 2290 SE Kiger Island Dr., Corvallis, OR 97333) containing commercial potting soil mix (Metro-Mix 360, Sungro Horticulture, 770 Silver Street, Agawam, MA 01001) and placed into a column module. After planting, conainers were surface irrigated with tap water and then subirrigated for the duration of the experiment. Plants were thinned to three plants per conainer within 1 wk of emergence, and grown at 35/30° C night/day temperature. Natural light was supplemented with light from sodium vapor lamps (General Electric Sodium Vapor Lamps, Lucalox LU 400, General Electric Consumer and Industrial Lighting, 1975 Noble Rd., Nela Park, Cleveland, OH 44112) to provide a 16-h photoperiod (Dodds et al. 2007).

Approximately 1 wk after thinning when plants had three to four fully expanded leaves, herbicide treatments were initiated using a compressed air spray chamber equipped with a single 80015EVS flat-fan nozzle (TeeJet Technologies, PO Box 7900, Wheaton, IL 60187) at an application volume of 140 l ha⁻¹ and a pressure of 240 kPa. Glufosinate at 594 g ai ha⁻¹ was applied 7, 3, and 1 d before, mixed with, or 1, 3 or 7 d after application of fluazifop-P at 210 g ai/ha, quizalofop-P at 56 g ai ha⁻¹ or clethodim at 76 g ai ha⁻¹ or none (Corken et al. 1998). Graminicides were also applied alone.
Graminicidcs were applied on day zero to eliminate differences in plant height and environmental differences at application. Crop oil concentrate at 1.0% v v⁻¹ was included with all graminicide treatments. No adjuvant was included when glufosinate was applied alone. Barnyardgrass height and growth stages for all applications were recorded at the time of application (Table 3.1).

Barnyardgrass control was visually estimated 7, 14, 21 and 28 DAT using a scale of 0 to 100%, where 0 = no control and 100 = complete control. Chlorosis, height reductions and regrowth were visually evaluated to estimate control. Barnyardgrass biomass was collected 28 DAT, oven dried at 65°C for 1 wk to and weighed to determine barnyardgrass biomass.

The experimental design was a randomized complete block with a factorial arrangement of treatments: Factor A was graminicide herbicide rate, Factor B was glufosinate application timing relative to the graminicide. Four replications for each treatment were used in each experiment and the experiment was replicated in time. Experimental replications were considered a random variable; therefore, data were pooled. Untransformed and arcsine square root transformed data were subjected to analysis of variance, but interpretations were similar to untransformed data; therefore, untransformed data were used for analysis. Data were subjected to ANOVA and means were separated using Fischer’s protected LSD test at P = 0.05.

Results and Discussion

Field Experiments

Barnyardgrass as affected by the interaction of clethodim rate by glufosinate application time was significant at all evaluations. When evaluated 7 DAT, the tank mix
of glufosinate plus clethodim controlled barnyardgrass greater than clethodim applied alone (Table 3.2). Barnyardgrass control with glufosinate applied alone on d 0 was similar to glufosinate plus clethodim. Glufosinate applied 3 d after clethodim provided 85% barnyardgrass control, compared to 51% by glufosinate 3 d after without clethodim.

At 14 DAT, glufosinate applied 7 d before clethodim controlled barnyardgrass 98% compared to 92% by glufosinate applied 7 d before without clethodim (Table 3.2). Glufosinate plus clethodim provided greater or equivalent barnyardgrass control compared to clethodim applied alone regardless of glufosinate application timing. Applications of glufosinate applied before or after clethodim provided 91 to 98% barnyardgrass control. Without the application of clethodim, glufosinate control of barnyardgrass was variable and may have been due to barnyardgrass height and growth stage differences at the time of application. Similarly, giant foxtail control by glufosinate applications was variable as plant height increased (Steckel et al. 1997).

At 21 DAT, applications of glufosinate made either before or after clethodim and glufosinate mixed with clethodim provided greater barnyardgrass control compared to clethodim alone, ranging from 93 to 98% (Table 3.2). Glufosinate applied 3 d after clethodim provided 94% barnyardgrass control, however control was reduced to 83% with the absence of clethodim. By 28 DAT, clethodim applied alone was not different from glufosinate plus clethodim. Barnyardgrass control was not affected by application timing of glufosinate when clethodim was applied on d 0, with control ranging from 95 to 98%. The sequential treatment of glufosinate applied 7 d before clethodim improved barnyardgrass control from 88 to 98% compared to glufosinate applied alone at the 7 d before timing. Similarly, the sequential treatment of glufosinate applied 3 d before
clethodim improved control from 77 to 95% compared to glufosinate applied alone at the 3 d before timing.

By 56 DAT, barnyardgrass regrowth was evident for all treatments, especially treatments that did not include clethodim (Table 3.2). Barnyardgrass control was not different between glufosinate plus clethodim and clethodim applied alone. Barnyardgrass control ranged from 94 to 97% when glufosinate was applied before or after clethodim. Compared to glufosinate plus clethodim, glufosinate applied 7 d before clethodim improved barnyardgrass control from 87 to 97%.

The glufosinate application timing by clethodim rate interaction was significant for barnyardgrass biomass. Barnyardgrass biomass in the untreated check yielded 43.4 g (Table 3.3). Applications of glufosinate without clethodim yielded 9.1 to 29.8 g compared to the untreated, whereas glufosinate applied before or after clethodim yielded 1.1 to 14.3 g. Glufosinate plus clethodim did not adversely affect barnyardgrass biomass compared to glufosinate and clethodim applied alone. Glufosinate applied 7 d before clethodim significantly reduced barnyardgrass biomass compared to clethodim applied alone. Unlike the barnyardgrass control and biomass data, soybean yield was not affected by application timing or clethodim rate, with yield ranging from 1,748 to 2,733 kg ha\(^{-1}\) (data not shown).

Gardner et al. (2006) reported annual grass control was not adversely affected when graminicides were applied 5 or 7 d after glufosinate and when graminicides were applied 3 or 5 d before glufosinate. In contrast to our results, applications of graminicides 1 d before and 1 and 3 d after were antagonistic to annual grass control (Gardner et al. 2006). Burke et al. (2005) reported goosegrass antagonism with
glufosinate applied before clethodim; however, clethodim applied before glufosinate did not negatively affect control.

