Weed Technology

www.cambridge.org/wet

Preemergence herbicide premixes reduce the risk of soil residual weed control failure in corn

Tatiane Severo Silva[1], Nicholas John Arneson[2], Ryan P. DeWerff[3], Daniel H Smith[4], Daniel Valadão Silva[5] and Rodrigo Werle[6]

[1]Ph.D, Postdoctoral Research Associate, Department of Agronomy, University of Wisconsin–Madison, Madison, WI, USA; [2]Outreach Program Manager, University of Wisconsin–Madison, Madison, WI, USA; [3]Research Specialist, University of Wisconsin–Madison, Madison, WI, USA; [4]Southwest Regional Agronomist, Nutrient and Pest Management Program, University of Wisconsin–Madison, Madison, WI, USA; [5]Assistant Professor, Department of Agronomy, Federal Rural University of the Semi-Arid Region, Mossoro, Brazil and [6]Associate Professor, Department of Agronomy, University of Wisconsin–Madison, Madison, WI, USA

Research Article

Cite this article: Silva TS, Arneson NJ, DeWerff RP, Smith DH, Silva DV, Werle R (2023) Preemergence herbicide premixes reduce the risk of soil residual weed control failure in corn. Weed Technol. **37**: 410–421. doi: 10.1017/wet.2023.45

Received: 7 April 2023
Revised: 9 June 2023
Accepted: 23 June 2023
First published online: 29 June 2023

Associate Editor:
Robert Nurse, Agriculture and Agri-Food Canada

Keywords:
Herbicide efficacy; herbicide mixture; residual herbicide; weed management

Nomenclature:
Common lambsquarters; *Chenopodium album* L.; corn; *Zea mays* L.; giant foxtail; *Setaria faberi* Herrm.; giant ragweed; *Ambrosia trifida* L.; waterhemp; *Amaranthus tuberculatus* [Moq.] J.D. Sauer

Corresponding author: Tatiane Severo Silva; Email: severosilva@wisc.edu

Abstract

Widespread occurrence of herbicide-resistant weeds and more variable weather conditions across the United States has made weed control in many crops more challenging. Preemergence (PRE) herbicides with soil residual activity have resurged as the foundation for early season weed control in many crops. Field experiments were conducted in Janesville and Lancaster, Wisconsin, in 2021 and 2022 (4 site-years) to evaluate the weed control efficacy of solo (single site of action [SOA]) and premix (two or more SOAs) PRE herbicides in conventional tillage corn. Treatments consisted of 18 PRE herbicides plus a nontreated check. At the Janesville-2021 site, S-metolachlor + bicyclopyrone + mesotrione, atrazine + S-metolachlor + bicyclopyrone + mesotrione, and clopyralid + acetochlor + mesotrione provided >72% giant ragweed control. At the Janesville-2022 site, none of the PRE herbicides evaluated provided >70% giant ragweed control due to the high giant ragweed density and the lack of timely rainfall. At the Lancaster-2021 site, atrazine, dicamba, and flumetsulam + clopyralid provided <45% waterhemp control, but the remaining treatments provided >90% control. At the Lancaster-2022 site, the efficacy of some PRE herbicides was reduced due to the high waterhemp density; however, most herbicides provided >75% control. At the Lancaster-2021 and Lancaster-2022 sites, only dicamba and S-metolachlor did not provide >75% common lambsquarters control. Group 15 PRE herbicides provided >75% control of giant foxtail. Across weed species, PRE herbicides with two (78%) and three (81%) SOAs provided greater weed control than PRE herbicides with a single SOA (68%), indicating that at least two SOA herbicides applied PRE result in better early season weed control. The efficacy of the PRE herbicide treatments evaluated herein varied according to the soil seedbank weed community composition and environmental conditions (i.e., rainfall following application), but the premixes were a more reliable option to improve early season weed control in conventional tillage corn.

