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Control of pervasive row crop weeds with dicamba and glufosinate applied alone, mixed, or sequentially

Eric A. L. Jones[1], Ramon G. Leon[2] and Wesley J. Everman[3]

[1]Graduate Research Assistant, Department of Crop and Soil Sciences, North Carolina State University, Raleigh, NC, USA; [2]Professor and University Faculty Scholar, Department of Crop and Soil Sciences, North Carolina State University, Raleigh, NC, USA and [3]Associate Professor, Department of Crop and Soil Sciences, North Carolina State University, Raleigh, NC, USA

Research Article

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Nomenclature:
dicamba; glufosinate; common ragweed, *Ambrosia artemisiifolia* L. 'AMBEL'; goosegrass, *Eleusine indica* (L.) Gaertn. 'ELEIN'; ivyleaf morningglory, *Ipomoea hederacea* L. 'IPOHE'; large crabgrass, *Digitaria sanguinalis* (L.) Scop. 'DIGSA'; Palmer amaranth, *Amaranthus palmeri* S. Watson 'AMAPA'; sicklepod, *Senna obtusifola* (L.) Irwin & Barneby 'CASOB'

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Author for correspondence:
Wesley J. Everman, Department of Crop and Soil Sciences, North Carolina State University, Raleigh, NC 27607.
Email: Wesley_Everman@ncsu.edu

Abstract

Dicamba and glufosinate are among the few effective postemergence herbicides to control multiple herbicide-resistant weeds in southeastern U.S. cotton and soybean production. Field studies were conducted to determine the effect of weed size and the application of dicamba and glufosinate individually, mixed, or sequentially on common ragweed, goosegrass, large crabgrass, ivyleaf morningglory, Palmer amaranth, and sicklepod control. Sequential herbicide treatments were applied 7 d after the initial treatment. The tested weeds sizes predominantly did not affect weed control. Control of broadleaf weed species with sequential herbicide applications never increased compared to the initial herbicide application. Two applications of glufosinate and/or dicamba + glufosinate controlled grasses better than one application. The order of the herbicides in the sequential applications did not affect broadleaf species control, whereas herbicide order was important for the control of grass weeds. Grass weed control was higher when glufosinate was applied before dicamba. Dicamba + glufosinate additively controlled the weeds, except for goosegrass, for which control was less for dicamba + glufosinate compared to glufosinate alone. The results of the experiment provide evidence that dicamba and glufosinate applied individually, mixed, and sequentially are effective on common row crop weeds found in the southeastern United States, but the species present may dictate how the herbicides are applied together.

Introduction

Farmers have traditionally mixed pesticides to increase the spectrum of control and to reduce the number of trips through the field, which may result in economic savings and delay the evolution of pesticide resistance (Green 1989; Putnam and Penner 1974; Wrubel and Gressel 1994). Mixtures of herbicides with different effective mechanisms of action (MOAs) may be applied in annual rotations and sequential applications to delay the evolution of resistance by minimizing the selection pressure imposed by the recurrent use of a single herbicide MOA (Beckie and Harker 2017; Gressel and Segel 1990; Norsworthy et al. 2012). Mixtures or sequential applications of herbicides with different MOAs can result in biochemically additive, antagonistic, or synergistic activity (Green 1989). Herbicide mixtures may result in lower control and may be exacerbated when applied to larger weeds (Colby 1967; Green 1989; Putnam and Penner 1974). Sequential herbicide applications may result in decreased or increased control when compared to the herbicides when mixed (Putnam and Penner 1974).

Applying dicamba (Herbicide Group [HG] 4) and glufosinate (HG 10) alone or sequentially controls weed species resistant to other herbicides in North Carolina (Cahoon et al. 2015; Everman et al. 2007; Oreja et al. 2021; Schrage 2018). Dicamba and glufosinate mixtures could be useful for weed control, but this mixture is not currently labeled. However, dicamba and glufosinate have different MOAs that result in plant death; thus mixed and sequential applications could result in additive, antagonistic, or synergistic control (Belz and Duke 2014; Gressel 2020). In addition, the herbicide mixtures and sequential applications could mitigate the evolution of target-site resistance (Beckie and Harker 2017; Gressel 2020; Gressel and Segel 1990). Dicamba is a selective, slow-acting systemic herbicide that binds to the *transport inhibitor response* gene, resulting in the uncontrolled transcription of auxin-responsive genes (Grossmann 2009). Glufosinate is a nonselective, fast-acting contact herbicide that inhibits glutamine synthetase (EC 6.3.1.2) (Takano et al. 2019). Because dicamba and glufosinate differentially affect plants, knowledge of potential interactions between these two herbicides when applied in combination is important for ensuring effective weed control (Comont et al. 2020; Green 1989; Gressel 2020).

Previous research demonstrated mixtures of herbicides, including dicamba or glufosinate, resulted in lower control due to biochemical antagonism on several weed species (Besançon

et al. 2018; Burke et al. 2005; Ou et al. 2018). Previous research has also demonstrated that sequential herbicide applications and the order in which herbicides were applied can circumvent antagonism (Burke et al. 2005; Culpepper et al. 1999; Koger et al. 2007). Dicamba and glufosinate have label restrictions that require sequential applications to occur between 7 to 14 days after the initial herbicide application (Anonymous 2017; Anonymous 2018). Investigations assessing the potential interaction of sequential applications of dicamba and glufosinate should include treatment timings within this labeled timeframe. Studies have investigated dicamba and glufosinate applied alone, mixed, and sequentially on Palmer amaranth; however the studies investigating potential herbicides interactions were applied to plants larger than the labeled-size to mimic delayed application induced by environmental conditions (Browne et al. 2020; Meyer and Norsworthy 2019; Priess et al. 2022a; Vann et al. 2017a, 2017b).