Glufosinate applied 7 d before yielded 29.8 g of biomass; however, the application of clethodim on d 0 reduced barnyardgrass biomass 96% (Table 3.3). Previous research has reported that in a glufosinate based system, sequential applications may be required to achieve adequate season long control. Although tissue desiccation and reduction in photosynthetic activity occurs soon after glufosinate is applied, photosynthesis may not be completely inhibited. Sellers et al. (2004) reported 72 hours after glufosinate was applied at 320 g ai ha\(^{-1}\), glutamine synthetase activity was still detected in velvetleaf (\textit{Abutilon theophrasti} Medik.). In our field experiment, enough new leaf tissue may have been present on day 0 to absorb and translocate clethodim, thus improving barnyardgrass control when glufosinate was applied 7 days prior.

Barnyardgrass control in a glufosinate based system may require additional management inputs. Previous research has reported annual grass control antagonism with glufosinate tank-mixed with clethodim and sequential applications of glufosinate and clethodim (Burke et al. 2005; Gardner et al. 2006; Irby et al. 2007). However, in the previous research, graminicides were applied either before or after glufosinate, which may have affected control (Burke et al. 2005; Gardner et al. 2006; Irby et al. 2007). In order to eliminate growth differences of barnyardgrass due to environmental conditions at the time of the clethodim application, these experiments utilized clethodim applied on a set day. In this experiment, barnyardgrass control was not adversely affected by glufosinate plus clethodim nor sequential applications of glufosinate applied before or after clethodim. Applications of glufosinate applied alone provide variable control
throughout the growing season. Regardless of clethodim rate or glufosinate timing, soybean yield was not affected.

**Greenhouse Experiments**

The graminicide by glufosinate application timing interaction was significant for barnyardgrass control at all evaluations. When evaluated 7 DAT, glufosinate applied 7 d before the graminicides provided greater control than glufosinate tank-mixed with the graminicides, applied 1, 3 or 7 d after graminicides and the graminicides applied alone (Table 3.5). Glufosinate plus fluazifop-P resulted in 62% barnyardgrass control, whereas fluazifop-P alone resulted in 49% control. Barnyardgrass control with clethodim improved from 57% when applied alone, to 79% when glufosinate was applied with clethodim. Barnyardgrass control levels by glufosinate applied alone at 7, 3 or 1 d before were similar to glufosinate applied 7, 3 and 1 d before with fluazifop-P, quizalofop-P and clethodim. However, glufosinate alone provided poor barnyardgrass control.

At 14 DAT, glufosinate tank-mixed with fluazifop-P or clethodim provided 35 and 14% greater barnyardgrass control compared to fluazifop-P and clethodim applied alone (Table 3.5). Glufosinate plus fluazifop-P and glufosinate applied before or after fluazifop-P improved barnyardgrass control compared to fluazifop-P applied alone. Barnyardgrass was controlled 95% when glufosinate was applied 7 d before quizalofop-P, whereas glufosinate plus quizalofop-P and quizalofop-P alone controlled barnyardgrass 80 and 81%, respectively. Glufosinate applied 7 d before and 1 or 3 d after clethodim provided 93 to 96% barnyardgrass control, compared to 75% control with clethodim applied alone. Glufosinate applied alone at -7 and -3 d provided greater control of barnyardgrass as compared to the later glufosinate applications.
By 21 DAT, barnyardgrass control with glufosinate applied before or after fluazifop-P was dramatically different among application timings (Table 3.5). Glufosinate applied 7 d before and 1, 3 or 7 d after fluazifop-P controlled barnyardgrass 90 to 94% compared with glufosinate applied 1 d before and tank-mixed with fluazifop-P. However, glufosinate tank-mixed with fluazifop-P or applied 1 d before were not different from fluazifop-P applied alone. Barnyardgrass control with quizalofop-P ranged from 85 to 96% regardless of glufosinate application timing and did not differ from quizalofop-P applied alone. Glufosinate applied 3 d before clethodim reduced barnyardgrass control by 12% as compared to clethodim applied alone. However, control improved with glufosinate applied 7 d before and 1, 3 or 7 d after clethodim, providing 92 to 97% control. Barnyardgrass control with glufosinate applied alone was significantly reduced when glufosinate was applied after the -3 d timing, with control ranging from 52 to 65% due to barnyardgrass size at the time of application.

At 28 DAT, barnyardgrass control was 73 to 79% with glufosinate plus fluazifop-P and when glufosinate was applied 1 or 3 d before fluazifop-P (Table 3.5). However, control increased when glufosinate was applied 1, 3 or 7 d after fluazifop-P. Barnyardgrass control was reduced to 76% when glufosinate was applied 1 d before quizalofop-P, compared to 95% control with quizalofop-P applied alone. All other quizalofop-P applications provided 87 to 99% control, regardless of glufosinate application timing. Clethodim applied alone controlled barnyardgrass 93%; however, control was reduced to 77 and 74% when glufosinate was applied 1 or 3 d before clethodim. Control improved with clethodim when glufosinate was applied 7 d before, tank-mixed or applied 1, 3 or 7 d after clethodim. Poor barnyardgrass control with
glufosinate applied alone occurred when glufosinate was applied after the -3 d timing due to barnyardgrass size at the time of application, with control ranging from 38 to 56%. Burke et al. (2005) reported decreased goosegrass control with increasing growth stage by glufosinate applications. Steckel et al. (1997) reported glufosinate weed control was sensitive to plant height at the time of application. Burke et al. (2005) reported poor goosegrass control when glufosinate was applied 7 or 14 d before clethodim. Clethodim applied prior to glufosinate provided similar control as clethodim applied alone (Burke et al. 2005).

Fluazifop-P and quizalofop-P treatments adequately reduced barnyardgrass biomass compared to the untreated, regardless of glufosinate application timing (Table 3.6). Glufosinate applied 1 and 3 d prior to clethodim resulted in significantly more biomass compared to glufosinate applied 1 and 3 d after clethodim. Barnyardgrass biomass with glufosinate applied alone was variable, with biomass reduction ranging from 42 to 65% compared to the untreated.

Barnyardgrass control in glufosinate based system may require additional management inputs. Previous research has reported grass antagonism with glufosinate plus clethodim and sequential applications of glufosinate and clethodim (Burke et al. 2005; Gardner et al. 2006; Irby et al. 2007). In this experiment, barnyardgrass control with sequential applications of glufosinate varied with the graminicide. However, glufosinate applied 1 and 3 d before graminicides generally reduced barnyardgrass control. Applications of glufosinate applied alone provided variable control throughout the growing season. Although significant visual barnyardgrass control differences were detected due to application timing of glufosinate, barnyardgrass biomass with fluazifop-P
and quizalofop-P did not differ between the application timings of glufosinate. However, glufosinate applied 1 and 3 days before clethodim had significantly greater biomass compared with glufosinate applied 1 and 3 days after clethodim. This research concurs with previous research that clethodim is more susceptible to decreased grass control when mixed with herbicides used for broadleaf weed control (Vidrine et al. 1995).