Introduction

Corn is the most cultivated crop in the United States, with an area of 32 million ha harvested for grain in 2022 (USDA-NASS 2023). The Midwest is the top-producing region, representing more than 85% of the harvested area and more than 88% of the corn produced in 2022 in the United States (USDA-NASS 2023). Weed management is a major challenge in corn production. U.S. corn growers rely primarily on herbicides and tillage for weed management (Dong et al. 2017; Grint et al. 2022a). Herbicides are the most extensively used pesticide on corn crops, applied to >95% of planted corn hectares in the United States in 2021 (USDA-NASS 2022). The dependence on chemical weed control has led to the widespread occurrence of herbicide resistance, mainly to postemergence (POST) herbicides (Heap 2022, Jha et al. 2017). An effective strategy to minimize the overreliance on POST herbicide applications is to apply soil residual preemergence (PRE) herbicides for early season weed control (Knezevic et al. 2019). The use of herbicides with effective soil residual activity applied PRE provides an extended period of early season weed control, protecting crop yields during their most vulnerable developmental stages from weed interference (Grint et al. 2022b; Oliveira et al. 2017a). PRE herbicides can reduce the weed density and delay the time to POST applications, thus lowering the selection pressure for further resistance to POST herbicides (Faleco et al. 2022a; Oliveira et al. 2017b). Including PRE herbicides as part of an integrated weed management program brings more diversity to effective sites of action (SOAs) and opportunities for broad-spectrum chemical weed control (Norsworthy et al. 2012; Somerville et al. 2017).

The residual weed control efficacy of a PRE herbicide depends on several variables, including environmental conditions (i.e., pattern and amount of rainfall following application, temperature), physicochemical properties of the herbicide (i.e., water solubility, vapor pressure, octanol-water coefficient, acid ionization constant), physicochemical properties of the soil (i.e., pH, organic matter, texture), and soil seedbank weed community composition (Varanasi et al. 2016; Zhao et al. 2017). Effective early season weed control can be achieved with PRE herbicides when these variables are favorable for a properly selected chemical program. However, when some of these conditions are not favorable, failure in early season weed control may occur (Hay et al. 2018; Urach Ferreira et al. 2020). For example, adequate rainfall following application increases the probability of effective waterhemp and common lambsquarters control with PRE herbicides (Landau et al. 2021a), which are two of the most troublesome weeds in Wisconsin corn production (Werle and Oliveira 2018). Low residual weed control has been commonly reported under dry weather conditions due to the lack of rainfall to dissolve the herbicide into a soil solution (Bell et al. 2015; Jursik et al. 2015; Priess et al. 2020).

A practice recommended to lower the risk of early season weed control failure and herbicide resistance is the use of PRE herbicide premixes containing multiple effective SOAs (Striegel et al. 2021a). PRE herbicides with multiple SOAs can expand the spectrum of weed control compared to a single SOA herbicide (Carneiro et al. 2020). Besides providing broader spectrum control, herbicides with multiple SOAs that simultaneously target the same weed spectrum reduce the selection intensity for the evolution of herbicide-resistant weed biotypes (Norsworthy et al. 2012). Their effectiveness is also improved when the active ingredients have similar soil residual activity (Beckie and Harker 2017; Palma-Bautista et al. 2021). Jha et al. (2015) reported high control (≥72%) of kochia (*Kochia scoparia* L.), common lambsquarters, and wild buckwheat (*Polygonum convolvulus* L.) with saflufenacil + dimethenamid-P and acetochlor + pendimethalin at 63 d after treatment (DAT) compared to these herbicides applied alone (≤47%). Other studies also demonstrated high efficacy of herbicide premixes (>90%) in controlling weeds in corn-soybean cropping systems (Oliveira et al. 2017b; Sarangi and Jhala 2018; Striegel et al. 2021a).

PRE herbicide mixes tend to be more effective than the same active ingredients applied solo when weather conditions are not favorable, but the extension of this effect may vary according to water solubility and soil sorption of each herbicide in the premix (Janak and Grichar 2016; Landau et al. 2021a; Stewart et al. 2010). It is well known that each herbicide has a unique behavior in the soil depending on edaphoclimatic conditions. For instance, clopyralid and dicamba dissipate faster in moist soils with warm temperatures; in contrast, under dry soils and cold temperatures, their residual activity can persist longer (Cahoon et al. 2015a; Pik et al. 1977; Seefeldt et al. 2014). As the weather becomes more variable across the corn-producing regions of the United States (Landau et al. 2021b), PRE herbicide premixes with multiple SOAs may play a significant role for early season weed control, mainly for troublesome weeds with an extended emergence window such as giant ragweed and waterhemp (Striegel et al. 2021b). In this context, PRE herbicide premixes that contain multiple SOAs may provide more consistent early season weed control due to the widespread occurrence of herbicide resistance across the United States coupled with the more variable and extreme weather conditions. In this study, we evaluated a comprehensive list of labeled corn residual PRE herbicides (18 products containing one or multiple SOAs) including commonly used PRE herbicides in Wisconsin corn production, a novel premix herbicide (clopyralid + pyroxasulfone + mesotrione), and a herbicide premix (saflufenacil + dimethenamid-P) not commonly used on corn. Results from this study can support corn growers and those who influence their weed management decisions by providing them with a selection of more effective PRE herbicides based on key weed species present in their fields.