Weeds other than Palmer amaranth are often present in sufficient amounts to justify treatment; thus it is of interest to determine the level of control from dicamba and glufosinate applications on common weed species. Dicamba does not provide grass control and may cause increased population densities of grass weeds if recurrently applied (Canode and Robocker 1966; Hodgskiss et al. 2020; Oreja et al. 2021). Although glufosinate is effective on large crabgrass (Corbett et al. 2004; Everman et al. 2007; Tharp et al. 1999), it provides variable control on other grass species, such as goosegrass (Burke et al. 2005). There is also a goosegrass population from Malaysia that has evolved resistance to glufosinate (Seng et al. 2010; Zhang et al. 2022). Decreased control of goosegrass when treated with glufosinate could be exacerbated when mixed or applied sequentially with dicamba (Flint and Barrett 1989; Hart and Wax 1996; Meyer et al. 2020). Currently there is no literature providing information about the control of goosegrass and large crabgrass with dicamba and glufosinate applied in combination or sequentially.

A similar situation occurs with common ragweed, ivyleaf morningglory, and sicklepod, which are also pervasive and hard-to-control weeds in the southeastern United States (Jones et al. 2022; Van Wychen 2017; Webster and Nichols 2012). Previous research has shown that dicamba and glufosinate are effective on these species; however, mixtures and sequential applications of these herbicides have not been evaluated (Everman et al. 2007; Kalina et al. 2021; Leon et al. 2016; Schrage 2018). The objectives of this study were to determine (1) if the order of dicamba and glufosinate in a sequential application influence control on certain weed species and sizes and (2) if dicamba + glufosinate mixtures demonstrate an antagonistic interaction on certain weed species and sizes.

Materials and Methods

Separate field experiments were conducted in 2019 and 2021 at Rocky Mount (35.89°N, 77.68°W) and Kinston (35.29°N, 77.65°W), NC, for a total of 4 site-years. The soil at the Rocky Mount location is an Aycock very fine sandy loam (fine-silty, siliceous, subactive, thermic Typic Paleudult), whereas the Kinston location encompasses a mosaic of Lumbee sandy loam (sandy-skeletal, siliceous, subactive, thermic Typic Endoaquult) and Portsmouth loam (sandy-skeletal, mixed, semiactive, thermic Typic Umbraquult) soils. Natural populations of large crabgrass and Palmer amaranth occurred at both locations both years (4 site-years). Ivyleaf morningglory populations were evaluated at both locations in 2021 (2 site-years). Goosegrass populations were evaluated at Kinston in 2019 and at both locations in 2021 (3 site-years). The populations of common ragweed and sicklepod were evaluated each year at Rocky Mount and Kinston, respectively, resulting in 2 site-years of data for each weed. The Palmer amaranth populations had evolved resistance to acetolactate synthase–inhibiting herbicides and glyphosate, whereas the other weed species at both experiment sites were herbicide susceptible. The field sites were tilled prior to experiment initiation to control established weeds, but preemergence herbicides were not applied to ensure maximum weed seedling emergence. Both experiment locations remained fallow for the duration of the study.

Treatments were arranged as a two-way factorial in a randomized complete block design with four replications. Individual plots were 3.6 m wide by 9.0 m long. Treatment factors were herbicide and weed size (Table 1). Herbicide treatments were applied to plots with a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 165 kPa and 46 cm above the target weed height. The sequential herbicide applications were made 1 wk after the initial herbicide application. A nontreated control was included in the experiment. Dicamba-only treatments were applied at the maximum labeled rate for use in dicamba-tolerant cotton and soybean (560 g ae ha^{-1}) with TeeJet® TTI11002-VP spray nozzles (TeeJet® Technologies, Spraying Systems, Wheaton, IL, USA) (Anonymous 2018). Glufosinate-only treatments were applied at a rate commonly used in North Carolina (590 g ai ha^{-1}) (W. J. E. Everman, personal communication, 2018) with 10 g L^{-1} of ammonium sulfate and with TeeJet® XR11002-VS spray nozzles. Ammonium sulfate was included with the glufosinate treatments to prevent the herbicide molecules from binding to cations in the water carrier and was excluded from the treatments including dicamba to prevent herbicide volatility per label requirements (Anonymous 2018; Mueller and Steckel 2019; Pratt et al. 2003). The dicamba + glufosinate treatments were applied with TeeJet® TTI11002-VP spray nozzles. The different nozzles were used to ensure the highest control based on the herbicide activity and to mimic a farmer application per label requirements (Anonymous 2017; Anonymous 2018; Sikkema et al. 2008). Herbicide treatments were applied at 2 ± hours of solar noon and at temperatures ranging between 30 C and 35 C with relative humidity greater than 30% to avoid environment-induced control reductions (Coetzer et al. 2001; Johnston et al. 2018; Sellers et al. 2003).

Weed control evaluations were made using estimates based on a scale ranging from 0% to 100%, where 0% equals no control (i.e., no injury symptoms on any tissue) and 100% equals complete control (i.e., total necrosis). Height reduction was determined by measuring from the soil surface to the apical growing point for three plants (representative of overall plot average height) of each species growing in the central region of each plot. Percentage height reduction was calculated by dividing the heights of the plants in the treated plots by the heights of the plants in the nontreated plots. Control and height reduction evaluations were made 28 d after initial treatment (DAIT) for each application timing. Clethodim was applied at the maximum labeled rate (560 g ai ha^{-1}) with TeeJet® XR11002-VS spray nozzles to dicamba-only treatments 21 DAIT to control grass weeds that could confound the control for broadleaf weeds. Thus no response variable data were recorded for grass species in these plots.