Not only were the results of the field experiment different from what has been reported in literature, results were different from the greenhouse experiments. The differences in environmental conditions and growth stages at the time of application may have contributed to barnyardgrass control response differences between the field and greenhouse experiments. Phenotypic and genetic variation among barnyardgrass ecotypes will also have differential responses with soil type and fertility level, thus affecting morphological development (Tasrif et al. 2004). Although barnyardgrass control in the field was not affected by glufosinate application timing, data from the greenhouse indicates that potential exists for reduced control if glufosinate is applied 1 or 3 d before graminicides. Glufosinate applied without a graminicide applied on d 0 had variable control throughout the growing season. Without a graminicide applied on d 0, glufosinate applied before d 0 resulted in reduced control due to plant regrowth; however, reduced control from glufosinate applied after d 0 was due to larger barnyardgrass plants at the time of application. To be incorporated into an effective weed control system with glufosinate, graminicides should be utilized for enhanced grass weed control. For maximum benefit from incorporating graminicides into a glufosinate weed control system, glufosinate should be applied 7 d prior to a graminicide application or 1, 3 or 7 d after a graminicide application.
Table 3.1  Barnyardgrass height and growth stage at the time of application for field experiments in 2013 and 2014\(^a\).

<table>
<thead>
<tr>
<th>Glufosinate application timings(^b)</th>
<th>Height</th>
<th>Growth Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2013</td>
<td>2014</td>
</tr>
<tr>
<td>d</td>
<td>------</td>
<td>cm</td>
</tr>
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<td>-7</td>
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<td>6</td>
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<tr>
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<td>9</td>
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<td>+3</td>
<td>14</td>
<td>11</td>
</tr>
<tr>
<td>+7</td>
<td>14</td>
<td>12</td>
</tr>
</tbody>
</table>

\(^a\) Average barnyardgrass population was 1,205 plants m\(^{-2}\) in 2013 and 269 plants m\(^{-2}\) in 2014.

\(^b\) Glufosinate applied relative to graminicide application in days before or after clethodim applied on d 0.

Glufosinate was tank-mixed with clethodim on d 0.
Table 3.2  Barnyardgrass control as affected by application timing of glufosinate when applied alone or tank-mixed with clethodim$^a$.

<table>
<thead>
<tr>
<th>Glufosinate application timings$^b$</th>
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<th>Barnyardgrass control</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>7 DAT</td>
<td>14 DAT</td>
<td>21 DAT</td>
<td>28 DAT</td>
<td>56 DAT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>76</td>
<td>0</td>
<td>76</td>
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<tr>
<td>d</td>
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<td>%</td>
<td>%</td>
<td>%</td>
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<td>%</td>
</tr>
<tr>
<td>-7</td>
<td>96AB$^c$</td>
<td>97A</td>
<td>92BCD</td>
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<td>96AB</td>
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<td>93A-D</td>
<td>96AB</td>
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</tr>
<tr>
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<td>92BCD</td>
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<td>96ABC</td>
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</tr>
<tr>
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<td>85DE</td>
<td>81G</td>
<td>91DC</td>
<td>83G</td>
<td>94A-D</td>
<td>77E</td>
<td>95ABC</td>
</tr>
<tr>
<td>+7</td>
<td>0I</td>
<td>51G</td>
<td>86FE</td>
<td>94A-D</td>
<td>87FG</td>
<td>97AB</td>
<td>90BCD</td>
<td>96AB</td>
</tr>
<tr>
<td>No glufosinate$^e$</td>
<td>0I</td>
<td>80E</td>
<td>0H</td>
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<td>0H</td>
<td>85FG</td>
<td>0F</td>
<td>87D</td>
</tr>
</tbody>
</table>

LSD (0.05) 8 4 5 7 6

$^a$ Crop Oil Concentrate at 1% v v$^{-1}$ was included in all clethodim treatments.

$^b$ Glufosinate (594 g ha$^{-1}$) applied relative to graminicide application in days before or after clethodim applied on d 0.

$^c$ Means within a DAT column followed by a similar letter are not different according to Fischer’s Protected LSD P = 0.05. A numerical LSD is given for each column within each DAT rating interval.

$^d$ Glufosinate (594 g ha$^{-1}$) and clethodim were tank-mixed on d 0.

$^e$ Applications of clethodim without glufosinate were applied on d 0.
Table 3.3  Barnyardgrass biomass as affected by application timing of glufosinate when applied alone or tank-mixed with clethodim.

<table>
<thead>
<tr>
<th>Glufosinate application timings&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Clethodim (g ai ha&lt;sup&gt;-1&lt;/sup&gt;)&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>d</td>
<td>----------------------------------------</td>
</tr>
<tr>
<td>-7</td>
<td>29.8A&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>-3</td>
<td>10.4DE</td>
</tr>
<tr>
<td>-1</td>
<td>14.3DE</td>
</tr>
<tr>
<td>0&lt;sup&gt;d&lt;/sup&gt;</td>
<td>9.1DE</td>
</tr>
<tr>
<td>+1</td>
<td>14.7BCD</td>
</tr>
<tr>
<td>+3</td>
<td>22.8ABC</td>
</tr>
<tr>
<td>+7</td>
<td>13.6CDE</td>
</tr>
<tr>
<td>No glufosinate&lt;sup&gt;e&lt;/sup&gt;</td>
<td>43.4A</td>
</tr>
</tbody>
</table>

<sup>a</sup> Glufosinate (594 g ha<sup>-1</sup>) applied relative to graminicide application in days before or after clethodim applied on d 0.

<sup>b</sup> Crop Oil Concentrate at 1% v v<sup>-1</sup> was applied with treatments that included clethodim.

<sup>c</sup> Means within a DAT column followed by a similar letter are not different according to Fischer's Protected LSD P = 0.05.

<sup>d</sup> Glufosinate (594 g ha<sup>-1</sup>) and clethodim were tank-mixed on d 0.

<sup>e</sup> Applications of clethodim without glufosinate were applied on d 0.
Table 3.4  Barnyardgrass height and growth stage at the time of application for greenhouse experiments in 2013 and 2014\textsuperscript{a}.