Materials and Methods

Field Experiments

Field experiments were conducted in 2021 and 2022 at the Rock County Farm, in Janesville, Wisconsin (42.43°N, 89.01°W), and at the University of Wisconsin–Madison Lancaster Agricultural Research Station, near Lancaster, Wisconsin (42.83°N, 90.76°W), to evaluate the residual weed control efficacy of solo (single SOA) and premix (commercial products with two or more SOAs) herbicides applied PRE to conventional tillage corn. PRE herbicide rates used herein are commonly recommended by the industry and adopted by growers in Wisconsin (DeWerff et al. 2022; Table 1). The rates of the single active ingredient herbicide treatments did not necessarily match their rates when used as a premix (Table 1).

The experimental areas were managed in a soybean-corn rotation; thus, soybean was grown at all experimental sites in the previous growing season before the experiment was established. Before corn planting, the experimental area was tilled using a field cultivator. Corn was planted 5 cm deep in 76-cm row spacing at all experimental sites. Soil at the Janesville site was a Plano silt loam, and at Lancaster it was a Fayette silt loam. Soil properties, corn hybrid, seeding rate, and planting and herbicide application dates for each site-year are described in Table 2.

The experiment was conducted as a randomized complete block design with four replications. The treatments consisted of 18 PRE herbicides plus a nontreated control (NTC; Table 1). The experimental units were 3 m wide (four corn rows) × 9 m long. Herbicides were applied within a day after corn planting (Table 2) using a CO_2-pressurized backpack sprayer equipped with six TTI110015 flat-fan nozzles (Teejet, Springfield, IL) spaced 51 cm apart at a boom height of 50 cm from the soil surface. The sprayer was calibrated to deliver 140 L ha^{-1} of spray solution at 240 kPa at a speed of 4.8 km h^{-1}.

Data Collection

Daily mean air temperature and total cumulative precipitation at each site-year were obtained from onsite weather stations (WatchDog 2700; Spectrum Technologies®, Aurora, IL; Figure 1). The density of the predominant weed species at each site-year was recorded from the NTC experimental units at 6 wk after treatment (WAT) for Janesville-2021, Lancaster-2021, and Lancaster-2022, and at 4 WAT for Janesville-2022. Weed control and weed aboveground biomass for Janesville-2021, Lancaster-2021, and Lancaster-2022 were assessed at 6 WAT. For Janesville-2022, visual weed control and aboveground weed biomass were assessed at 4 WAT because of the high population of giant ragweed (*Ambrosia trifida* L.) and its rapid growth. All response variables were assessed between the two center corn rows of each experimental unit. Weed control in each experimental unit was estimated using a visual scale (0 = no control, 100% = complete control). Weed aboveground biomass was collected using two quadrats (0.25 m^{-2}) randomly placed between the center two rows of each experimental unit. Weeds were enumerated and harvested by species. Weed biomass for each species from both quadrats within an experimental unit was combined into a single paper bag. Weed biomass was dried at 60 C until a constant weight was

Table 1. PRE herbicides evaluated in the corn field experiments.