Dicamba + glufosinate mixtures were further evaluated to determine whether control was additive, antagonistic, or synergistic 28 DAIT. Colby's method (Colby 1967) has been frequently used to evaluate herbicide interactions (de Sanctis and Jhala 2021; Meyer and Norsworthy 2019). Colby's method calculates an expected control value for an herbicide mixture based on the

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Table 1. Dicamba (560 g ae ha^{-1}) and glufosinate (590 g ai ha^{-1}) treatments tested in the fallow field experiment conducted at Rocky Mount and Kinston, NC, in 2019 and 2021.[a,b]

Initial	Sequential	Herbicide treatment
No initial treatment	Dicamba	N fb D
No initial treatment	Glufosinate	N fb G
No initial treatment	Dicamba + glufosinate	N fb DG
Dicamba	No sequential treatment	D
Dicamba	Dicamba	D fb D
Dicamba	Glufosinate	D fb G
Dicamba	Dicamba + glufosinate	D fb DG
Glufosinate	No sequential treatment	G
Glufosinate	Dicamba	G fb D
Glufosinate	Glufosinate	G fb G
Glufosinate	Dicamba + glufosinate	G fb DG
Dicamba + glufosinate	No sequential treatment	DG
Dicamba + glufosinate	Dicamba	DG fb D
Dicamba + glufosinate	Glufosinate	DG fb G
Dicamba + glufosinate	Dicamba + glufosinate	DG fb DG

[a]Each herbicide treatment was tested on two sizes of common ragweed (5 and 15 cm), goosegrass (10 and 20 cm), ivyleaf morningglory (5 and 15 cm), large crabgrass (10 and 20 cm), Palmer amaranth (5 and 15 cm), and sicklepod (5 and 15 cm).
[b]Abbreviations: D, dicamba; DG, dicamba + glufosinate; fb, followed by; G, glufosinate.

control of the individual herbicides and compared to the control of the tested mixture. If the observed control of the herbicide mixture deviates from the expected control, then the herbicide mixture can be considered antagonistic or synergistic, depending on the nature of the deviation. Dicamba + glufosinate treatments were analyzed using the equation for Colby's method:

$$E = (X + Y) - \left(\frac{xy}{100}\right)$$

where E is expected control (%) of two herbicides applied in a mixture, X is control (%) of X herbicide when applied alone, and Y is control (%) of Y herbicide when applied alone. The expected control was compared with the observed control using a two-sided t-test ($\alpha = 0.05$). If the control was greater than the expected, the mixture was considered synergistic, whereas if the control was lower than the expected, the mixture was considered antagonistic (Colby 1967). If the observed and expected controls were equal, the mixture was considered additive (Colby 1967). The height reduction of the weeds when treated with dicamba, glufosinate, and dicamba + glufosinate was subjected to Colby's equation as well. Because dicamba does not control goosegrass or large crabgrass, statistical deviations from the single and mixed applications of dicamba and glufosinate can provide evidence of antagonism or synergism (Flint and Barrett 1989; Meyer and Norsworthy 2019). The control of sequential herbicide treatments was compared to the control of the dicamba + glufosinate mixture to determine if incurred antagonism could be overcome with a particular sequential herbicide treatment (Burke et al. 2005).

Control and height reduction 28 DAIT data were subjected to analysis of variance (ANOVA) using the *Glimmix* procedure in SAS 9.4 (Statistical Analysis Software Institute, Cary, NC, USA) ($\alpha = 0.05$). Herbicide, weed size, and their interactions were considered fixed effects, whereas block, year, location, and their interactions were considered random effects. Year and location were considered random to allow inferences to be made across broader conditions and locations (Blouin et al. 2011; Moore and Dixon 2015). Treatment means were separated using Tukey's honestly significant difference test ($P \leq 0.05$). Control and height reduction data were also subjected to the *Corr* procedure in SAS 9.4 to determine Pearson's correlation coefficients between the evaluations. The nontreated control was excluded from control and height reduction analyses for all weed species. All dicamba-only treatments were excluded from the statistical analyses for goosegrass and large crabgrass, as no control was incurred and clethodim was applied.

Results

Common Ragweed

Common ragweed control was affected by herbicide ($P < 0.0001$) but not size ($P = 0.69$). The interaction was significant ($P = 0.0005$); thus common ragweed control data were analyzed by herbicide and size. The single herbicide treatments controlled the 5-cm and 15-cm common ragweed similarly, respectively (Table 2). All sequential herbicide treatments completely controlled the 5-cm and 15-cm common ragweed, respectively (Table 2). No initial treatment fb glufosinate controlled the 5-cm common ragweed approximately 11% less than all sequential herbicide treatments (Table 2). No initial treatment fb dicamba controlled 15-cm common ragweed approximately 24% less than all sequential herbicide treatments (Table 2).

Common ragweed height reduction was affected by treatment ($P < 0.0001$) but not size ($P = 0.97$), and a significant interaction was not detected ($P = 0.06$); thus common ragweed height reduction data were averaged over size. Common ragweed height reduction was the same when treated with dicamba, glufosinate, and dicamba + glufosinate (Table 3). No initial treatment fb glufosinate and no initial treatment fb dicamba + glufosinate reduced common ragweed height similarly. All sequential herbicide treatments controlled common ragweed, resulting in no vegetative growth (Table 3). No initial treatment fb dicamba and no initial treatment fb glufosinate reduced common ragweed height approximately 25% less than dicamba and sequential herbicide treatments (Table 3). A high correlation between common ragweed control and height reduction was detected ($R = 0.82$; $P < 0.0001$).

Dicamba + glufosinate and no initial treatment fb dicamba + glufosinate additively controlled 5-cm common ragweed (Table 4). Dicamba + glufosinate and no initial treatment fb dicamba + glufosinate also additively controlled 15-cm common ragweed. Furthermore, dicamba + glufosinate and no initial treatment fb dicamba + glufosinate additively reduced common ragweed height (Table 4).