<table>
<thead>
<tr>
<th>Glufosinate application timings\textsuperscript{b}</th>
<th>Height 2013</th>
<th>Height 2014</th>
<th>Growth Stage 2013</th>
<th>Growth Stage 2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>Run 1</td>
<td>Run 2</td>
<td>Run 3</td>
<td>Run 4</td>
</tr>
<tr>
<td>-7</td>
<td>2.7</td>
<td>2.2</td>
<td>1.5</td>
<td>2.2</td>
</tr>
<tr>
<td>-3</td>
<td>3.1</td>
<td>2.3</td>
<td>1.9</td>
<td>2.7</td>
</tr>
<tr>
<td>-1</td>
<td>3.5</td>
<td>2.7</td>
<td>2.3</td>
<td>4.3</td>
</tr>
<tr>
<td>0\textsuperscript{c}</td>
<td>3.8</td>
<td>2.8</td>
<td>2.5</td>
<td>4.5</td>
</tr>
<tr>
<td>+1</td>
<td>3.8</td>
<td>2.8</td>
<td>2.7</td>
<td>4.7</td>
</tr>
<tr>
<td>+3</td>
<td>4.0</td>
<td>2.9</td>
<td>4.3</td>
<td>5.1</td>
</tr>
<tr>
<td>+7</td>
<td>5.1</td>
<td>3.5</td>
<td>5.9</td>
<td>5.1</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Barnyardgrass population of three plants per conetainer.
\textsuperscript{b} Glufosinate (594 g ha\textsuperscript{-1}) applied relative to graminicide application in days before or after graminicides, applied on d 0.
\textsuperscript{c} Glufosinate was tank-mixed with graminicides on d 0.
Table 3.5  Barnyardgrass control as affected by application timing of glufosinate when applied alone or tank-mixed with fluazifop-P, quizalofop-P or clethodim

<table>
<thead>
<tr>
<th>Glufosinate application timings</th>
<th>Barnyardgrass Control</th>
<th>Barnyardgrass Control</th>
<th>Barnyardgrass Control</th>
<th>Barnyardgrass Control</th>
<th>Barnyardgrass Control</th>
<th>Barnyardgrass Control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fluazifop-P Quizalofop-P Clethodim</td>
<td>None</td>
<td>Fluazifop-P Quizalofop-P Clethodim</td>
<td>None</td>
<td>Fluazifop-P Quizalofop-P Clethodim</td>
<td>None</td>
</tr>
<tr>
<td>d</td>
<td>7 DAT</td>
<td>14 DAT</td>
<td>21 DAT</td>
<td>28 DAT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-7</td>
<td>95AB</td>
<td>96A</td>
<td>96A</td>
<td>89A-D</td>
<td>89A-F</td>
<td>95AB</td>
</tr>
<tr>
<td>+3</td>
<td>92ABC</td>
<td>90ABC</td>
<td>91ABC</td>
<td>95AB</td>
<td>90A-F</td>
<td>90A-F</td>
</tr>
<tr>
<td>-1</td>
<td>87A-E</td>
<td>83C-F</td>
<td>86A-E</td>
<td>79D-G</td>
<td>84A-G</td>
<td>87A-G</td>
</tr>
<tr>
<td>0d</td>
<td>62IJ</td>
<td>72F-I</td>
<td>79D-G</td>
<td>65IJ</td>
<td>81D-G</td>
<td>80EFG</td>
</tr>
<tr>
<td>+1</td>
<td>83C-F</td>
<td>85C-E</td>
<td>85B-E</td>
<td>63IJ</td>
<td>91A-E</td>
<td>91A-E</td>
</tr>
<tr>
<td>+3</td>
<td>71GH</td>
<td>78E-H</td>
<td>68HI</td>
<td>40KL</td>
<td>90A-F</td>
<td>93A-D</td>
</tr>
<tr>
<td>+7</td>
<td>49KL</td>
<td>68HJ</td>
<td>60J</td>
<td>0M</td>
<td>80EFG</td>
<td>89A-F</td>
</tr>
<tr>
<td>No glufosinate</td>
<td>49K</td>
<td>65IJ</td>
<td>57JK</td>
<td>0M</td>
<td>60IJ</td>
<td>81D-G</td>
</tr>
<tr>
<td>LD (0.05)</td>
<td>10</td>
<td>12</td>
<td>12</td>
<td>13</td>
<td>13</td>
<td>13</td>
</tr>
</tbody>
</table>

Glufosinate (594 g ha⁻¹) applied relative to graminicide application in days before or after graminicides, applied on d 0.

A numerical LSD is given for each column within each DAT rating interval.

Applications of graminicides without glufosinate were applied on d 0.

# Glufosinate (139 g ha⁻¹) applied relative to graminicide application in days before or after graminicides, applied on d 0. Crop Oil Concentrate at 1% v/v was included with all graminicide herbicide applications.

Glufosinate (594 g ha⁻¹) and graminicides were tank-mixed on d 0.
Table 3.6  Barnyardgrass biomass\textsuperscript{a} as affected by application timing of glufosinate when applied alone or tank-mixed with fluazifop-P, quizalofop-P or clethodim\textsuperscript{b}

<table>
<thead>
<tr>
<th>Glufosinate application timings\textsuperscript{c}</th>
<th>Fluazifop-P</th>
<th>Quizalofop-P</th>
<th>Clethodim</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-7</td>
<td>0.6FGH\textsuperscript{d}</td>
<td>0.5GH</td>
<td>0.8D-H</td>
<td>1.1B-E</td>
</tr>
<tr>
<td>-3</td>
<td>0.8D-H</td>
<td>0.5GH</td>
<td>1.0C-F</td>
<td>1.0C-D</td>
</tr>
<tr>
<td>-1</td>
<td>0.9C-G</td>
<td>0.7E-H</td>
<td>1.0C-F</td>
<td>1.3BC</td>
</tr>
<tr>
<td>0\textsuperscript{e}</td>
<td>0.8D-H</td>
<td>0.6FGH</td>
<td>0.5GH</td>
<td>1.5B</td>
</tr>
<tr>
<td>+1</td>
<td>0.5GH</td>
<td>0.5GH</td>
<td>0.5GH</td>
<td>1.2BCD</td>
</tr>
<tr>
<td>+3</td>
<td>0.6FGH</td>
<td>0.4H</td>
<td>0.5GH</td>
<td>0.9C-G</td>
</tr>
<tr>
<td>+7</td>
<td>0.7E-H</td>
<td>0.8D-H</td>
<td>0.6FGH</td>
<td>1.5B</td>
</tr>
<tr>
<td>No glufosinate\textsuperscript{f}</td>
<td>0.7E-H</td>
<td>0.6FGH</td>
<td>0.6FGH</td>
<td>2.6A</td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{a} Barnyardgrass biomass was pooled over replications with a population of three plants container\textsuperscript{-1}.

\textsuperscript{b} Fluazifop-P, quizalofop-P and clethodim applied at 210, 56 and 76 g ai ha\textsuperscript{-1}. Crop Oil Concentrate at 1% v v\textsuperscript{-1} was applied with treatments that included graminicides.

