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Comparison of a premix of atrazine, bicyclopyrone, mesotrione, and *S*-metolachlor with other preemergence herbicides for weed control and corn yield in no-tillage and reduced-tillage production systems in Nebraska, USA

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ABSTRACT

A premix of atrazine, bicyclopyrone, mesotrione, and *S*-metolachlor (ABMS) has recently been registered for broad-spectrum weed control in corn (*Zea mays* L.) in the USA. The objectives of this study were to compare the efficacy of ABMS applied preemergence (PRE) with other commonly used PRE herbicides for weed control, corn injury, and yield in no-tillage (no-till) and reduced-tillage (reduced-till) corn production systems, and to determine the biologically effective doses of ABMS for controlling Palmer amaranth (*Amaranthus palmeri* S. Wats.) in field conditions. Field experiments were conducted in 2015 and 2016 at South Central Agricultural Laboratory, Clay Center, Nebraska, USA. ABMS applied at the labeled dose (2.89 kg ai ha^{-1}) resulted in 92–99% Palmer amaranth control in both tillage systems. A similar level of Palmer amaranth control (86–99%) was observed with mesotrione plus rimsulfuron in the no-till system; however, the control was higher with ABMS than with other premixes in the reduced-till system at 42 days after treatment (DAT) and at harvest. Applications of ABMS at 2.89 kg ai ha^{-1} provided 99 and 81% control of velvetleaf (*Abutilon theophrasti* Medik.) and foxtail (*Setaria* spp.), respectively, in the no-till system at 28 DAT, whereas control was ≥93% in the reduced-till system. ABMS applied at 2.89 kg ai ha^{-1} resulted in 3% corn injury at 14 DAT regardless of the tillage system, whereas 15% corn injury was observed with acetochlor plus clopyralid plus flumetsulam, and dimethenamid-P plus saflufenacil in the reduced-till. ABMS or mesotrione plus rimsulfuron at labeled doses resulted in 16.0–16.3 t ha^{-1} corn yield, comparable to the weed-free control (16.4 t ha^{-1}). The biologically effective doses of ABMS to provide 90% control (ED_{90}) of Palmer amaranth at 42 DAT were 2.44 and 2.81 kg ai ha^{-1} in no-till and reduced-till systems, respectively. The efficacy of ABMS for broadleaf weed control and early-season grass weed control, and corn yield was the same or sometimes better than most of the PRE herbicides tested in this study; therefore, ABMS can be considered as an additional option for management of problem weeds, including Palmer amaranth in corn in the USA.

1. Introduction

The shift from conventional tillage to conservation tillage, including no-tillage (no-till) and reduced-tillage (reduced-till) production systems, had an impact on agricultural practices, specifically on weed management in corn (*Zea mays* L.)-soybean [*Glycine max* (L.) Merr.] cropping systems in the Midwestern United States (Buhler, 1995; Price et al., 2011). Pre-plant conventional tillage aided in higher crop production by minimizing weed interference (Barnes et al., 2017; Ganie et al., 2017); however, the introduction of residual herbicides such as atrazine promoted conservation tillage in the early 1960s (Triplett et al., 1964). Conservation tillage has several environmental and crop production benefits over conventional tillage, including timely establishing crops (Hobbs and Giri, 1997), supplying moisture and nutrients for crop growth (Triplett and Dick, 2008), reducing soil erosion and runoff by dissipating rain drop energy (Gicheru et al., 2004; Zhang et al., 2007), increasing soil aggregate formation and stability, and increasing soil organic matter near the soil surface (Beare et al., 1994; Six et al., 1999). Conservation tillage also requires less fuel and energy input compared to conventional tillage (Frye, 1984). Widespread adoption of conservation tillage began in the United States during the 1980s and was later adopted in Australia, Canada, and several South American countries (Triplett and Dick, 2008). The introduction of glyphosate-resistant crops in 1996 dramatically changed weed control practices: a survey conducted by Givens et al. (2009) in six states including Nebraska reported that after the adoption of

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Table 1
Details of herbicide treatments and doses applied preemergence for broadleaf and grass weed control in glyphosate-resistant corn in field experiments conducted in Nebraska.

Treatment	Dose kg ai ha^{-1}	Trade Name	Manufacturer
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	0.96	Acuron	Syngenta Crop Protection, Inc., Greensboro, NC 27419
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	1.93	Acuron	Syngenta Crop Protec., Inc.
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	2.89	Acuron	Syngenta Crop Protec., Inc.
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	3.86	Acuron	Syngenta Crop Protec., Inc.
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	4.82	Acuron	Syngenta Crop Protec., Inc.
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	5.78	Acuron	Syngenta Crop Protec., Inc.
Atrazine + fluthiacet-methyl + pyroxasulfone	1.26	Anthem ATZ	FMC Corporation, Philadelphia, PA 19103
Atrazine + isoxaflutole + thiencarbazone-methyl	0.50 + 0.10	AAtrex 4L + Corvus	Syngenta Crop Protec., Inc. Bayer CropScience LP, Research Triangle Park, NC 27709
Mesotrione + rimsulfuron	0.19	Instigate	E. I. du Pont de Nemours and Company, Wilmington, DE 19805
Acetochlor + clopyralid + flumetsulam	1.19	Surestart II	Dow AgroSciences LLC, Indianapolis, IN 46268
Dimethenamid-P + saflufenacil	0.78	Verdict	BASF Corporation, Research Triangle Park, NC 27709

glyphosate-resistant crops, 25% and 31% of producers transitioned from conventional tillage to no-till and reduced-till, respectively. By 2015, more than 156 million ha agricultural land was in conservation tillage throughout the world, with the United States as the leading country (70 million ha including no-till area) followed by Brazil and Argentina (FAOSTAT, 2017, USDA-NASS,2012). Nebraska has the second largest area (after Kansas) in no-till crop production of any state in the United States (USDA-NASS, 2012).

Tillage affects the distribution of the weed seedbank, which overall impacts weed emergence. Yenish et al. (1992) noted that no-till and reduced-till (chisel plowing) left 60% and 30% of weed seeds in the upper 1 cm soil layer, respectively, compared with conventional tillage, where seeds were distributed uniformly throughout the top 19 cm. Different types of tillage practices, including no-till, can alter the dynamics of the weed population (Buhler, 1995); Clements et al. (1994) described that the changes in tillage operations influenced weed species diversity. Widespread adoption of no-till and reduced-till systems aided in the weed population shift towards small-seeded broadleaves [such as common waterhemp (*Amaranthus rudis* Sauer) and Palmer amaranth (*Amaranthus palmeri* S. Wats.)], grasses [such as foxtail (*Setaria* spp.)], and perennial weeds such as Canada thistle [*Cirsium arvense* (L.) Scop.], dandelion (*Taraxacum officinale* G.H. Weber ex Wiggers), and field bindweed (*Convolvulus arvensis* L.) (Buhler, 1995; Costea et al., 2005; Felix and Owen, 1999; Price et al., 2011; Shrestha et al., 2006).