Goosegrass

Goosegrass control was affected by herbicide ($P < 0.0001$) but not size ($P = 0.53$). The interaction was not significant ($P = 0.12$); thus goosegrass control data were averaged over size. Goosegrass control was 20% and 17% greater with glufosinate and no initial treatment fb glufosinate compared to dicamba + glufosinate and no initial treatment fb dicamba + glufosinate, respectively (Table 5). Sequential herbicide treatments controlled goosegrass similarly, with the exception that dicamba fb dicamba + glufosinate control was 16% less than glufosinate fb dicamba + glufosinate (Table 5). All other sequential treatments provided similar goosegrass control compared to glufosinate and no initial treatment fb glufosinate (Table 5). Glufosinate fb dicamba + glufosinate and glufosinate fb glufosinate provided 18% to 31% more control compared to dicamba + glufosinate and no initial treatment fb dicamba + glufosinate (Table 5).

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Table 2. Broadleaf weed control with dicamba and glufosinate 28 d after the initial herbicide application in fallow field experiments conducted at Kinston and Rocky Mount, NC, in 2019 and 2021.[a,b]

Herbicide treatment	'AMAPA'		'AMBEL'		'CASOB'
	5 cm	15 cm	5 cm	15 cm	
	%				
N fb D	76 bc	70 de	94 ab	76 b	73 b
N fb G	66 c	71 cde	89 b	96 a	87 ab
N fb DG	83 abc	77 bcde	99 ab	100 a	100 a
D	95 a	83 abcde	100 a	99 a	87 ab
D fb D	98 a	94 ab	100 a	100 a	94 a
D fb G	98 a	93 ab	100 a	100 a	94 a
D fb DG	99 a	98 a	100 a	100 a	100 a
G	96 a	77 bcde	92 ab	100 a	95 a
G fb D	98 a	96 ab	100 a	100 a	99 a
G fb G	96 a	87 abcd	100 a	100 a	91 a
G fb DG	98 a	97 a	100 a	100 a	100 a
DG	94 ab	87 abcd	99 ab	97 a	90 ab
DG fb D	100 a	90 abc	100 a	100 a	96 a
DG fb G	100 a	95 ab	100 a	100 a	100 a
DG fb DG	94 ab	96 ab	100 a	100 a	100 a

[a]Abbreviations: 'AMAPA,' Palmer amaranth; 'AMBEL,' common ragweed; 'CASOB,' sicklepod; D, dicamba; DG, dicamba + glufosinate; fb, followed by; G, glufosinate; N, no initial treatment.
[b]Means followed by the same letter are not statistically different based on Tukey's honestly significant difference ($P < 0.05$).

Table 3. Broadleaf weed height reduction with dicamba and glufosinate 28 d after the initial herbicide application in fallow field experiments conducted at Kinston and Rocky Mount, NC, in 2019 and 2021.[a,b]

Herbicide treatment	'AMAPA'	'AMBEL'	'CASOB'
	%		
N fb D	63 cd	76 b	82 b
N fb G	60 d	83 ab	82 b
N fb DG	64 cd	97 a	98 ab
D	82 abc	100 a	87 ab
D fb D	87 ab	100 a	91 ab
D fb G	91 a	100 a	93 ab
D fb DG	91 a	100 a	100 a
G	70 bcd	92 ab	97 ab
G fb D	84 ab	100 a	98 a
G fb G	84 ab	100 a	93 ab
G fb DG	89 a	100 a	100 a
DG	80 abc	94 a	90 ab
DG fb D	82 ab	100 a	97 ab
DG fb G	93 a	100 a	97 ab
DG fb DG	93 a	100 a	100 a

[a]Abbreviations: 'AMAPA,' Palmer amaranth; 'AMBEL,' common ragweed; 'CASOB,' sicklepod; D, dicamba; DG, dicamba + glufosinate; fb, followed by; G, glufosinate; N, no initial treatment.
[b]Means that share the same letter are not statistically different based on Tukey's honestly significant difference ($P < 0.05$).

Goosegrass height reduction was affected by herbicide ($P < 0.0001$) but not size ($P = 0.12$), and the interaction was not significant ($P = 0.35$); thus goosegrass height reduction data were averaged over size. Goosegrass height reduction was similar across all single herbicide treatments, with the exception that glufosinate reduced height by 23% more than no initial treatment fb dicamba + glufosinate (Table 6). Sequential herbicide treatments reduced goosegrass height similarly (Table 6). The sequential treatments provided similar goosegrass height compared to glufosinate and no initial treatment fb glufosinate (Table 6). Most treatments that included glufosinate (alone or mixed with dicamba) reduced goosegrass height more than dicamba + glufosinate and no initial treatment fb dicamba + glufosinate (Table 6). A high correlation between goosegrass control and height reduction was detected ($R = 0.84$; $P < 0.0001$).

Table 4. Broadleaf weed control and height reduction (expected and observed) with dicamba and glufosinate 28 d after initial herbicide application in fallow field experiments conducted at Kinston and Rocky Mount, NC, in 2019 and 2021.[a]

Species	Size	Herbicide treatment	Expected	Observed	P-value
	cm				
Control					
'AMAPA'	5	DG	100	94	0.48
	15	DG	96	87	0.48
		N fb DG	91	77	0.34
'AMBEL'	5	DG	99	99	NC
	15	DG	100	97	0.4
		N fb DG	97	100	0.73
'CASOB'		DG	90	99	0.25
		N fb DG	100	96	0.57
Height reduction					
'AMAPA'		DG	80	95	0.16
		N fb DG	64	80	0.11
'AMBEL'		DG	94	100	0.43
		N fb DG	93	92	0.87
'CASOB'		DG	100	90	0.20
		N fb DG	96	90	0.30

[a]Abbreviations: 'AMAPA,' Palmer amaranth; 'AMBEL,' common ragweed; 'CASOB,' sicklepod; DG, dicamba + glufosinate; fb, followed by; N, no initial treatment; NC, not calculated.