\textsuperscript{c} Glufosinate (594 g ha\textsuperscript{-1}) applied relative to graminicide application in days before or after graminicides, applied on d 0.

\textsuperscript{d} Means within a DAT column followed by a similar letter are not different according to Fischer’s Protected LSD P = 0.05. A numerical LSD is given for each column within each DAT rating interval.

\textsuperscript{e} Glufosinate (594 g ha\textsuperscript{-1}) and graminicides were tank-mixed on d 0.

\textsuperscript{f} Applications of graminicides without glufosinate were applied on d 0.
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Craigmyle BD, Ellis JM, Bradley KW (2013) Influence of herbicide programs on weed management in soybean with resistance to glufosinate and 2, 4-D. Weed Technol 27:78-84


73


CHAPTER IV
APPLICATION TIME OF DAY EFFECT ON GLUFOSINATE WHEN TANK-MIXED WITH CLETHODIM ON BARNYARDGRASS EFFICACY.

Abstract

Field studies were conducted to evaluate the effect of clethodim and glufosinate tank mixtures applied at differing times of day on barnyardgrass control. Clethodim at 76 g ai ha\(^{-1}\), pooled over glufosinate rates provided 91 to 97% barnyardgrass control, regardless of time of day of application. At 21 and 28 DAT, glufosinate controlled barnyardgrass 88 to 89% compared to 95% control by clethodim applied alone. By 56 DAT, clethodim was more efficacious than glufosinate or glufosinate plus clethodim. Barnyardgrass control as affected by glufosinate rate and application time of day was significant at all rating intervals. Barnyardgrass control with glufosinate at 594 g ai ha\(^{-1}\) differed significantly at the different times of application. Applied at midnight, glufosinate applications reduced barnyardgrass control compared to applications made at noon and 6 P.M. Early morning applications at 6 A.M. also showed reduced barnyardgrass efficacy compared to applications at 6 P.M. Environmental factors such as temperature, dew, relative humidity and light at the time of application are likely responsible for the time of day effects observed in this study. These data suggest that in order to optimize barnyardgrass efficacy with tank mixtures of glufosinate and clethodim, applications should be made at noon or early evening to avoid potential time of day effects.
Nomenclature: Clethodim; glufosinate; barnyardgrass, *Echinochloa crus-galli* (L.) Beauv. ECHCG.

Key words: Antagonism, glutamine synthetase, tank mixture, environmental effects.

Introduction

The widespread infestation of GR Palmer amaranth (*Amaranthus palmeri* S. Wats.) in soybean (*Glycine max* Merr.) has been a major contributor to the greater adoption of LibertyLink® (LL) soybean in the Midsouthern United States (Riar et al. 2013a; Riar et al. 2013b). The LL system utilizes the genetically modified crop resistance to the herbicide glufosinate. Glufosinate is a non-selective, non-residual POST herbicide used in genetically modified crops including canola (*Brassica napus* L.), corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.) and soybeans (Anonymous 2011 and Senesman 2007).

Glufosinate controls a broad spectrum of annual and perennial grass and broadleaf weeds (Anonymous 2011a and Senesman 2007). Additionally, glufosinate can control weeds that are difficult to control with glyphosate such as the *Ipomoea* spp. and hemp sesbania [*Sesbania herbacea* (P. Mill.) McVaugh], as well as GR weeds such as horseweed [*Conyza canadensis* (L.) Cronq.], and *Amaranthus* spp (Culpepper et al. 2000; Green and Owen 2011; Whitaker et al. 2011). However, compared to glyphosate, glufosinate applied alone may provide less than adequate summer annual grass control; thus, producers may choose to tank-mix glufosinate with other herbicides to broaden the weed control spectrum, reduce application cost by combining applications and reduce yield loss due to weed competition. (Beyers et al. 2002; Corkern et al. 1998; Culpepper
et al. 2000; Green 1989; Kim et al. 2005; Vidrine 1989; Vidrine et al. 1995; Zhang et al. 1995). Clethodim, a graminicide herbicide, is utilized for POST annual and perennial grass control without causing injury to dicotyledonous weeds or crops (Anonymous 2010; Devine et al. 1993; Senesman 2007). In order to improve grass weed control performance in the LL cropping system, producers can combine applications of glufosinate and clethodim for enhanced grass weed control.

Recent trends in increasing farm size and reliance on non-selective POST herbicides for weed control have forced pesticide applicators to make POST applications over a wider application interval (Anonymous 2014; Sellers et al. 2004). Wind velocity is often times lower near sunrise and sunset, thus reducing the potential for herbicide drift to non-target plants. The reduced efficacy of herbicides applied near or after sunset is referred to as the time of day effect (Sellers et al. 2004). Several POST herbicides, including glufosinate have been reported to be sensitive to application time of day (Anderson et al. 1993a; Anderson et al. 1993b; Martinson, et al. 2005; Sellers et al. 2003; Sellers et al. 2004; Stewart et al. 2009; Stopps et al. 2013; Waltz et al. 2004). Several environmental factors contribute to the influence of herbicide efficacy throughout the day. For instance, POST herbicide applications may be impacted by high wind speed, increasing the potential of spray drift onto non-target crops (Duke 2005). Therefore, producers will apply herbicides in the morning or late evening hours, when wind speeds are lowest to minimize the potential for off-target movement (Waltz et al. 2004). However, herbicide efficacy may be reduced at these times of day. The presence of dew on leaf surfaces at these times may interfere with herbicide absorption and may increase herbicide loss through runoff (Anderson 1996; Fausey and Renner 2001; Kogan and
Zungia 2001; Waltz et al. 2004). To avoid the interaction with dew, POST herbicide applications can be made during the day, after the dew has evaporated from the leaf surface. Increased relative humidity and air temperature during this time frame may also improve POST herbicide efficacy (Anderson 1996; Anderson et al. 1993a; Coetzer et al. 2001; Fausey and Renner 2001; Friesen and Wall 1991; Kumaratilake and Preston 2005; Martinson et al. 2005; Peterson and Hurle 2001; Stopps et al. 2013; Waltz et al. 2004). Control of giant foxtail was less than 50% when fluazifop-P plus bromoxynil were applied in temperatures less than 25°C, regardless of application time of day (Friesen and Wall 1991). Uptake and translocation of radiolabeled glyphosate was significantly greater in Florida beggarweed [*Desmodium tortuosum* (Sw.) DC.] at 95% relative humidity than 45 and 70% (Sharma and Singh 2001). Differential herbicide response to diurnal leaf movement can also contribute to the time of day effect. However, diurnal leaf movement is not known to exist in grass species; therefore, reduced grass efficacy following a herbicide application due to diurnal fluctuations can be eliminated as a contributing factor to the time of day effect.