Palmer amaranth is a summer annual weed native to the Southwestern United States (Sauer, 1957). A recent survey by the Weed Science Society of America listed Palmer amaranth as the topmost troublesome weed in the United States (Van Wychen, 2016). Palmer amaranth is also considered the most problematic weed in cotton (*Gossypium hirsutum* L.), corn, and soybean in the southern United States (Price et al., 2011; Prince et al., 2012), and the infestation is becoming more common in Midwestern states, including Nebraska (Chahal et al., 2015; Jhala et al., 2014b). It is a highly competitive weed and can compete with crops for resources such as light, water, and nutrients (Massinga et al., 2003). Massinga et al. (2001) reported that Palmer amaranth emerging with corn reduced yield 91% at a density of 8 plants m^{-1} row. It is an erect plant growing up to 2 m tall, and a single female plant can produce 200,000–600,000 seeds, resulting in the quick establishment of a soil seed bank (Keeley et al., 1987; Legleiter and Johnson, 2013).

The widespread adoption of glyphosate-resistant crops and subsequent multiple applications of glyphosate resulted in high selection pressure, promoting the rapid evolution of glyphosate-resistant weeds. Glyphosate-resistant Palmer amaranth has been reported in 27 states in the United States, along with several cases of multiple herbicide resistance (Heap, 2017). Palmer amaranth has also evolved resistance to five other modes of action, including acetolactate synthase (ALS)-, microtubule-, photosystem (PS) II-, protoporphyrinogen oxidase (PPO)-, and 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibitors (Chahal et al., 2015; Heap, 2017). Palmer amaranth resistant to HPPD, PS-II, and glyphosate has already been confirmed in Nebraska with two discrete population showing multiple resistance (Chahal et al., 2017; Jhala et al., 2014b).

Herbicides play a significant role in weed management in conservation tillage systems. Acuron® (Syngenta Crop Protection, LLC, Greensboro, NC 27419) is a new herbicide premix labeled for controlling broadleaf and grass weed species in corn in the United States (Anonymous, 2016). It contains four active ingredients from three modes of action [atrazine (PS II-), bicyclopyrone (HPPD-), mesotrione (HPPD-), and *S*-metolachlor (very long-chain fatty acid-inhibitor)] plus a crop safener, benoxacor; thereafter abbreviated as “ABMS”. This is the first bicyclopyrone-containing herbicide available in the marketplace. Previously, several premixes containing at least two of the following components: atrazine, mesotrione, and *S*-metolachlor, have been studied to determine their weed-control efficacy in corn (Dobbels and Kapusta, 1993; Ferrell and Witt, 2002; Johnson et al., 2002; Taylor-Lovell and Wax, 2001); however, limited literature is available on the efficacy of a premix containing the aforementioned three components and bicyclopyrone (Kohrt and Sprague, 2017; Sarangi and Jhala, 2017a). Herbicide active ingredients from a new mode of action have not been commercialized in corn since the 1990s (Duke, 2012); therefore, the use of herbicide premixes, combining existing active ingredients are becoming important tool for the weed control in no-till and reduced-till production systems (Beckie, 2006; Beckie and Reboud, 2009; Owen, 2016).

Although the application of the preemergence (PRE) herbicides (especially atrazine and/or HPPD inhibitor) is common in corn (USDA-NASS, 2015), it is important to compare the efficacy of newly commercialized herbicide premixtures with commonly used PRE herbicides in corn for broad-spectrum weed management. In this study, the efficacy of ABMS was compared with five commonly used PRE herbicides by Nebraska corn growers (Table 1). The duration of residual activities of PRE herbicides can be altered by soil disturbances, or by plant residue present on the soil surface (Bauman and Ross, 1983; Curran et al., 1992; Johnson et al., 1989). Scientific literature is not available on the efficacy of ABMS compared with commonly used PRE herbicides in no-till and reduced-till corn production systems. Additionally, Devlin et al. (1991) mentioned that the recommended doses of herbicides are usually set high, or sometimes within a range so they will work on a broad range of weed species in different environmental conditions. As this premix is new for the corn growers, it is also important to determine the biologically effective doses to control problem weeds such as Palmer amaranth. The objectives of this research were to 1) evaluate the efficacy of ABMS for control of broadleaf and grass weeds in no-till and reduced-till production systems compared with commonly used corn herbicides applied PRE, along with their effect on corn injury and yield, and 2) determine the biologically effective doses of ABMS applied PRE for Palmer amaranth control in field conditions.

2. Materials and methods

2.1. Study site and soil

Field experiments were conducted at the South Central Agricultural Laboratory, University of Nebraska-Lincoln near Clay Center, NE (40.57°N, 98.14°W) in 2015 and 2016. The most common weed species at the experimental site were Palmer amaranth, velvetleaf (*Abutilon theophrasti* Medik.), and foxtails. Among the foxtails, green foxtail [*Setaria viridis* (L.) Beauv.] and yellow foxtail [*Setaria pumila* (Poir.) Roemer & J.A. Schultes] were the major species present, and here they are grouped as "foxtail." No herbicide resistance, apart from ALS inhibitor resistance in *Amaranthus* sp., has been reported at this site. Thus, a natural seedbank of Palmer amaranth and other summer annuals was used in this study to evaluate the efficacy of PRE herbicides for broad-spectrum weed control in no-till and reduced-till production systems. The soil texture at the experimental site was Crete silt loam (montmorillonitic, mesic, Pachic Argiustolls) with a pH of 6.5, 17% sand, 58% silt, 25% clay, and 3% organic matter.

2.2. Treatments and plots

Treatments were arranged in a two-by-thirteen factorial arrangement in a randomized complete block design with four replications, where the treatment factors were tillage types (no-till and reduced-till) and PRE herbicide (Table 1). A nontreated control and a weed-free control were included for comparison. The weed-free control plots were kept clean (no weeds) with a pre-plant application of *S*-metolachlor (Dual II Magnum,® Syngenta Crop Protection, LLC, Greensboro, NC 27419; at 1.42 kg ai ha^{-1}) plus glyphosate (Roundup® PowerMAX, Monsanto Company, St. Louis, MO 63167; at 0.87 kg ae ha^{-1}) plus ammonium sulfate (N-Pak® AMS Liquid, Winfield Solutions, LLC, St. Paul, MN 55164; at 5% v/v), and a late-postemergence (POST) application of dicamba plus tembotrione (DiFlexx® DUO, Bayer CropScience LP, Research Triangle Park, NC 27709; at 0.53 kg ae ha^{-1}) plus crop oil concentrate (Agri-Dex®, Helena Chemical Company, Collierville, TN 38017; at 1% v/v) plus ammonium sulfate at 5% v/v, using drop nozzles to avoid corn injury. Reduced-till treatment was accomplished by a single pass of vertical tillage using a tandem disk harrow (< 10 cm deep) 4–5 d prior to corn planting. At that time, the no-till plots received a burndown herbicide application of paraquat (Gramoxone® SL, Syngenta Crop Protection, LLC, Greensboro, NC 24719; at 0.84 kg ai ha^{-1}) plus nonionic surfactant (Induce®, Helena Chemical Company, Collierville, TN 38017; at 0.25% v/v). PRE treatments included six doses (0.3×, 0.7×, 1×, 1.3×, 1.7×, and 2×, where 1× = labeled dose, i.e., 2.89 kg ai ha^{-1} for 3% organic matter) of ABMS; therefore, a dose-response bioassay was also conducted on Palmer amaranth. Additional herbicide treatments included selected registered corn herbicides applied at their labeled doses (Table 1).