Table 5. Grass weed control with dicamba and glufosinate 28 d after the initial herbicide application in fallow field experiments conducted at Kinston and Rocky Mount, NC, in 2019 and 2021.[a,b]

Herbicide treatment	'DIGSA'	'ELEIN'
	%	
N fb G	76 c	81 abcd
N fb DG	75 c	64 e
D fb G	80 bc	81 abcd
D fb DG	83 abc	79 bcde
G	84 abc	90 abc
G fb D	76 c	81 abcd
G fb G	95 ab	94 a
G fb DG	98 a	96 a
DG	75 c	70 de
DG fb D	77 c	74 cde
DG fb G	97 a	98 a
DG fb DG	96 a	91 a

[a]Abbreviations: D, dicamba; DG, dicamba + glufosinate; 'DIGSA,' large crabgrass; 'ELEIN,' goosegrass; fb, followed by; G, glufosinate; N, no initial treatment.
[b]Means that share the same letter are not statistically different based on Tukey's honestly significant difference ($P < 0.05$).

Differential control and height reduction of goosegrass when treated with glufosinate and dicamba + glufosinate suggests that the mixture may be antagonistic (Table 5). Reduced control was realized between no initial treatment fb glufosinate and no initial treatment fb dicamba + glufosinate, further suggesting that the mixture may be antagonistic (Table 6). Conversely, goosegrass height reductions were no different with the no initial treatment fb herbicide treatments. These results suggest that applying dicamba + glufosinate to goosegrass may be antagonistic.

Ivyleaf Morningglory

All herbicides controlled ivyleaf morningglory at both locations in 2021 (data not shown). Because there was no variation of control or height reduction, ANOVA could not be conducted. This result was

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Table 6. Grass weed height reduction with dicamba and glufosinate treatments 28 d after the initial herbicide application in fallow field experiments conducted at Kinston and Rocky Mount, NC, in 2019 and 2021.[a,b]

Herbicide treatment	'DIGSA'	'ELEIN'
	%	
N fb G	77 cd	78 abcde
N fb DG	68 d	61 de
D fb G	77 cd	80 abcd
D fb DG	81 bcd	74 bcde
G	83 bc	85 abc
G fb D	82 bcd	83 abc
G fb G	95 ab	93 a
G fb DG	100 a	93 ab
DG	76 cd	59 e
DG fb D	81 bcd	70 cde
DG fb G	97 a	96 a
DG fb DG	97 a	88 abc

[a]Abbreviations: D, dicamba; DG, dicamba + glufosinate; 'DIGSA,' large crabgrass; 'ELEIN,' goosegrass; fb, followed by; G, glufosinate; N, no initial treatment.
[b]Means that share the same letter are not statistically different based on Tukey's honestly significant difference ($P < 0.05$).

expected, as ivyleaf morningglory is highly susceptible to both dicamba and glufosinate applied individually (Everman et al. 2007; Kalina et al. 2021; Merchant et al. 2013). Control and height reduction data were not subjected to Colby's equation because of the complete control achieved.

Large Crabgrass

Large crabgrass control was affected by herbicide ($P < 0.0001$) and size ($P = 0.009$). The interaction was not significant ($P = 0.28$); thus large crabgrass control data were averaged over size. All single herbicide treatments provided similar control of large crabgrass (Table 5). Differential control was realized across the sequential herbicide treatments. Largely, treatments containing glufosinate in both applications provided 24% to 27% greater control than treatments containing a single glufosinate (alone or mixed with dicamba) application (initial or sequential) (Table 5). Glufosinate provided similar control to sequential herbicide treatments (Table 5).

Large crabgrass height reduction was affected by herbicide ($P < 0.001$) but not size ($P = 0.23$), and the interaction was not significant ($P = 0.42$). Thus large crabgrass height reduction data were averaged over size. Large crabgrass height reduction was similar across all single herbicide treatments, with the exception that glufosinate reduced height by 15% more than no initial treatment fb dicamba + glufosinate (Table 6). Similar to the control evaluations, treatments containing glufosinate (alone or mixed with dicamba) in both applications provided 27% to 32% greater height reduction than treatments containing a single glufosinate (alone or mixed with dicamba) application (initial or sequential) (Table 6). A high correlation between large crabgrass control and height reduction was detected ($R = 0.72$; $P < 0.0001$).

Control and height reduction of large crabgrass when treated with glufosinate and dicamba + glufosinate were similar (Tables 5 and 6). Similar control and height reduction were also observed with no initial treatment fb dicamba + glufosinate and no initial treatment fb glufosinate (Tables 5 and 6). These results suggest that dicamba + glufosinate additively controls and reduces the height of large crabgrass. Differential control of the sequential herbicide treatments suggests that including glufosinate (alone or mixed with dicamba) in both applications provides greater large crabgrass control over a single application of glufosinate (alone or mixed with dicamba) (Tables 5 and 6).

Palmer Amaranth

Palmer amaranth control was affected by herbicide and size ($P < 0.0001$), and a significant interaction was detected ($P = 0.02$); thus Palmer amaranth control data were analyzed by herbicide and size. Dicamba, glufosinate, and dicamba + glufosinate controlled the 5-cm Palmer amaranth similarly (Table 2). No initial treatment fb dicamba and no initial treatment fb glufosinate provided 19% to 30% less control of 5-cm Palmer amaranth compared to dicamba and glufosinate, respectively (Table 2). However, no initial treatment fb dicamba + glufosinate was as effective as all other treatments. All sequential herbicide treatments completely controlled the 5-cm Palmer amaranth (Table 2). The single herbicide treatments controlled 15-cm Palmer amaranth similarly, but control was lower compared to when these treatments were applied to 5-cm Palmer amaranth (Table 2). The sequential herbicide treatments provided approximately 30% higher control on 15-cm Palmer amaranth when compared to no initial treatment fb dicamba and no initial treatment fb glufosinate (Table 2). No initial treatment fb dicamba + glufosinate was efficacious on 15-cm Palmer amaranth, where only the dicamba fb dicamba + glufosinate and glufosinate fb dicamba + glufosinate provided 20% higher control (Table 2).