Previous research has shown that glufosinate is sensitive to many factors contributing to the time of day effect. Glufosinate applications made at 95% relative humidity caused greater control of giant foxtail, compared to applications made at 40% relative humidity (Anderson et al. 1993a). Kumaratilake and Preston (2005) reported that absorption of glufosinate was not affected by temperature; however, translocation of glufosinate to the meristematic regions of wild radish (*Raphanus raphanistrum* L.) increased in warm temperatures compared to translocation of glufosinate in cold temperatures. For a herbicide like glufosinate that has very minimal translocation, it can
be expected that increased translocation to meristematic regions will result in increased efficacy. Anderson et al. (1993b) reported greater ammonia accumulation and visual injury of giant foxtail when glufosinate was applied at the end of the photoperiod, rather than at the beginning. Sellers et al. (2004) reported that radiolabeled glufosinate applied at 10 P.M. had greater translocation than when applied at 2 P.M.; however, less glutamine synthetase inhibition and ammonia accumulation occurred at the 10 P.M. application. The difference in glutamine synthetase inhibition and ammonia accumulation between the application times may explain the differences in the time of day effect with glufosinate.

Barnyardgrass is one of the most troublesome grasses in soybean production systems in the Midsouthern United States. As one of the top 10 most common and troublesome weed in the southern U. S., it can produce up to 39,000 seed per plant (Bagavathiannan et al. 2012; Webster 2013). Barnyardgrass exhibits prolific seed dormancy, prolonged emergence period, ability to grow rapidly and flower in a range of photoperiod and environmental conditions (Bagavathiannan et al. 2011; Maun and Barrett 1986; Mitch 1990; Potvin 1986). Barnyardgrass densities of 0 to 500 per m of row reduced soybean yield 0 to 78%, with an average yield reduction of 0.25% for each barnyardgrass plant per m of soybean row (Vail and Oliver 1993).

Information pertaining to time of day effects on barnyardgrass control when clethodim is applied with glufosinate may be valuable to producers who want to optimize barnyardgrass control in LL soybeans. Therefore, it is important to define optimum times during the day when environmental and physiological conditions exist to achieve maximum barnyardgrass control. The objective of this research was to determine the
optimal time of day to apply tank mixtures of glufosinate with clethodim to maximize barnyardgrass control.

**Materials and Method**

Field studies were conducted in 2013 and 2014 to evaluate the effect of clethodim and glufosinate tank-mixtures applied at differing times of day on barnyardgrass control. Experiments were conducted at the Black Belt Branch Experiment Station in Brooksville, MS on an Okolona silty clay (Fine, smectitic, thermic Oxyaquic Hapluderts) with 8% sand, 51% silt, 41% clay, 2% organic matter and pH of 6.8. Experiments were conducted in a field naturally infested with populations of barnyardgrass. The experiment in both 2013 and 2014 were conducted in a fallowed field with an average barnyardgrass density of 1,205 plants m\(^{-2}\).

Herbicide treatments consisted of clethodim (Select Max®, 116 g ai l\(^{-1}\), Valent U. S. A. Co., PO Box 8025, Walnut Creek, CA 94596) at 0 or 76 g ai ha\(^{-1}\) applied separately or tank-mixed with glufosinate (Liberty® 280 SL, 280 g ai l\(^{-1}\), Bayer CropScience LP, PO Box 12014, 2 T.W. Alexander Drive, Research Triangle Park, NC 27709) at 0 or 594 g ai ha\(^{-1}\). Herbicide treatments were applied at 12:00 and 6:00 A.M. and 12:00 and 6:00 P.M. (Table 4.1). Crop oil concentrate (Agri-dex®, Helena Chemical Company, 225 Schilling Blvd., Suite 300, Collierville, TN 38017) at 1.0% v v\(^{-1}\) was included with all clethodim treatments. No adjuvant was included when glufosinate was applied alone. Herbicide treatments were applied with a CO\(_2\)-pressurized backpack sprayer equipped with XR8002 flat-fan nozzle (TeeJet Technologies, PO Box 7900, Wheaton, IL 60187) at an application volume of 140 l ha\(^{-1}\) and a pressure of 220 kPa. Herbicide treatments were applied when barnyardgrass plants had three to four fully expanded leaves. Visual
estimates of barnyardgrass control were recorded 7, 14, 21, 28 and 56 days after treatment (DAT), using a scale of 0 to 100%, where 0 = no control and 100 = complete control. Chlorosis, height reductions and regrowth were visually evaluated to estimate control. During the 2014 growing season, significant rainfall events provided excellent growing conditions for barnyardgrass and due to the lack of residual activity of clethodim and glufosinate, barnyardgrass control 56 DAT was not evaluated.

The experimental design was a factorial arrangement of treatments in a randomized complete block: Factor A was clethodim rate, Factor B was glufosinate rate and Factor C was application time of day. Four replications for each treatment were used in each experiment. Data were pooled across years because replications were considered a random variable. Untransformed and square root transformed data were subjected to analysis of variance, but interpretations were similar to untransformed data; therefore, untransformed data were used for analysis. Data were subjected to ANOVA and means were separated using Fischer’s protected LSD test at P = 0.05.

Results and Discussion

Pooled over glufosinate rate, the interaction of clethodim rate by time of day was not significant (data not shown). When pooled over glufosinate rates, clethodim at 0 g ai ha⁻¹ provided 42 to 47% barnyardgrass control as compared to 91 to 97% control from clethodim at 76 g ai ha⁻¹ regardless of time of day. Similar to these results, fluazifop-P controlled wild oat (Avena fatua L.) 92 to 100% regardless of the application time of day (Friesen and Wall 1991). On the contrary, green foxtail control was greatest when with fluazifop-P was applied between 3 and 11 P.M. (Friesen and Wall 1991). Stopps et al. (2013) reported fomesafen plus quizalofop-P control of common ragweed (Ambrosia
*artemisifolia* L.), common lambsquarters (*Chenopodium album* L.), pigweed and velvetleaf was not affected by application time of day.

The interaction of glufosinate rate by clethodim rate was significant when pooled over application time of day at all data evaluations. Barnyardgrass control 7 DAT was greatest when glufosinate was applied with clethodim (Table 4.2). Glufosinate plus clethodim controlled barnyardgrass 96%, compared to 89% and 94% control by clethodim and glufosinate applied alone, respectively. However, at 14 DAT clethodim applied alone and glufosinate plus clethodim control was similar, providing 96% barnyardgrass control. At 21 and 28 DAT, glufosinate controlled barnyardgrass 88 to 89% compared to 95% control by clethodim applied alone. By 56 DAT, clethodim was more efficacious than glufosinate or glufosinate plus clethodim. These results are consistent with previous research where clethodim controlled annual grasses more effectively than clethodim plus glufosinate (Burke et al. 2005; Gardner et al. 2006). Burke et al. (2005) reported clethodim provided greater goosegrass control than glufosinate, regardless of growth stage at the time of application.