Herbicide[a]	Trade name	Manufacturer	Chemical Family	Half-life[b]	Rate
				d	g ai or ae ha^{-1}
Dicamba (4)	Diflexx™	Bayer CropScience[c]	Benzoates	14	560
Atrazine (5)	AAtrex®	Syngenta Crop Protection[d]	Triazines	60	1,120
Simazine (5)	Princep® 4L	Syngenta Crop Protection[d]	Triazines	60	2,240
Acetochlor (15)	Harness®	Bayer CropScience[c]	α-Chloroacetamides	12	1,960
S-metolachlor (15)	Dual II Magnum®	Syngenta Crop Protection[d]	α-Chloroacetamides	112–124	1,791
Isoxaflutole (27)	Balance® Flexx	Bayer CropScience[c]	Isoxazoles	0.5–2.4	79
Mesotrione (27)	Callisto®	Syngenta Crop Protection[d]	Triketones	5–15	175
Acetochlor (15) + mesotrione (27)	Harness® Max	Bayer CropScience[c]	α-Chloroacetamides + Triketones	–	1,971 + 185
Thiencarbazone-methyl (2) + isoxaflutole (27)	Corvus®	Bayer CropScience[c]	Triazolinones + Isoxazoles	–	34 + 85
Atrazine (5) + S-metolachlor (15)	Bicep Lite II Magnum®	Syngenta Crop Protection[d]	Triazines + α-Chloroacetamides	–	1,310 + 1,634
Atrazine (5) + acetochlor (15)	Harness® Xtra	Bayer CropScience[c]	Triazines + α-Chloroacetamides	–	952 + 2,408
Saflufenacil (14) + dimethenamid-P (15)	Verdict®	BASF Corporation[e]	N-Phenyl-imides + α-Chloroacetamides	–	75 + 655
Flumetsulam (2) + clopyralid (4)	Hornet® WDG	Corteva Agriscience[f]	Triazolopyrimidine + Pyridine-carboxylates	–	52 + 168
S-metolachlor (15) + bicyclopyrone (27) + mesotrione (27)	Acuron® Flexi	Syngenta Crop Protection[d]	α-Chloroacetamides + Triketone + Triketone	–	1,602 + 45 + 179
Atrazine (5) + S-metolachlor (15) + bicyclopyrone (27) + mesotrione (27)	Acuron®	Syngenta Crop Protection[d]	Triazines + α-Chloroacetamides + Triketones + Triketones	–	700 + 1,498 + 42 + 168
Flumetsulam (2) + clopyralid (4) + acetochlor (15)	Surestart® II	Corteva Agriscience[f]	Triazolopyrimidine + Pyridine-carboxylates + α-Chloroacetamides	–	42 + 133 + 1,315
Clopyralid (4) + acetochlor (15) + mesotrione (27)	Resicore®	Corteva Agriscience[f]	Pyridine-carboxylates + α-Chloroacetamides + Triketones	–	133 + 1,960 + 210
Clopyralid (4) + pyroxasulfone (15) + mesotrione (27)	Maverick™	Valent[g]	Pyridine-carboxylates + Isoxazolines + Triketones	–	194 + 194 + 233

[a]The number in parentheses indicates the Group number as categorized by the Weed Science Society of America (WSSA).
[b]Average field half-life of the herbicides. Obtained from the WSSA Herbicide Handbook (10th ed.; Shaner 2014) and Pesticide Properties DataBase (PPDB 2022).
[c]Located in St. Louis, MO.
[d]Located in Greensboro, NC.
[e]Located in Durham, NC.
[f]Located in Indianapolis, IN.
[g]Located in Walnut Creek, CA.

Table 2. Soil properties, corn hybrids, seeding rates, and planting and herbicide application dates for corn field experiments.[a]

Site-year	pH	Organic matter	Sand	Silt	Clay	Corn hybrid	Seeding rate	Planting date	Herbicide application date
		———————%———————					Seeds ha^{-1}		
Janesville-2021	5.4	4.1	8	68	24	NK 9653-5222EZ[b]	87,600	April 26	April 28
Janesville-2022	5.9	2.6	26	63	12	NK 9653-5222EZ[b]	87,600	May 10	May 11
Lancaster-2021	6.6	2.5	10	76	14	B97T04SXE[c]	80,200	April 28	April 29
Lancaster-2022	5.3	4.1	18	65	18	P9998Q-N802[d]	80,200	May 11	May 13

[a]Janesville-2021was fertilized with 200 kg ha^{-1} of nitrogen (46-0-0); Lancaster-2021: 128 kg ha^{-1} of nitrogen (46-0-0); 2022-Janesvile: 112 kg ha^{-1} of nitrogen (32-0-0) and 32 kg ha^{-1} of sulfur in the form of ammonium thiosulfate (12-0-0-26S); 2022-Lancaster: 55 kg ha^{-1} of phosphorus + 112 kg ha^{-1} of potassium nitrate (4-19-38) applied early spring, and 160 kg ha^{-1} of nitrogen (46-0-0).
[b]Brevant®, Indianapolis, IN 46268.
[c]Syngenta®, Greensboro, NC 27419.
[d]Pioneer®, Johnston, IA 50131.