Palmer amaranth height reduction was affected by herbicide ($P < 0.0001$) but not size ($P = 0.74$), and a significant interaction ($P = 0.70$) was not detected; thus Palmer amaranth height reduction data were averaged over size. Palmer amaranth height was reduced similarly with all single herbicide treatments (Table 3). All sequential herbicide treatments reduced Palmer amaranth height similarly (Table 3). Height reduction with dicamba and dicamba + glufosinate was no different than the sequential herbicide treatments (Table 3). Palmer amaranth height reduction from glufosinate was similar to dicamba fb dicamba, dicamba + glufosinate fb dicamba, and glufosinate fb glufosinate; all other sequential herbicide treatments reduced Palmer amaranth height to a greater degree (Table 3). The no initial treatment fb herbicide treatments reduced Palmer amaranth height 22% to 33% less than all the sequential herbicide treatments (Table 3). A significant correlation between Palmer amaranth control and height reduction was detected ($R = 0.46$; $P < 0.0001$).

Dicamba + glufosinate additively controlled 5-cm Palmer amaranth (Table 4). Additive control of 15-cm Palmer amaranth was also achieved with dicamba + glufosinate and no initial treatment fb dicamba + glufosinate. Furthermore, dicamba + glufosinate and no initial treatment fb dicamba + glufosinate additively reduced Palmer amaranth height (Table 4). Although dicamba + glufosinate did not have an antagonistic or synergistic interaction in the presented study, other research has demonstrated that this mixture can incur control antagonism or synergism on Palmer amaranth of similar sizes (Merchant et al. 2013; Priess et al. 2022a). The dissimilar results between the studies suggest that control with dicamba + glufosinate is influenced by the environment (e.g., humidity, light intensity, temperature) when applied on larger Palmer amaranth (Hammerton 1967; Richter et al. 2002).

Sicklepod

Sicklepod control was affected by herbicide ($P < 0.0001$) but not size ($P = 0.06$). The interaction between the main effects was not significant ($P = 0.65$); thus sicklepod control data were averaged

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over size. Most single and sequential herbicide treatments controlled sicklepod similarly (Table 3). No initial treatment fb dicamba controlled sicklepod 21% to 24% less than most of the single and all sequential herbicide treatments (Table 3). Sicklepod height reduction was affected by herbicide ($P = 0.0008$) and size ($P = 0.004$). The interaction was not significant ($P = 0.37$); thus sicklepod height reduction data were averaged over size (Table 4). Most single and sequential herbicide treatments reduced sicklepod height similarly (Table 5). The no initial treatment fb dicamba treatment reduced sicklepod height 20% less than many of the sequential herbicide treatments (Table 5). A high correlation between sicklepod control and height reduction was detected ($R = 0.83$; $P < 0.0001$). Dicamba + glufosinate and no initial treatment fb dicamba + glufosinate resulted in additive control of sicklepod (Table 4). Furthermore, dicamba + glufosinate and no initial treatment fb dicamba + glufosinate additively reduced sicklepod height (Table 4).

Discussion

The results of this experiment provide evidence that differential weed control is achieved when glufosinate is applied before dicamba for grass species compared to the broadleaf species. Grass weeds were controlled better when two applications of glufosinate (alone or mixed with dicamba) were applied in sequential herbicide treatments. Additionally, the results of the experiments provide evidence that dicamba + glufosinate mixtures result in additive control, with the exception that goosegrass control was antagonized. While dicamba + glufosinate additively controlled the other tested weed species, this mixture is not labeled and should be not applied or recommended. If dense stands of goosegrass and large crabgrass are present in the field, glufosinate should be applied initially to enhance control. Because glufosinate was not applied at the maximum labeled rate (875 g ai ha^{-1}) in this experiment, the glufosinate rate could be increased to improve grass control. Future research should investigate the interaction between dicamba and glufosinate with varying rates of each for optimal grass and broadleaf weed control. However, across all tested broadleaf species, control never increased compared to the initial glufosinate application. If glufosinate is applied to the weed species at the tested sizes, a sequential application may not be necessary. Although a scheduled sequential application with these herbicides seems unnecessary on the tested weed species and sizes, the sequential treatments could be of great value by reducing selection pressure on a single herbicide group. Though weed size did not predominantly affect control or height reduction, the no initial treatment fb herbicide treatments provided less control for many of the tested weed species. This result further demonstrates that herbicides should be applied in a timely fashion and not delayed.

Dicamba and glufosinate are among the few effective postemergence herbicide options to control herbicide-resistant weeds in cotton and soybean production systems of the southeast United States (Heap 2022). Palmer amaranth has evolved resistance to both dicamba and glufosinate in the United States (Carvalho-Moore et al. 2022; Heap 2022; Priess et al. 2022b). Thus these two unique herbicides should be stewarded to increase the longevity of usefulness instead of continuing the herbicide selection cycle (Comont et al. 2020; Wrubel and Gressel 1994; Young 2006). It is also important to note that glufosinate has no residual activity and that dicamba has minimal residual activity (Altom and Stritzke 1973; Anonymous 2017; Edwards 2013). Thus additional management inputs should be included to control species that exhibit prolonged emergence (Hartzler 2017; Mohler and Callaway 1995; Myers et al. 2004; Reinhardt Piskackova et al. 2020).