Pooled across clethodim rates, barnyardgrass control as affected by the interaction of glufosinate rate and application time of day was significant at all ratings (Table 4.3). Averaged over clethodim rates, barnyardgrass control did not differ with application time of day when glufosinate was applied at 0 g ai ha$^{-1}$, with control ranging from 44 to 49%, indicating that clethodim efficacy was unaffected by time of day (Table 4.3). However, barnyardgrass control with glufosinate at 594 g ai ha$^{-1}$ varied with the times of application. Throughout the entire experiment, significantly less barnyardgrass control occurred with glufosinate at 594 g ai ha$^{-1}$ applied at 12 A.M. compared to 12 or 6 P.M. At
14 DAT, glufosinate at 594 g ai ha\(^{-1}\) applied at 6 A.M. and at 12 and 6 P.M. resulted in 95% barnyardgrass control. At 28 DAT, glufosinate applied at 6 A.M. provided less barnyardgrass control and was not different from the 12 A.M. application time (Table 4.3). Glufosinate applied at 6 pm resulted in greater barnyardgrass control than the 6 and 12 A.M. applications.

Glufosinate has been reported to be effected by relative humidity, ambient air temperature and light conditions at the time of application (Anderson et al. 1993a; Anderson et al. 1993b; Kumaratilake and Preston 2005; Sellers et al. 2004). High relative humidity may help increase foliar absorption of herbicides by delaying the evaporation of spray droplets and reducing water stress in plants (Anderson 1996). Anderson et al. (1993a) reported that green foxtail and barley had greater tolerance to glufosinate when the relative humidity was at 40% compared to 95%. Similarly, Coetzer et al. (2001) reported at 90% relative humidity, redroot pigweed (Amaranthus retroflexus L.), Palmer amaranth and common waterhemp (Amaranthus rudis Sauer) control ranged from 81 to 90%. However, at 35% relative humidity, control of Palmer amaranth, common waterhemp and redroot pigweed decreased, ranging from 70 to 72% (Coetzer et al. 2001). Martinson et al. (2005) reported that relative humidity, ranging from 41% to 96%, was not a significant factor in relation to glufosinate efficacy. In our experiments relative humidity varied but was consistently greater at the 12 A.M. application, ranging from 86 to 94%. However, barnyardgrass control was reduced at the 12 A.M. application, compared to the 12 and 6 P.M. applications, when relative humidity was lowest. Although results from previous research indicate that relative humidity may play a role in the time of day effect, our data is indifferent to the effect of relative humidity on
barnyardgrass control; however, the effect of relative humidity may be overshadowed by the application time of day.

Ambient air temperature may alter foliar herbicide absorption by altering the nature of the cuticle by either improving or hindering herbicide permeability (Anderson 1996). Kumaratilake and Preston (2005) reported that glufosinate was rapidly absorbed into leaves of wild radish regardless of the temperature at which the plants were grown. Likewise, Coetzer et al. (2001) reported that glufosinate absorption was not altered by temperature when averaged over amaranth species. However, herbicide translocation in the phloem tends to increase at higher temperatures due to increased metabolic processes and enzyme activities (Anderson 1996). Glufosinate has very little translocation following application due to rapid phytotoxicity (Coetzer et al. 2001; Devine et al 1993). Kumaratilake and Preston (2005) reported increased glufosinate translocation to the shoot meristem and the untreated leaves at warm temperatures; whereas at cold temperatures, the majority of glufosinate was translocated to tip of the treated leaf. When plants were moved from a cold to a warm temperature after glufosinate was applied, glufosinate efficacy increased compared to plants kept under cold conditions throughout the entire study (Kumaratilake and Preston 2005). Anderson et al. (1993a) reported greater green foxtail injury when glufosinate was applied in warmer temperature as compared to glufosinate applications in cooler temperatures. However, cooler temperatures didn’t remove the phytotoxic injury, but merely reduced the rate of injury development (Anderson et al. 1993a). In these experiments, the highest temperatures were recorded at the 12 and 6 P.M. compared to the 12 and 6 A.M. applications, 28 DAT. These data
suggests that ambient air temperature at the time of glufosinate application may also play a role in the time of day effect on barnyardgrass efficacy.

Glufosinate inhibits glutamine synthetase, an enzyme that combines ammonium with glutamate to form glutamine, requiring ATP, a product of the light reactions of photosynthesis (Devine et al. 1993; Hess 2000; Tiaz and Zeiger 2006). Glutamine synthetase activity has been found to be altered by light and carbohydrate levels (Tiaz and Zeiger 2006). Glutamine synthetase is catalytically active in the chloroplast of plant cells during period of light and is a sink for glufosinate (Sellers et al. 2004; Tiaz and Zeiger 2006). Sellers et al. (2004) reported when glufosinate was applied at 2 P.M., glutamine synthetase inhibition was irreversible and was not reversed by the onset of a dark period. However, glufosinate applied at 10 P.M. merely minimized glutamine synthetase activity and upon illumination, glutamine synthetase activity was greater when compared to glufosinate applied at 2 P.M. (Sellers et al. 2004). Sellers et al. (2004) also reported that glufosinate was translocated 2-times greater when applied at 10 P.M. compared to the 2 P.M. application. Yet, in dark period, glutamine synthetase is no longer a sink for glufosinate and it is thought that glufosinate is sequestered into the vacuole, making glufosinate molecules unavailable for glutamine synthetase inhibition (Sellers et al. 2004). These data may help explain why the 12 A.M. application of glufosinate had reduced efficacy of barnyardgrass compared to the 12 and 6 P.M. applications.

Researchers at the University of Georgia (2014) reported 13, 56%, 88 and 98% control of Palmer amaranth when glufosinate was applied at sunrise, 0.5, 1 and 2 hr after sunrise. Applications of glufosinate applied 2 hr after sunrise were not different from applications made 4 to 6 hr after sunrise (UGA 2014). These data may also explain why the 6 A.M.
application had slightly reduced control compared to the 12 and 6 P.M. application timings, yet was slightly greater than the 12 A.M. application. In contrast to these results, Stewart et al. (2009) reported that barnyardgrass efficacy was not affected by glufosinate at 400 g ai ha\(^{-1}\) applied at differing times of day. However, Stewart et al. (2009) used a spray volume of 200 l ha\(^{-1}\), whereas our treatments were applied at a spray volume of 140 l ha\(^{-1}\), which may explain the difference in time of day response in regard to barnyardgrass control.