Experimental plots were 9 m long and 3 m wide and glyphosate-resistant corn was seeded at 78,300 seeds ha^{-1} in rows spaced 76 cm apart on May 13, 2015, and May 18, 2016. The experimental site was fertilized with 11-52-0 fertilizer at 112 kg ha^{-1}, plus an additional 202 kg ha^{-1} of nitrogen in the form of anhydrous ammonia applied early spring. Herbicides were applied PRE on the day following corn planting using a handheld CO_2-pressurized backpack sprayer equipped with AIXR 110015 flat fan nozzles (TeeJet® Technologies, Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60187) calibrated to deliver 140 L ha^{-1} at 276 kPa at a constant speed of 4.8 km h^{-1}.

2.3. Data collection

Control of Palmer amaranth, velvetleaf, and foxtail was assessed visually at 14, 28, 42, 70 days after PRE herbicide treatment (DAT), and at corn harvest on a scale of 0 to 100%, with 0% meaning no control and 100% meaning complete control/death. Weed densities were recorded by counting the number of plants in two 0.25 m^2 quadrats placed randomly between the two center corn rows in each plot, and are presented as the weeds m^{-2}. Aboveground biomass was measured only for Palmer amaranth, as it was the dominant weed species among the three-aforementioned species at the research site. At 70 DAT, Palmer amaranth plants surviving the PRE treatments were cut at the soil surface from two randomly selected 0.25 m^2 65 °C for five days. Percent aboveground biomass reduction was calculated using the equation (Sarangi et al., 2017):

$$\text{Aboveground biomass reduction (\%)} = [(C - B)/C] \times 100 \quad (1)$$

where C is the aboveground biomass of the nontreated control plot and B is the biomass of an individual treated plot.

Corn injury due to herbicide application was evaluated at 14 and 28 DAT. The injury was assessed visually on a 0 to 100% scale (0% meaning no injury, and 100% meaning total plant death) based on leaf tissue bleaching, chlorosis and necrosis, malformation of leaves, and plant stunting. Plant stand data were recorded at 14 and 28 DAT from two randomly selected 1 m rows from the center two corn rows in each plot. Corn was harvested from the two center rows in each plot using a plot combine and grain yield was adjusted to 15.5% moisture and converted in t ha^{-1}.

2.4. Statistical analysis

Data were subjected to ANOVA using PROC GLIMMIX in SAS version 9.3 (SAS Institute Inc, Cary, NC). Year, replication (nested within years), and all interactions containing either of these effects were considered random effects. Other variables such as herbicide treatments and tillage were considered fixed effects in the model. Percent weed control and aboveground biomass reduction data for the nontreated and weed-free control were excluded from the analysis, as the values were 0% and 100%, respectively. Similarly, crop injury ratings for those two treatments were also excluded from the analysis, as no injury was recorded. Normality and homogeneity of variance were tested using PROC UNIVARIATE in SAS. To satisfy the assumptions of ANOVA, percent weed control, aboveground biomass reduction, and corn injury data were arcsine square root transformed before analysis; however, back-transformed data are presented with mean separation based on the transformed data. Treatment means were separated using Fisher's protected LSD at a 5% level of significance. To compare the two tillage systems (no-till vs. reduced-till), *a priori* orthogonal contrasts (single degree of freedom contrasts) were performed for the control and density of Palmer amaranth, velvetleaf, and foxtail. The treatments including only the labeled dose of the premixes were included in the contrast analysis.

2.5. Dose-response bioassay analysis

A four-parameter log-logistic function (Equation (2)) was used to regress the Palmer amaranth control and aboveground biomass reduction against the doses of ABMS using the package *drc* in R (R Core Team, 2016). Dose-response models were constructed to evaluate the effect of tillage systems on Palmer amaranth control and aboveground biomass reduction, where a relatively simpler model (not considering tillage as a factor) was compared with a complex model (considering tillage as a factor) using the ANOVA method (approximate F-test).

The biologically effective doses to control (or reduce aboveground biomass of) Palmer amaranth by 50 and 90% (ED_{50} and ED_{90}) were determined using the equation (Knezevic et al., 2007):

$$Y = c + \{d - c/1 + exp[b(\log x - \log e)]\} \quad (2)$$

where Y is the response variable (percent control or reduction in the aboveground biomass); x is the premix dose; c and d are the lower limit (which was set to 0) and estimated maximum values of Y, respectively;

and e represents the herbicide dose resulting in 50% of d (i.e., ED_{50}). The parameter b is the relative slope around the parameter e. In the final model, d, b, and e varied with the tillage types.

2.6. Model goodness-of-fit

Estimation of R^2 is not an adequate measure for nonlinear regression. [Equation (2)], as R^2 is extremely biased to highly parametrized models (Spiess and Neumeyer, 2010). Therefore, Sarangi et al. (2016) suggested that goodness-of-fit parameters, such as root-mean-square error (RMSE) and model efficiency coefficient (EF) need to be evaluated for a nonlinear function. The goodness-of-fit parameters were calculated using the equation:

$$\text{RMSE} = \left[\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2\right]^{1/2} \quad (3)$$

$$\text{EF} = 1 - \left[\sum_{i=1}^{n}(O_i - P_i)^2 / \sum_{i=1}^{n}(O_i - \bar{O}_i)^2\right] \quad (4)$$

where P_i is the predicted value, O_i is the observed value, $\bar{O}_i$ is the mean observed value, and n is the total number of observations. A smaller RMSE value means better model fit, and an EF value (which is different from R^2 by EF having a lower bound) closer to 1.00 means a more accurate prediction.

3. Results and discussion

A significant interaction ($P < .05$) was observed between tillage and herbicide treatments for weed control, density, and biomass reduction; therefore, data were presented separately for the no-till and reduced-till production systems combined across years. In reduced-till, 30–35% of surface residue (crop residue from previous cropping season) was left after planting. Rainfall within a month after PRE applications was sufficient for the activity of the soil-applied residual herbicides (Table 2).

3.1. Palmer amaranth control, density, and biomass reduction

3.1.1. No-tillage system

ABMS applied at ≥0.96 kg ai ha^{-1} provided 99% control of Palmer amaranth at 14 DAT, which was comparable with other herbicide treatments except for acetochlor plus clopyralid plus flumetsulam (Table 3). Literature suggested that the efficacy of acetochlor plus clopyralid plus flumetsulam may vary depending on the environment and weed species present. For example, Owen et al. (2016) listed the premix of acetochlor plus clopyralid plus flumetsulam as one of the most effective PRE options (98% control) for the control of common waterhemp (a closely related species of Palmer amaranth), velvetleaf, and giant foxtail in corn in Northeast Iowa. Similarly, Oliveira et al. (2017) reported that PRE application of acetochlor plus clopyralid plus flumetsulam resulted in 93 and 85% control of HPPD-inhibiting herbicide-resistant common waterhemp at 30 and 41 DAT, respectively, in Nebraska, but the same premix provided only 23–66% control of kochia [*Kochia scoparia* (L.) Schrad.] in Montana (Kumar and Jha, 2015).