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References

Altom JD, Stritzke JF (1973) Degradation of dicamba, picloram, and four phenoxy herbicides in soils. Weed Sci 21:556–560

Anonymous (2017) Liberty® herbicide label. Research Triangle Park, NC: Bayer CropScience. 27 p

Anonymous (2018) Xtendimax® herbicide label. St. Louis, MO: Monsanto. 8 p

Beckie HJ, Harker KN (2017) Our top 10 herbicide-resistant weed management practices. Pest Manag Sci 73:1045–1052

Belz RG, Duke SO (2014) Herbicides and plant hormesis. Pest Manag Sci 70:698–707

Besançon TE, Penner D, Everman WJ (2018) Reduced translocation is associated with antagonism of glyphosate by glufosinate in giant foxtail (*Setaria faberi*) and velvetleaf (*Abutilon theophrasti*). Weed Sci 66:159–167

Blouin DC, Webster EP, Bond JA (2011) On the analysis of combined experiments. Weed Technol 25:165–169

Browne FB, Li X, Price KJ, Langemeier R, Sanz-Saez de Jaureguy A, McElroy S, Feng Y, Price A (2020) Sequential applications of synthetic auxins and glufosinate for escaped Palmer amaranth control. Agronomy 10:1425

Burke IC, Askew SD, Corbett JL, Wilcut JW (2005) Glufosinate antagonizes clethodim control of goosegrass (*Eleusine indica*). Weed Technol 19:664–668

Cahoon CW, York AC, Jordan DL, Everman WJ, Seagroves RW, Culpepper AS, Eure PM (2015) Palmer amaranth (*Amaranthus palmeri*) management in dicamba-resistant cotton. Weed Technol 29:758–770

Canode CL, Robocker WC (1966) Annual weed control in seedling grasses. Weeds 14:306–309

Carvalho-Moore P, Norsworthy JK, González-Torralva F, Hwang J, Patel JD, Barber T, Butts TR, McElroy JS (2022) Unraveling the mechanism of resistance in a glufosinate-resistant Palmer amaranth (*Amaranthus palmeri*) accession. Weed Sci 70:370–379

Coetzer E, Al-Khatib K, Loughin TM (2001) Glufosinate efficacy, absorption, and translocation in amaranth as affected by relative humidity and temperature. Weed Sci 49:8–13

Colby SR (1967) Calculating synergistic and antagonistic responses of herbicide combinations. Weeds 15:20–22

Comont D, Lowe C, Hull R, Crook L, Hicks HL, Onkokesung N, Beffa R, Childs DZ, Edwards R, Freckleton RP, Neve P (2020) Evolution of generalist resistance to herbicide mixtures reveals a trade-off in resistance management. Nat Commun 11:3086

Corbett JL, Askew SD, Thomas WE, Wilcut JW (2004) Weed efficacy evaluations for bromoxynil, glufosinate, glyphosate, pyrithiobac, and sulfosate. Weed Technol 18:443–453

Culpepper AS, York AC, Jordan DL, Corbin FT, Sheldon YS (1999) Basis for antagonism in mixtures of bromoxynil plus quizalofop-P applied to yellow foxtail (*Setaria glauca*). Weed Technol 13:515–519

de Sanctis JHS, Jhala AJ (2021) Interaction of dicamba, fluthiacet-methyl, and glyphosate for control of velvetleaf (*Abutilon theopharsti*) in dicamba/glyphosate-resistant soybean. Weed Technol 35:761–767

Edwards CB (2013) Postemergence and residual control of glyphosate-resistant palmer amaranth (*Amaranthus palmeri*) with dicamba. MS thesis, Mississippi State University. 23 p

Everman WJ, Burke IC, Allen JR, Collins J, Wilcut JW (2007) Weed control and yield with glufosinate-resistant cotton weed management systems. Weed Technol 21:695–701

Flint JL, Barrett M (1989) Antagonism of glyphosate toxicity to johnsongrass (*Sorghum halepense*) by 2,4-D and dicamba. Weed Sci 37:700–705

https://doi.org/10.1017/wet.2022.80 Published online by Cambridge University Press