The presence of heavy dew on the leaves of target plants may result in poor weed control with applications before 6 A.M. or after 9 P.M. from increased herbicide dilution and or runoff (Anonymous 2011; Doran and Anderson 1976). In contrast, the presence of dew on leaf surfaces may aid in herbicide absorption by allowing the herbicide to remain in solution for a longer period of time before drying (Kogan and Zuniga 2001). Martinson et al. (2005) reported glyphosate efficacy was affected when dew formation occurred after application; however, glufosinate efficacy was not affected by presence or absence of dew. Stewart et al. (2009) reported that although dew was present at 12 and 6 A.M., it was not found to contribute to reduced glufosinate efficacy as much as other time of day effect factors. In these experiments, dew was present at the 12 and 6 A.M. applications. Glufosinate at 594 g ai ha\(^{-1}\) applied 12 A.M. provided the least amount of control among the application times; however barnyardgrass control at the 6 A.M. application was variable. Dew may have influenced barnyardgrass control but did not have as significant of an effect compared to other time of day effect factors.

This experiment showed that clethodim applied alone provided greater barnyardgrass control compared to glufosinate plus clethodim and glufosinate alone.
Clethodim was not effected by application time of day. Glufosinate applications at midnight reduced barnyardgrass control compared to applications made at noon and 6 P.M. Early morning applications at 6 A.M. also showed reduced barnyardgrass efficacy compared to applications at 6 P.M. Environmental factors such as temperature and light at the time of application could contribute to the time of day effects observed in this study. These data suggest that in order to optimize barnyardgrass efficacy with tank mixtures of glufosinate and clethodim, applications should be made at noon or early evening to avoid potential time of day effects.

Table 4.1  Environmental data at the time of the glufosinate application.

<table>
<thead>
<tr>
<th>Application date</th>
<th>Sunrise/sunset&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Application time</th>
<th>Relative humidity</th>
<th>Air temperature</th>
<th>Dew&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>August 20, 2013</td>
<td>5:21 A.M.</td>
<td>6:00 A.M.</td>
<td>94</td>
<td>24</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td>12:00 P.M.</td>
<td></td>
<td>71</td>
<td>30</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>6:34 P.M.</td>
<td>6:00 P.M.</td>
<td>66</td>
<td>27</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>12:00 A.M.</td>
<td></td>
<td>94</td>
<td>24</td>
<td>Y</td>
</tr>
<tr>
<td>June 13, 2014</td>
<td>4:45 A.M.</td>
<td>6:00 A.M.</td>
<td>66</td>
<td>18</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td>12:00 P.M.</td>
<td></td>
<td>73</td>
<td>28</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>7:05 P.M.</td>
<td>6:00 P.M.</td>
<td>58</td>
<td>30</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>12:00 A.M.</td>
<td></td>
<td>86</td>
<td>22</td>
<td>Y</td>
</tr>
</tbody>
</table>

<sup>a</sup>Times from Astronomical Applications Department, U. S. Naval Observatory, Washington, DC 20392.

<sup>b</sup>Abbreviations: Y, yes; N, no.
Table 4.2  Barnyardgrass control as affected by clethodim and glufosinate interaction pooled over time of day.

<table>
<thead>
<tr>
<th>Clethodim rate a</th>
<th>Glufosinate rate</th>
<th>7 DAT</th>
<th>14 DAT</th>
<th>21 DAT</th>
<th>28 DAT</th>
<th>56 DAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>g ai ha(^{-1})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0D(^b)</td>
<td>0C</td>
<td>0D</td>
<td>0C</td>
<td>0C</td>
</tr>
<tr>
<td>76</td>
<td>0</td>
<td>94B</td>
<td>93B</td>
<td>89C</td>
<td>88B</td>
<td>90B</td>
</tr>
<tr>
<td>76</td>
<td>594</td>
<td>96A</td>
<td>96A</td>
<td>92B</td>
<td>92A</td>
<td>92B</td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td></td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

\(^a\) Crop oil concentrate at 1\% v v\(^{-1}\) was included with clethodim.

\(^b\) Means within a column followed by a common letter are not different according to Fisher’s Protected LSD P=0.05. A numerical LSD is given for each column.

Table 4.3  Barnyardgrass control as affected by glufosinate and time of day interaction pooled over clethodim rates.

<table>
<thead>
<tr>
<th>Glufosinate rate</th>
<th>Time of day</th>
<th>7 DAT</th>
<th>14 DAT</th>
<th>21 DAT</th>
<th>28 DAT</th>
<th>56 DAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>g ai ha(^{-1})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>6:00 A.M.</td>
<td>44C(^a)</td>
<td>48C</td>
<td>48D</td>
<td>47C</td>
<td>49D</td>
</tr>
<tr>
<td>0</td>
<td>12:00 P.M.</td>
<td>45C</td>
<td>48C</td>
<td>47D</td>
<td>47C</td>
<td>49D</td>
</tr>
<tr>
<td>0</td>
<td>6:00 P.M.</td>
<td>44C</td>
<td>48C</td>
<td>47D</td>
<td>48C</td>
<td>49D</td>
</tr>
<tr>
<td>0</td>
<td>12:00 A.M.</td>
<td>45C</td>
<td>48C</td>
<td>47D</td>
<td>47C</td>
<td>48D</td>
</tr>
<tr>
<td>594</td>
<td>6:00 A.M.</td>
<td>95AB</td>
<td>95A</td>
<td>90B</td>
<td>87B</td>
<td>90BC</td>
</tr>
<tr>
<td>594</td>
<td>12:00 P.M.</td>
<td>96A</td>
<td>95A</td>
<td>92AB</td>
<td>91A</td>
<td>92AB</td>
</tr>
<tr>
<td>594</td>
<td>6:00 P.M.</td>
<td>96A</td>
<td>95A</td>
<td>94A</td>
<td>94A</td>
<td>94A</td>
</tr>
<tr>
<td>594</td>
<td>12:00 A.M.</td>
<td>94B</td>
<td>93B</td>
<td>87C</td>
<td>87B</td>
<td>89C</td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td></td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

\(^a\) Means within a column followed by a common letter are not different according to Fisher’s Protected LSD P=0.05. A numerical LSD is given for each column.
Literature Cited


Anonymous (2010) Select Max herbicide specimen label. Walnut Creek, CA: Valent. 43 p


Doran DL, Anderson RN (1976) Effectiveness of bentazon applied at various times of the day. Weed Sci 24:567-570