achieved and then weighed. Weed biomass data were reported as percentage biomass reduction compared to the NTC:

$$\%\ \text{Biomass reduction} = [NTC - T)/NTC] * 100 \qquad [1]$$

where *NTC* is the mean weed biomass (in grams) of the NTC across replications within a specific site-year, and *T* is the weed biomass (in grams) of the experimental unit of interest.

https://doi.org/10.1017/wet.2023.45 Published online by Cambridge University Press

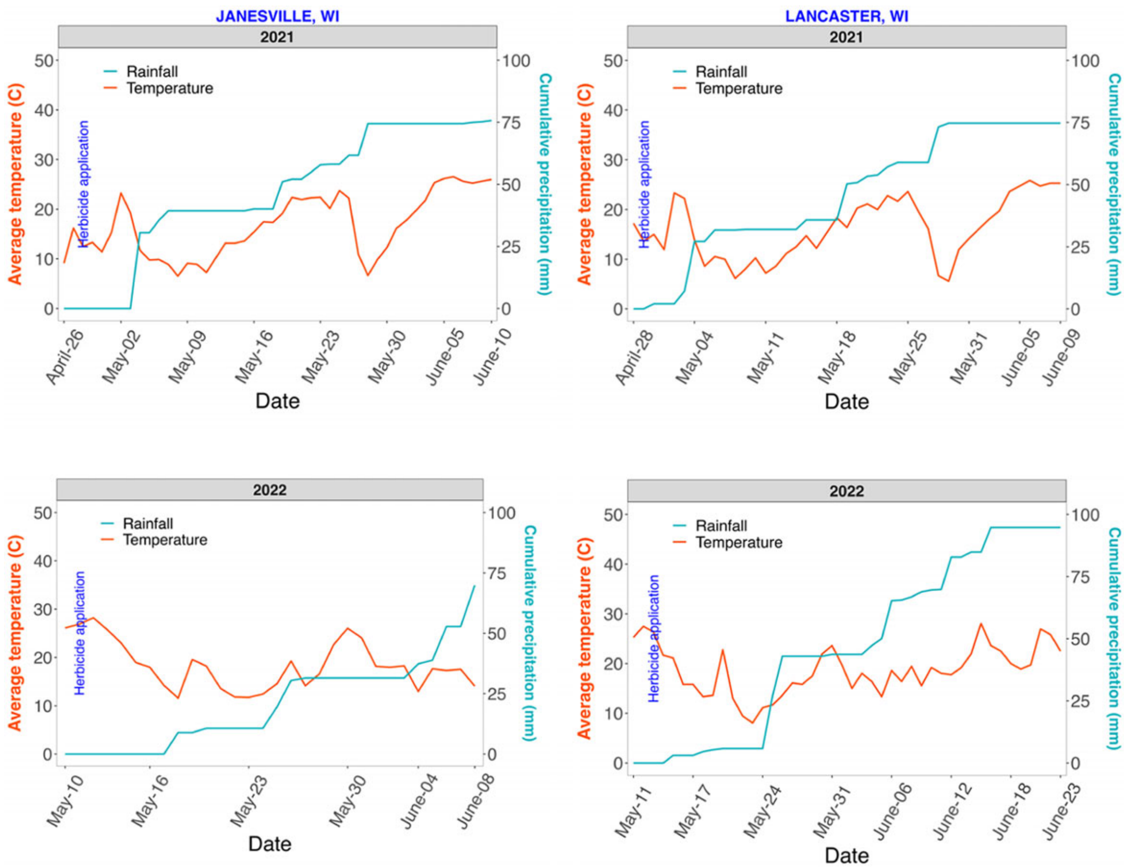

Figure 1. Mean daily air temperature and total cumulative precipitation at the experimental sites in Janesville (left) and Lancaster (right), Wisconsin, in 2021 (top) and 2022 (bottom) during the corn field experiment.