ABMS applied at ≥1.93 kg ai ha^{-1} resulted in ≥96% control of Palmer amaranth at 28 DAT (Table 3). Reduction in the residual activity of the premixes reduced Palmer amaranth control from 28 DAT to 42 DAT: for example, ABMS applied at 2.89 kg ai ha^{-1} provided 94% control at 42 DAT compared to 98% control at 28 DAT. In this study, atrazine plus fluthiacet-methyl plus pyroxasulfone, mesotrione plus rimsulfuron, and dimethenamid-P plus saflufenacil showed 86–90% control of Palmer amaranth at 42 DAT and reduced weed density to 9–13 plants m^{-2} (vs. 58 plants m^{-2} in nontreated control), which was similar to the ABMS applied at 2.89 kg ai ha^{-1} (Table 3). At harvest, ABMS applied at 2.89 kg ai ha^{-1} resulted in 93% control of Palmer amaranth, comparable with mesotrione plus rimsulfuron (86% control). Similarly, Sarangi and Jhala, 2017b) reported that the PRE application of ABMS at the labeled dose in no-till conditions provided 88–91% control of glyphosate-resistant horseweed [*Conyza canadensis* (L.) Cronq.] up to 63 DAT, with 90% reduction in the aboveground biomass.

Results of biomass reduction were consistent with the aforementioned Palmer amaranth control and density data. ABMS at the labeled dose (2.89 kg ai ha^{-1}) resulted in 94% reduction in Palmer amaranth aboveground biomass, which was similar to the biomass reduction with atrazine plus fluthiacet-methyl plus pyroxasulfone, mesotrione plus rimsulfuron, and dimethenamid-P plus saflufenacil (Table 3). Janak and Grichar (2016) reported that PRE application of mesotrione plus rimsulfuron, or dimethenamid-P plus saflufenacil resulted in a similar level of Palmer amaranth control to ABMS, though their efficacy varied with the location. Oliveira et al. (2017) reported that PRE application of atrazine plus fluthiacet-methyl plus pyroxasulfone resulted in 92% control of HPPD-inhibiting herbicide-resistant common waterhemp at 56 DAT, and the results were comparable to dimethenamid-P plus saflufenacil, and atrazine plus mesotrione plus *S*-metolachlor plus acetochlor.

3.1.2. Reduced-tillage system

ABMS applied at 2.89 kg ai ha^{-1} resulted in 99% control of Palmer amaranth at 14 DAT, which was similar to other treatments in the reduced-till (Table 4). All herbicide treatments at 14 DAT reduced Palmer amaranth density up to 2 plants m^{-2} compared with the nontreated control (57 plants m^{-2}). ABMS applied at 2.89 kg ai ha^{-1} provided 98% control at 28 DAT, comparable with mesotrione plus rimsulfuron (94%). Application of ABMS at the labeled dose resulted in 94 and 92% control of Palmer amaranth at 42 DAT and at harvest, respectively, with an 88% reduction in the density (9 plant vs. 77 plant m^{-2} in the nontreated control) at 42 DAT. ABMS applied at 2.89 kg ai ha^{-1} reduced aboveground biomass by 94% in this study, whereas a similar level of aboveground biomass reduction was observed with mesotrione plus rimsulfuron (Table 4). A field experiment conducted in reduced-till production system in Michigan, Kohrt and Sprague (2017) reported that the PRE application of ABMS at labeled dose provided 90–93% control of multiple herbicide-resistant (glyphosate-, ALS inhibitor-, and PS II inhibitor- resistant) Palmer amaranth up to 72 DAT, with 86% reduction in the aboveground biomass. Similarly, Sarangi and Jhala, 2017a) showed that in reduced-till, PRE application of ABMS at the labeled dose resulted in 91% control of common waterhemp at 63 DAT, reducing density by 90% compared to the nontreated control.

The contrast analysis revealed that Palmer amaranth control and biomass reduction was not affected by tillage systems when averaged across treatments, including ABMS at the labeled dose (data for Palmer amaranth control at harvest and biomass reduction not shown in Table 7). On the contrary, Palmer amaranth density was lower (13 plants m^{-2}) in the no-till system compared to the reduced-till system (19 plants m^{-2}) at 42 DAT. ABMS applied at the labeled dose showed a

Table 2
Average air temperature and total precipitation during the 2015 and 2016 growing seasons and the 30 yr average at the experiment site in Nebraska.[a]

Timing[b]	Average temperature			Total precipitation		
	2015	2016	30 yr average	2015	2016	30 yr average
	°C			mm		
1 to 10 DAT	13.7	18.5	–	20.8	49.3	–
11 to 20 DAT	18.7	20.9	–	11.9	33.0	–
21 to 30 DAT	23.0	27.4	–	171.7	3.8	–
31 to 60 DAT	23.0	24.5	–	80.0	38.9	–
May to October	20.2	20.5	19.3	581.9	406.7	540.5
Annual	11.8	12.2	10.3	795.5	623.8	717.0

[a] Air temperature and precipitation data were obtained from HPRCC, the High Plains Regional Climate Center (2017).
[b] Abbreviation: DAT, days after preemergence herbicide treatment.

Table 3
Palmer amaranth control, density, and aboveground biomass reduction as affected by preemergence applications of the premix of atrazine, bicyclopyrone, mesotrione, and *S*-metolachlor and several other commonly used premixes in no-tillage corn in field experiments conducted in Nebraska.[a,b]

Treatment	Dose	Palmer amaranth control[c,d]				Palmer amaranth density[d]		Biomass reduction[c,d]
		14 DAT	28 DAT	42 DAT	At harvest	14 DAT	42 DAT	
	kg ai ha^{-1}	%				#pl m^{-2}		%
Nontreated control	–	0	0	0	0	19 a	58 a	0
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	0.96	99 a	92 bc	73 de	65 e	0 c	22 b	68 d
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	1.93	99 a	96 ab	82 cd	74 de	0 c	12 cd	80 cd
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	2.89	99 a	98 a	94 ab	93 bc	0 c	6 de	94 ab
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	3.86	99 a	98 a	97 a	95 ab	0 c	5 de	99 a
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	4.82	99 a	99 a	98 a	97 ab	0 c	2 e	99 a
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	5.78	99 a	99 a	98 a	98 a	0 c	2 e	98 a
Atrazine + fluthiacet-methyl + pyroxasulfone	1.26	99 a	93 bc	90 bc	80 d	0 c	10 cde	87 bc
Atrazine + isoxaflutole + thiencarbazone-methyl	0.50 + 0.10	99 a	91 c	84 c	82 d	0 c	13 c	82 c
Mesotrione + rimsulfuron	0.19	99 a	93 bc	87 bc	86 cd	0 c	9 cde	85 bc
Acetochlor + clopyralid + flumetsulam	1.19	93 b	75 d	67 e	66 e	7 b	24 b	66 d
Dimethenamid-P + saflufenacil	0.78	99 a	91 c	86 bc	82 d	1 c	13 c	88 bc
P-value		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