Green JM (1989) Herbicide antagonism at the whole plant level. Weed Technol 3:217–226
Gressel J (2020) Perspective: present pesticide discovery paradigms promote the evolution of resistance—learn from nature and prioritize multi-target site inhibitor design. Pest Manag Sci 76:421–425
Gressel J, Segel LA (1990) Modelling the effectiveness of herbicide rotations and mixtures as strategies to delay or preclude resistance. Weed Technol 4:186–198
Grossmann K (2009) Auxin herbicides: current status on mechanism and mode of action. Pest Manag Sci 66:113–120
Hammerton JL (1967) Environmental factors and susceptibility to herbicides. Weeds 15:330–336
Hart SE, Wax LM (1996) Dicamba antagonizes grass weed control with imazethapyr by reducing foliar absorption. Weed Technol 10:828–834
Hartzler RG (2017) Dicamba: past, present, and future. Pages 71–76 *in* Proceedings 2017 ICM Conference 29. Ames, IA: ICM.
Heap I (2022) International survey of herbicide resistant weeds. http://www.weedscience.org/. Accessed: June 29, 2022
Hodgskiss CL, Legleiter TR, Young BG, Johnson WG (2020) Effects of herbicide management practices on the weed density and richness in dicamba-resistant cropping systems in Indiana. Weed Sci 69:88–94
Johnston CR, Eure PM, Grey TL, Culpepper AS, Vencill WK (2018) Time of application influences translocation of auxinic herbicides in Palmer amaranth (*Amaranthus palmeri*). Weed Sci 66:4–14
Jones EAL, Cahoon CW, Leon RG, Everman WJ (2022). Surveying stakeholder's perception of glufosinate and use in North Carolina. Weed Technol 36:443–450
Kalina JR, Corkern CB, Shilling DG, Basinger NT, Gret TL (2021) Influence of time of day on dicamba and glyphosate efficacy. Weed Technol 36:21–27
Koger CH, Burke IC, Miller DK, Kendig JA, Reddy KN, Wilcut JW (2007) MSMA antagonizes glyphosate and glufosinate efficacy on broadleaf and grass weeds. Weed Technol 21:159–165
Leon RG, Ferrell JA, Sellers BA (2016) Seed production and control of sicklepod (*Senna obtusifolia*) and pitted morningglory (*Ipomoea lacunosa*) with 2,4-D, dicamba, and glyphosate combinations. Weed Technol 30:76–84
Merchant RM, Sosnoskie LM, Culpepper AS, Steckel LE, York AC, Braxton LB, Ford JC (2013) Weed response to 2,4-D, 2,4-DB, and dicamba applied alone or with glufosinate. J Cotton Sci 17:212–218
Meyer CM, Falco P, Norsworthy JK, Beffa R (2020) Uptake, translocation, and metabolism of glyphosate, glufosinate, and dicamba mixtures in *Echinochloa crus-galli* and *Amaranthus palmeri*. Pest Manag Sci 76:3078–3087
Meyer CM, Norsworthy JK (2019) Influence of weed size on herbicide interactions for Enlist™ and Roundup Ready® Xtend® technologies. Weed Technol 33:569–577
Mohler CL, Callaway MB (1995) Effects of tillage and mulch on weed seed production and seed banks in sweet corn. J Appl Ecol 32:627–639
Moore KJ, Dixon PM (2015) Analysis of combined experiments revisited. Agron J 107:763–771
Mueller TC, Steckel LE (2019) Spray mixture pH as affected by dicamba, glyphosate, and spray additives. Weed Technol 33:547–554
Myers MW, Curran WS, VanGessel MJ, Calvin DD, Mortensen DA, Majek BA, Karsten HD, Roth GW (2004) Predicting weed emergence for eight annual species in the northeastern United States. Weed Sci 52:913–919
Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60:31–62
Oreja FH, Inman MD, Jordan DL, Leon RG (2021) Population growth rates of weed species in response to herbicide programme intensity and their impact on weed community. Weed Res 61:509–518
Ou J, Thompson CR, Stahlman PW, Bloedow N, Jugulam M (2018) Reduced translocation of glyphosate and dicamba in combination contributes to poor control of *Kochia scoparia*: evidence of herbicide antagonism. Sci Rep 8:5330
Pratt D, Kells JJ, Penner D (2003) Substitutes for ammonium sulfate as additives with glyphosate and glufosinate. Weed Technol 17:576–581
Priess GL, Norsworthy JK, Godara N, Mauromoustakos A, Butts TL, Roberts TL, Barber T (2022b) Confirmation of glufosinate-resistant Palmer amaranth and response to other herbicides. Weed Technol 36:368–372
Priess GL, Popp MP, Norsworthy JK, Mauromoustakos A, Roberts TL, Butts TR (2022a) Optimizing weed control using dicamba and glufosinate in eligible crop systems. Weed Technol 36:468–480
Putnam AR, Penner D (1974) Pesticide interactions in higher plants. Pages 73–110 *in* Gunthur FA ed. Residue Reviews. New York, NY: Springer
Reinhardt Piskackova TA, Reberg-Horton SC, Richardson RJ, Jennings KM, Leon RG (2020) Integrating emergence and phenology models to determine windows of action for weed control: a case study using *Senna obtusifolia*. Field Crops Res 258:107959
Richter O, Zwerger P, Bottcher U (2002) Modeling spatiotemporal dynamics of herbicide resistance. Weed Res 42:52–64
Schrage BW (2018). Confirmation and control of glyphosate-, ALS-, and PPO-resistant common ragweed (*Ambrosia artemisiifolia*) in North Carolina. PhD thesis, North Carolina State University. 263 p
Sellers BA, Smeda RJ, Johnson WG (2003) Diurnal fluctuations and leaf angle reduce glufosinate efficacy. Weed Technol 17:302–306
Seng CT, Lun LV, San CT, Sahid IB (2010) Initial report of glufosinate and paraquat multiple resistance that evolved in a biotype of goosegrass (*Eleusine indica*) in Malaysia. Weed Biol Manag 10:229–233
Sikkema PH, Brown L, Shropshire C, Spieser H, Soltani N (2008) Flat fan and air induction nozzles affect soybean herbicide efficacy. Weed Biol Manag 8:31–38
Takano HK, Beffa R, Preston C, Westra P, Dayan FE (2019) Reactive oxygen species trigger the fast action of glufosinate. Planta 249:1837–1849
Tharp BE, Schabenberger O, Kells JJ (1999) Response of annual weed species to glufosinate and glyphosate. Weed Technol 13:542–547
Vann RA, York AC, Cahoon CW, Buck TB, Askew MC, Seagroves RW (2017a) Effect of delayed dicamba plus glufosinate application on Palmer amaranth (*Amaranthus palmeri*) control and XtendFlex™ cotton yield. Weed Technol 31:633–640
Vann RA, York AC, Cahoon CW, Buck TB, Askew MC, Seagroves RW (2017b) Glufosinate plus dicamba for rescue Palmer amaranth control in XtendFlex™ cotton. Weed Technol 31:666–674
Van Wychen L (2017) WSSA survey ranks most common and most troublesome weeds in broadleaf crops, fruits and vegetables. Weed Science Society of America National Weed Survey Dataset. http://wssa.net/wp-content/uploads/2016_Weed_Survey_Final.xlsx. Accessed: June 25, 2022
Webster TM, Nichols RL (2012) Changes in the prevalence of weed species in the major agronomic crops of the Southern United States: 1994/1995 to 2008/2009. Weed Sci 60:145–157
Wrubel RP, Gressel J (1994) Are herbicide mixtures useful for delaying the rapid evolution of resistance? A case study. Weed Technol 8:635–648
Young BG (2006) Changes in herbicide use patterns and production practices resulting from glyphosate-resistant crops. Weed Technol 20:301–307
Zhang C, Yu Q, Han H, Yu C, Nyporko A, Tian X, Beckie H, Powles S (2022) A naturally evolved mutation (Ser59Gly) in glutamine synthetase confers glufosinate resistance in plants. J Exp Bot 73:2251–2262

https://doi.org/10.1017/wet.2022.80 Published online by Cambridge University Press