Data Analyses

All response variables (visual weed control [%] and biomass reduction [%]) were analyzed using R statistical software (version 4.2.1; R Core Team, 2022). A generalized linear mixed model with a beta distribution and logit family (GLMMTMB package; Brooks et al. 2017) was used to analyze both response variables. PRE herbicide efficacy is known to vary by year and location because of weather and soil conditions (Glaspie et al. 2021; Landau et al. 2021a) and soil seedbank weed community composition (Striegel et al. 2021a). Therefore, data were analyzed separately by weed species and site-year. Herbicide treatments were considered as fixed effects, while replications nested within site-year were treated as a random effect. ANOVA was performed for giant ragweed control and biomass reduction for Janesville-2021 and Janesville-2022. For Lancaster-2021, ANOVA was performed for waterhemp and common lambsquarters, whereas giant foxtail control and biomass reduction were also analyzed for Lancaster-2022 in addition to waterhemp and common lambsquarters. Evaluation of homogeneity of residual variance was carried out using Levene's test (the CAR package; Fox and Weisberg 2019). When ANOVA (the GLMMTMB package) indicated a significant PRE herbicide treatment effect, means were compared using Fisher's LSD test ($P \leq 0.05$; EMMEANS package; Lenth 2022).

Pearson's correlation was performed (the *cor.test* function) to estimate the linear correlation between visual weed control and weed biomass reduction. A linear mixed model was also performed to analyze weed control (%) according to the number of herbicide SOAs for each weed species and for weed species combined (combined across species, site-years pooled together). The number of herbicide SOA groups in each treatment (one, two, and three SOAs) were considered as fixed effects, and replications nested within site-years were included as a random effect. If ANOVA indicated a significant effect of number of PRE herbicide SOA groups ($P \leq 0.05$), means were compared using Fisher's protected LSD test.

Results and Discussion

Environmental Conditions

Daily precipitation varied across site-years (Figure 1). At the Janesville-2021 site, the first rain occurred 6 DAT (30 mm), whereas 40 mm of rain fell within 15 DAT. At Janesville-2022, the first rain occurred 7 DAT (9 mm), accumulating 21 mm within 15 DAT. The average air temperature in the first week after treatment was lower in 2021 (15 C) compared with 2022 (22 C). At Lancaster-2021, the first rain occurred 1 DAT (2 mm), whereas 32 mm accumulated within 7 d and 35 mm within 15 DAT. At Lancaster-2022, the first rain occurred within 1 d (3 mm), accumulating 6 mm within 7 d and 42 mm within 15 DAT. The average air temperature in the first week after treatment was 15 C in 2021 and 18 C in 2022.

https://doi.org/10.1017/wet.2023.45 Published online by Cambridge University Press