[a] Abbreviation: DAT, days after preemergence herbicide treatment.
[b] Data presented in this table were pooled across the years (2015 and 2016).
[c] Data were arc-sine square-root transformed before analysis; however, back-transformed original mean values are presented based on the interpretation of the transformed data.
[d] Means presented within each column with no common letter(s) are significantly different according to Fisher's protected LSD where α = 0.05.

similar level of control regardless of the tillage system; however, the efficacy of other premixes differed with the tillage system, believed to lead to the significant interaction between tillage and herbicide treatments (Tables 3 and 4). For example, dimethenamid-P plus saflufenacil provided 86 and 82% control at 42 DAT and at harvest, respectively, in no-till system, whereas control was estimated 79 and 73% at the same time in reduced-till. In evaluating corn premixes, Janak and Grichar (2016) mentioned that the performance of the premixes (applied PRE) may vary with the environmental conditions, weed density, and species composition; for example, the same study reported that PRE application of ABMS at labeled dose provided 99% control of Palmer amaranth at one location at 101 DAT, whereas the control estimate was 72% at another location at 44 DAT.

Performing shallow tillage (< 10 cm deep) in the reduced-till system possibly increased the soil aeration and elevated the soil temperature compared to the no-till, which may have promoted the emergence of Palmer amaranth in the reduced-till system. Lal (1976) reported that soil temperatures measured at the 5-cm depth were higher in conventional tillage compared to no-till, which led to more weed pressure in tillage conditions. Similarly, Leon and Owen (2006) reported that tillage increased soil temperature by at least 2–4 °C compared to no-till, and the temperature fluctuations were more frequent in plots receiving tillage. In accordance with the report of Steckel et al. (2004) that alternating temperatures can stimulate Palmer amaranth emergence more than a constant temperature, in our study, the change in soil microclimate in reduced-till along with better soil-seed contact are believed to stimulate more Palmer amaranth emergence than no-till. On the contrary, Farmer et al. (2017), and Jha and Norsworthy (2009) reported that tillage systems (no-till vs. reduced-till) had no effect on the cumulative emergence of *Amaranthus* sp., including Palmer amaranth.

3.2. Velvetleaf control and density

3.2.1. No-tillage system

ABMS applied at the labeled dose (2.89 kg ai ha^{-1}) resulted in 99% control of velvetleaf at 14 DAT, which was comparable to the control obtained with other premixes with the exception of acetochlor plus

Table 4
Palmer amaranth control, density, and aboveground biomass reduction as affected by preemergence applications of the premix of atrazine, bicyclopyrone, mesotrione, and *S*-metolachlor and several other commonly used premixes in reduced-tillage corn in field experiments conducted in Nebraska.[a,b]

Treatment	Dose	Palmer amaranth control[c,d]				Palmer amaranth density[d]		Biomass reduction[c,d]
		14 DAT	28 DAT	42 DAT	At harvest	14 DAT	42 DAT	
	kg ai ha^{-1}	%				#pl m^{-2}		%
Nontreated control	–	0	0	0	0	57 a	77 a	0
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	0.96	97 b	82 de	64 d	51 f	2 b	29 bc	64 e
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	1.93	99 a	93 c	79 c	68 e	0 b	25 bcd	75 cde
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	2.89	99 a	98 ab	94 b	92 b	1 b	9 cde	94 ab
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	3.86	99 a	97 ab	96 ab	96 ab	0 b	6 de	99 a
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	4.82	99 a	97 ab	96 ab	96 ab	0 b	5 de	98 a
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	5.78	99 a	99 a	98 a	98 a	0 b	1 e	99 a
Atrazine + fluthiacet-methyl + pyroxasulfone	1.26	98 ab	89 cd	82 c	79 cd	2 b	22 bcde	79 cde
Atrazine + isoxaflutole + thiencarbazone-methyl	0.50 + 0.10	98 ab	90 c	84 c	80 cd	1 b	18 bcde	81 cd
Mesotrione + rimsulfuron	0.19	98 ab	94 bc	87 c	84 c	1 b	13 bcde	85 bc
Acetochlor + clopyralid + flumetsulam	1.19	99 a	79 e	70 d	63 e	1 b	32 b	69 de
Dimethenamid-P + saflufenacil	0.78	99 a	91 c	79 c	73 de	0 b	17 bcde	79 cde
P-value		0.03	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

[a] Abbreviation: DAT, days after preemergence herbicide treatment.
[b] Data presented in this table were pooled across the years (2015 and 2016).
[c] Data were arc-sine square-root transformed before analysis; however, back-transformed original mean values are presented based on the interpretation of the transformed data.
[d] Means presented within each column with no common letter(s) are significantly different according to Fisher's protected LSD where α = 0.05.

Table 5
Velvetleaf and foxtail control and density as affected by preemergence applications of the premix of atrazine, bicyclopyrone, mesotrione, and *S*-metolachlor and several other commonly used premixes in no-tillage corn in field experiments conducted in Nebraska.[a,b]

Treatment	Dose	Velvetleaf control[c,d]			Velvetleaf density[d]	Foxtail control[c,d]			Foxtail density[d]
		14 DAT	28 DAT	42 DAT	42 DAT	14 DAT	28 DAT	42 DAT	42 DAT
	kg ai ha^{-1}		%		#pl m^{-2}		%		#pl m^{-2}
Nontreated control	–	0	0	0	30 a	0	0	0	41 a
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	0.96	95 a	93 b	90 b	9 bc	65 e	53 f	43 e	28 bc
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	1.93	99 a	96 ab	91 b	9 bc	84 cde	71 def	63 d	25 bc
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	2.89	99 a	99 a	98 a	1 e	90 abc	81 cd	71 d	19 cd
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	3.86	99 a	99 a	98 a	2 de	95 abc	87 bcd	80 bcd	10 def
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	4.82	99 a	99 a	98 a	1 e	98 ab	96 ab	92 ab	5 ef
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	5.78	99 a	99 a	98 a	1 e	99 a	99a	97 a	2 f
Atrazine + fluthiacet-methyl + pyroxasulfone	1.26	97 a	90 b	85 b	12 bc	89 bcd	74 de	63 d	21 cd
Atrazine + isoxaflutole + thiencarbazone-methyl	0.50 + 0.10	96 a	92 b	89 b	6 cde	92 abc	82 cd	75 cd	17 cde
Mesotrione + rimsulfuron	0.19	96 a	93 b	92 ab	6 cde	99 a	94 abc	89 abc	11 def
Acetochlor + clopyralid + flumetsulam	1.19	81 b	74 c	70 c	14 b	72 de	57 ef	36 e	33 ab
Dimethenamid-P + saflufenacil	0.78	97 a	95 ab	93 ab	6 cde	92 abc	82 cd	68 d	16 cde
P-value		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

[a] Abbreviation: DAT, days after preemergence herbicide treatment.
[b] Data presented in this table were pooled across the years (2015 and 2016).
[c] Data were arc-sine square-root transformed before analysis; however, back-transformed original mean values are presented based on the interpretation of the transformed data.
[d] Means presented within each column with no common letter(s) are significantly different according to Fisher's protected LSD where α = 0.05.

clopyralid plus flumetsulum (81% control) (Table 5). ABMS at ≥1.93 kg ai ha^{-1} (0.7 × dose) provided 96–99% control of velvetleaf at 28 DAT, which was comparable to dimethenamid-P plus saflufenacil (95% control). ABMS applied at the labeled dose, mesotrione plus rimsulfuron, or dimethenamid-P plus saflufenacil resulted in ≥92% control of velvetleaf at 42 DAT, reducing density to ≤6 plants m^{-2} compared to the nontreated control (30 plants m^{-2}). In the field trials conducted in Minnesota and Wisconsin, Bollman et al. (2008) reported that PRE application of atrazine plus mesotrione plus *S*-metolachlor at 0.84 + 0.23 + 2.25 kg ai ha^{-1} resulted in ≥98% control of velvetleaf at 35 DAT.

3.2.2. Reduced-tillage system

Velvetleaf control at 14 DAT in reduced-till varied slightly from the no-till system. ABMS applied at the labeled dose (2.89 kg ai ha^{-1}) provided 97% control of velvetleaf at 14 DAT, comparable to velvetleaf control obtained with atrazine plus isoxaflutole plus thiencarbazone-methyl, mesotrione plus rimsulfuron, and dimethenamid-P plus saflufenacil (Table 6). Similarly, Schuster et al. (2008) showed that application of mesotrione plus rimsulfuron at the labeled dose resulted in 99% control of velvetleaf at 21 DAT. However, Miller et al. (2012) reported that PRE applications of dimethenamid-P plus saflufenacil at 0.13 to 0.91 kg ai ha^{-1} provided 80% control of velvetleaf at 14 DAT in Ontario, Canada.

Reduction in the residual activities of ABMS (applied at the labeled dose) reduced velvetleaf control from 94% at 28 DAT to 83% at 42 DAT. Likewise, Stephenson et al. (2004) reported that PRE application of atrazine plus *S*-metolachlor in conventional tillage provided 92 and 87% control of velvetleaf at 28 and 42 DAT, respectively. ABMS at 2.89 kg ai ha^{-1} reduced velvetleaf density to 9 plants m^{-2} at 42 DAT compared with 41 plants m^{-2} in the nontreated control (Table 6). However, applications of atrazine plus isoxaflutole plus thiencarbazone-methyl, and mesotrione plus rimsulfuron resulted in similar levels of velvetleaf control (85%) and density (≤13 plants m^{-2}) at 42 DAT compared to ABMS applied at the labeled dose.

A priori orthogonal contrasts analysis showed that velvetleaf control (88 vs. 77% in no-till vs. reduced-till, respectively) and density (8 vs. 16 plants m^{-2} in no-till vs. reduced-till, respectively) at 42 DAT differed in both tillage systems. It has been reported that velvetleaf seedlings germinating from the soil surface had a lower percentage of survival (Buhler and Daniel, 1988; Mester and Buhler, 1991); therefore, velvetleaf germination can be relatively higher in reduced-till systems compared to no-till.

3.3. Foxtail control and density

3.3.1. No-tillage system

ABMS applied at the labeled dose (2.89 kg ai ha^{-1}) resulted in 90% and 81% control of foxtail at 14 and 28 DAT, respectively, comparable with the other herbicides tested (≥89% and ≥74% control at 14 and 28 DAT, respectively) in this study, except for acetochlor plus clopyralid plus flumetsulam (Table 5). Bollman et al. (2008) reported that PRE application of atrazine plus mesotrione plus *S*-metolachlor resulted in 84–100% control of giant foxtail (*Setaria faberi* Herrm.) at 35 DAT. Similarly, Currie and Geier (2015) mentioned that ABMS plus atrazine applied PRE, followed by glyphosate as POST provided 99% control of green foxtail at 104 days after planting. Mesotrione plus rimsulfuron resulted in 89% control of foxtail at 42 DAT compared to 71% control with the labeled dose of ABMS; however, foxtail densities were similar (11 and 19 plants m^{-2} with mesotrione plus rimsulfuron, and ABMS, respectively) (Table 5).

3.3.2. Reduced-tillage system

The labeled dose of ABMS provided a similar level of foxtail control (≥90%) at 14 DAT as the other herbicide treatments. ABMS applied at 2.89 kg ai ha^{-1} (1 × dose) resulted in 93 and 88% control of foxtail at 28 and 42 DAT, respectively, which was similar to the control (≥86% at 28 DAT, and ≥79% at 42 DAT) obtained with mesotrione plus rimsulfuron, and acetochlor plus clopyralid plus flumetsulam (Table 6).

Contrast analysis showed that foxtail control at 28 and 42 DAT differed in both tillage systems (Table 7). Averaged across the labeled doses of premixes, foxtail control at 28 and 42 DAT was 78 and 67%, respectively, in no-till condition, compared to the 86 and 79%, respectively, in reduced-till. A relatively lower foxtail density (14 plants m^{-2}) was observed with reduced-till compared to the no-till system (20 plants m^{-2}) at 42 DAT. In a long-term integrated pest management study, Schreiber (1992) noted the increase in giant foxtail densities in no-till management compared to reduced- or conventional-tillage systems. In a field experiment conducted in Wisconsin, Buhler and Daniel (1988) reported that the giant foxtail density was similar at all observation dates in no-till and reduced-till systems with the exception of 14 and 77 days after corn planting, where densities were higher in no-till.

Table 6
Velvetleaf and foxtail control and density as affected by preemergence applications of the premix of atrazine, bicyclopyrone, mesotrione, and *S*-metolachlor and several other commonly used premixes in reduced-tillage corn in field experiments conducted in Nebraska.[a,b]

Treatment	Dose	Velvetleaf control[c,d]			Velvetleaf density[d]	Foxtail control[c,d]			Foxtail density[d]
		14 DAT	28 DAT	42 DAT	42 DAT	14 DAT	28 DAT	42 DAT	42 DAT
	kg ai ha^{-1}		%		#pl m^{-2}		%		#pl m^{-2}
Nontreated control	–	0	0	0	41 a	0	0	0	45 a
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	0.96	93 cd	81 ef	71 de	17 bc	83 d	67 d	50 e	28 b
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	1.93	95 bc	87 d	75 d	17 bc	92 c	81 c	76 d	14 cde
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	2.89	97 ab	94 bc	83 c	9 de	96 abc	93 ab	88 bc	9 defg
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	3.86	98 a	98 a	92 ab	5 ef	98 ab	96 a	93 ab	3 fg
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	4.82	97 ab	97 ab	89 bc	8 def	98 ab	95 a	91 ab	5 efg
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	5.78	99 a	99 a	97 a	3 f	99 a	97 a	96 a	2 g
Atrazine + fluthiacet-methyl + pyroxasulfone	1.26	86 e	78 f	65 e	22 b	92 c	82 c	73 d	20 bc
Atrazine + isoxaflutole + thiencarbazone-methyl	0.50 + 0.10	95 bc	93 c	85 c	10 de	90 cd	84 c	76 d	15 cd
Mesotrione + rimsulfuron	0.19	97 ab	91 cd	85 c	13 cd	95 bc	89 bc	81 cd	13 cde
Acetochlor + clopyralid + flumetsulam	1.19	89 de	79 ef	68 de	22 b	95 bc	86 bc	79 cd	12 cdef
Dimethenamid-P + saflufenacil	0.78	98 a	86 de	74 de	17 bc	94 bc	82 c	75 d	14 cde
P-value		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

[a] Abbreviation: DAT, days after preemergence herbicide treatment.
[b] Data presented in this table were pooled across the years (2015 and 2016).
[c] Data were arc-sine square-root transformed before analysis; however, back-transformed original mean values are presented based on the interpretation of the transformed data.
[d] Means presented within each column with no common letter(s) are significantly different according to Fisher's protected LSD where α = 0.05.

Table 7
Contrast means for comparison of tillage systems (no-tillage vs. reduced-tillage) for weed control and density across the labeled doses of premix herbicides applied preemergence in glyphosate-resistant corn in field experiments conducted in Nebraska.[a,b]

Tillage treatments	14 DAT	28 DAT	42 DAT	Palmer amaranth density (#pl m^{-2})[c]
	Palmer amaranth control (%)			
No-till vs. Reduced-till	98 vs. 99 NS	90 vs. 90 NS	85 vs. 83 NS	13 vs. 19*
	Velvetleaf control (%)			Velvetleaf density (#pl m^{-2})[b]
No-till vs. Reduced-till	94 vs. 94 NS	91 vs. 87 NS	88 vs. 77**	8 vs. 16**
	Foxtail control (%)			Foxtail density (#pl m^{-2})[b]
No-till vs. Reduced-till	89 vs. 94 NS	78 vs. 86*	67 vs. 79*	20 vs. 14*

[a] Abbreviation: DAT, days after preemergence herbicide treatment; NS, nonsignificant.
[b] Data presented in this table were pooled across the years (2015 and 2016).
[c] Weed density was measured at 42 DAT.
* Significant at P < .05.
** significant at P < .01.

3.4. Corn injury and yield

Tillage-by-herbicide treatment interaction was nonsignificant (P = .43) for corn injury; however, foliar injury and corn height were influenced by tillage at 14 DAT (P = .04). Therefore, injury data were presented separately for tillage systems (Table 8). No to minimal (≤9%) corn injury was observed at 14 DAT in no-till; however, the injury was 9–15% in reduced-till with several premixes, including atrazine plus isoxaflutole plus thiencarbazone-methyl, acetochlor plus clopyralid plus flumetsulam, and dimethenamid-P plus saflufenacil. In a field study conducted in Delaware, Vollmer et al. (2017) reported that labeled dose of clopyralid plus flumetsulam, or isoxaflutole plus thiencarbazone-methyl to sandy-loam (coarse-textured) soil showed 8–22% corn injury in conventional tillage. However, several other studies mentioned that atrazine plus isoxaflutole plus thiencarbazone-methyl, and dimethenamid-P plus saflufenacil applied PRE to a wide range of soil types, showed no or low level (≤3%) of corn injury (Janak and Grichar, 2016; Kohrt and Sprague, 2017; Stephenson and Bond, 2012). In this study, application of ABMS at labeled dose resulted in 3% corn injury at 14 DAT, regardless the tillage systems (Table 8). Similarly, Janak and Grichar (2016); Kohrt and Sprague (2017); Sarangi and Jhala, 2017a) reported that ABMS applied PRE at the labeled dose was safe on corn under field conditions. The corn injury symptoms from all the treatments had dissipated rapidly as slight (≤ 5%) to no corn injury was observed at 28 DAT (data not shown). The plant (corn) stand was not affected by the tillage systems or by premix treatments (data not shown).

Tillage-by-herbicide treatment interaction was nonsignificant for corn yield; therefore, data were pooled for both production systems (no-till vs. reduced tillage). From a 6 yr study conducted in Ontario (Canada), Murphy et al. (2006) concluded that tillage has little or no effect on crop yield. Additionally, long-term experiments also revealed that corn yield was not sensitive to tillage operations (Kapusta et al., 1996; Van Doren et al., 1976). Application of ABMS at 2.89 kg ai ha^{-1} (1 × dose) resulted in 16.3 t ha^{-1} corn yield, comparable with the weed-free control (16.4 t ha^{-1}) and with mesotrione plus rimsulfuron (16.0 t ha^{-1}) (Table 8). It is believed that overall higher weed control and the low extent of corn injury with ABMS, and mesotrione plus rimsulfuron resulted in higher corn yield compared to the other premix treatments. In contrast with the weed-free control, corn yield was reduced by 38% when weeds were left uncontrolled (nontreated control).

3.5. Palmer amaranth dose-response bioassay

Comparison of two dose-response models (with and without considering the effect of tillage) showed that the inclusion of tillage in the dose-response model had a better prediction (P < .05) for the response variables (Palmer amaranth control and biomass reduction). Therefore, regression parameters (*b*, *d*, *e* in Equation 2) and biologically effective doses (ED_{50} and ED_{90}) of ABMS were presented separately for both tillage systems (no-till and reduced-till). ABMS even at the lowest dose (0.96 kg ai ha^{-1}) tested in this study, provided > 80% control of Palmer amaranth at 14 and 28 DAT (Tables 3 and 4), which resulted in a significant lack-of-fit (P < .05) for the log-logistic function. Therefore, biologically effective doses (ED_{50} and ED_{90}) were only predicted at 42 DAT and at harvest (Table 9).

In the no-till production system, the dose-response bioassay showed that 90% Palmer amaranth control obtained at 42 DAT was with the ABMS dose of 2.44 kg ai ha^{-1}; however, due to reduction in the residual

Table 8
Corn injury and yield as affected by preemergence application of the premix of atrazine, bicyclopyrone, mesotrione, and *S*-metolachlor and several other commonly used premixes in no-tillage and reduced-tillage field experiments conducted in Nebraska.[a]

Treatment	Dose	Corn injury[b,c]		Corn yield[c]
		No-till	Reduced-till	
	kg ai ha^{-1}	%		t ha^{-1}
Nontreated control	–	0	0	10.1 f
Weed-free control	–	0	0	16.4 a
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	0.96	0	0 c	14.8 de
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	1.93	0	0 c	15.2 cd
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	2.89	3	3 bc	16.3 a
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	3.86	3	4 bc	16.5 a
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	4.82	3	5 bc	16.6 a
Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	5.78	5	9 ab	16.4 a
Atrazine + fluthiacet-methyl + pyroxasulfone	1.26	0	0 c	14.9 cde
Atrazine + isoxaflutole + thiencarbazone-methyl	0.50 + 0.10	4	9 ab	15.6 bc
Mesotrione + rimsulfuron	0.19	6	4 bc	16.0 ab
Acetochlor + clopyralid + flumetsulam	1.19	4	15 a	14.5 e
Dimethenamid-P + saflufenacil	0.78	9	15 a	15.4 bcd
P-value		0.37	0.001	< 0.001

[a] Data presented in this table were pooled across the years (2015 and 2016).
[b] Corn injury was evaluated at 14 days after preemergence herbicide treatment (DAT).
[c] Means presented within each column with no common letter(s) are significantly different according to Fisher's protected LSD where α = 0.05.

activity, the premix dose was relatively higher (3.09 kg ai ha^{-1}) to achieve similar level of control later in the season (Table 9). Similarly, Knezevic et al. (2009), estimating biologically effective doses for pyroxasulfone for common waterhemp control, reported an increase in ED_{90} values (0.26 kg ai ha^{-1}) at 65 DAT compared to 28 and 45 DAT (< 0.20 kg ai ha^{-1}). In this study, Palmer amaranth aboveground biomass reduction showed a similar trend as the control estimates. The doses of ABMS required to reduce the aboveground biomass by 50 and 90% (ED_{50} and ED_{90}) were 0.65 and 2.51 kg ai ha^{-1}, respectively, in no-till production system.

In reduced-till, the biologically effective doses were slightly higher than the no-till production system. Considering the standard error of the mean (± SE), ED_{90} values did not differ in two tillage systems; however, ED_{50} values were different (Table 9). The premix doses (ED_{90}) required to control Palmer amaranth by 90% were 2.81 and 3.38 kg ai ha^{-1} at 42 DAT and at harvest, respectively. The ED_{50} and ED_{90} values for the aboveground biomass reduction were 0.77 and 2.75 kg ai ha^{-1} (Table 9). Similarly, Sarangi and Jhala, 2017a) reported ED_{90} values ranged from 2.39 to 2.82 kg ai ha^{-1} of ABMS at 63 DAT for common waterhemp control and biomass reduction.

The goodness-of-fit parameters (RMSE and EF) showed a good-fit for the dose-response curves for Palmer amaranth control and aboveground biomass reduction. The RMSE values ranged between 4.0 to 8.7 and the model efficiency coefficient (EF) values were ≥0.93 for both tillage systems (Table 9). Similarly, Sarangi and Jhala, 2017b) reported RMSE values ranging from 7.3 to 8.9 with EF values of ≥0.95 in a PRE dose-response bioassay of ABMS to horseweed.

Table 9
Estimation of regression parameter and model goodness-of-fit for the dose-response model,[a] and prediction of the biologically effective doses of the premix of atrazine, bicyclopyrone, mesotrione, and *S*-metolachlor (applied preemergence) required to control Palmer amaranth by 50% (ED_{50}) and 90% (ED_{90}) in a field study conducted in no-tillage and reduced-tillage corn in field experiments conducted in Nebraska.[b]

Timing[b]	Regression parameter	Model goodness of fit[c]		ED_{50} (± SE)[c]	ED_{90} (± SE)[c]
	b (± SE)[c]	RMSE	EF	kg ai ha^{-1}	
No-till					
Control of Palmer amaranth					
42 DAT	−1.4 (± 0.10)	4.0	0.98	0.51 (± 0.04)	2.44 (± 0.14)
At Harvest	−1.5 (± 0.11)	5.5	0.97	0.69 (± 0.05)	3.09 (± 0.22)
Aboveground biomass reduction of Palmer amaranth					
70 DAT	−1.6 (± 0.21)	7.2	0.95	0.65 (± 0.07)	2.51 (± 0.26)
Reduced-till					
Control of Palmer amaranth					
42 DAT	−1.6 (± 0.16)	6.7	0.96	0.71 (± 0.06)	2.81 (± 0.24)
At Harvest	−1.8 (± 0.15)	8.1	0.94	1.00 (± 0.06)	3.38 (± 0.28)
Aboveground biomass reduction of Palmer amaranth					
70 DAT	− 1.7 (± 0.22)	8.7	0.93	0.77 (± 0.08)	2.75 (± 0.32)

[a] $Y = c + \{d - c/1 + exp[b(\log x - \log e)]\}$, where Y is the response variable (control or reduction in the aboveground biomass); x is the premix dose; c and d are the lower limit (which is 0) and the estimated maximum value of Y, respectively; and e represents the premix dose causing 50% control or aboveground biomass reduction (i.e., ED_{50}) of Palmer amaranth. The parameter b is the relative slope around the parameter e.
[b] Data presented in this table were pooled across the years (2015 and 2016).
[c] Abbreviations: DAT, days after treatment; EF, modelling efficiency coefficient; RMSE, root mean square error; SE, standard error of mean.

3.6. Practical implications

One of the greatest challenges faced by conservation tillage (including no-till and reduced-till systems) is the planning for an effective, environmentally sound but economical weed management program (Bajwa, 2014; Gebhardt et al., 1985; Jhala et al., 2014a; Koskinen and McWhorter, 1986). The results of this study showed that ABMS was on par or even sometimes better than other PRE herbicides tested in this study. The reduced or shallow-tillage treatment was not effective to reduce Palmer amaranth emergence compared to the no-till system. Palmer amaranth's small seed size requires a shallow depth in the soil profile for successful emergence and establishment. In a greenhouse experiment, Keeley et al. (1987) found that Palmer amaranth seedlings emerged readily from a depth of ≤2.5 cm and the emergence was 36 to 44%; however, emergence reduced to ≤7.2% at 5.1 to 7.6 cm soil depth. Therefore, it is expected that pre-plant deep-tillage would have a greater impact in reducing Palmer amaranth emergence compared to no-till or reduced-till. In a field experiment conducted in South Carolina, Norsworthy (2008) reported that one year of conventional or deep-tillage along with an effective herbicide program reduced Palmer amaranth soil-seedbank (in the top 5 cm of soil) by 80–99%.

The objective of this study was to compare efficacy of ABMS with commonly used PRE herbicides in no-till and reduced-till corn production systems; therefore, POST herbicides were not included; however, *Amaranthus* sp. including Palmer amaranth can emerge throughout the growing season (Jha and Norsworthy, 2009) and PRE-only herbicide program cannot control the later-emerging plants (Jhala et al., 2017; Whitaker et al., 2010). For a season-long control of Palmer amaranth, early- or late-POST application following a PRE treatment is important (Hoffner et al., 2012; Meyer et al., 2015).

4. Conclusion

The results of this study indicated that ABMS applied at the labeled dose (2.89 kg ai ha^{-1}) showed a similar level of Palmer amaranth control regardless of the tillage system. Velvetleaf control was relatively higher in no-till compared to reduced-till; however, the opposite was found for foxtail control. Results indicated that ABMS had similar or better efficacy in broadleaf weed (Palmer amaranth and velvetleaf) control compared to the other premixes tested in both tillage systems, but foxtail control was higher with mesotrione plus rimsulfuron in no-till. Application of ABMS, or mesotrione plus rimsulfuron appeared to be the most effective in terms of corn yield. The dose-response study indicated that the labeled dose of ABMS can provide 90% or more control of Palmer amaranth up to 42 DAT regardless of the tillage. Results of the dose-response bioassay indicated that Palmer amaranth control was not affected by the tillage systems at higher doses, but at lower doses control was better in no-till. However, the application of herbicides at sub lethal doses should be avoided as it may accelerate the evolution of weed resistance due to stress-induced mutations. It is concluded that ABMS has potential for becoming an effective PRE herbicide in no-till and reduced-till corn production systems.

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