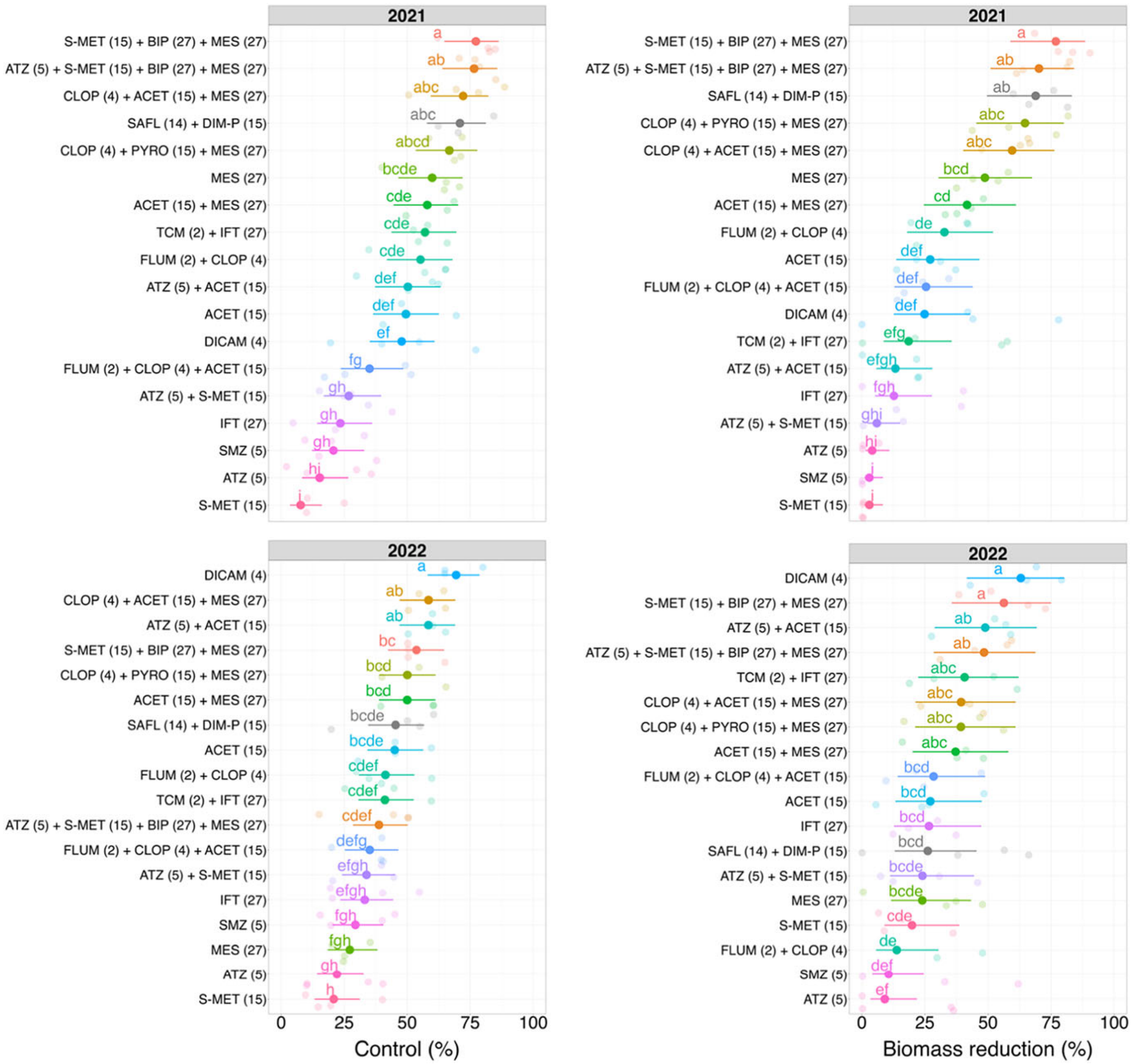

Figure 2. Giant ragweed control (% of nontreated control; left) and biomass reduction (% of nontreated control; right) in Janesville, Wisconsin, 2021 at 6 wk after treatment and 2022 at 4 wk after treatment. Jittered points represent replicates, centered solid points denote the means, and error bars represent the upper and lower 95% confidence interval limits. Means were compared using Fisher's LSD, and herbicide treatments with the same letters are not different at $\alpha = 0.05$. Numbers in parentheses in the y-axis represent the site of action of each herbicide treatment. Abbreviations: DICAM, dicamba; ATZ, atrazine; SMZ, simazine; ACET, acetochlor; S-MET, S-metolachlor; IFT, isoxaflutole; MES, mesotrione; TCM, thiencarbazone-methyl; SAFL, saflufenacil; DIM-P, dimethenamid-P; FLUM, flumetsulam; CLOP, clopyralid; BIP, bicyclopyrone; PYRO, pyroxasulfone.

Weed Species Composition at Each Site-year

Giant ragweed was the predominant weed species observed at the Janesville location in both years (24 ± 2 plants m^{-2}, average ± standard error from NTC, in 2021 [6 WAT] and 104 ± 4 plants m^{-2} in 2022 [4 WAT]). At the Lancaster location, common lambsquarters (109 ± 24 plants m^{-2}) and waterhemp (41 ± 13 plants m^{-2}) were the predominant weed species in 2021; and waterhemp (100 ± 18 plants m^{-2}), common lambsquarters (37 ± 12 plants m^{-2}), and giant foxtail (27 ± 9 plants m^{-2}) were predominant in 2022. The weed species present at these site-years comprise some of the most common weeds in Wisconsin corn production (Werle and Oliveira 2018).

Giant Ragweed Control

At the Janesville-2021 site, the PRE herbicide treatment effect was significant for giant ragweed control ($P < 0.01$) and biomass reduction ($P < 0.01$), and efficacy across treatments was low at 6 WAT (<75% of control; Figure 2). Giant ragweed control was higher with certain herbicide premixes containing two or more SOAs compared with herbicide treatments with a single SOA (Figures 2 and 3). For instance, premixes containing mesotrione (S-metolachlor + bicyclopyrone + mesotrione, atrazine + S-metolachlor + bicyclopyrone + mesotrione, and clopyralid + acetochlor + mesotrione) provided ≥72% control and ≥60% biomass reduction of giant ragweed (Figure 2). These premixes

https://doi.org/10.1017/wet.2023.45 Published online by Cambridge University Press

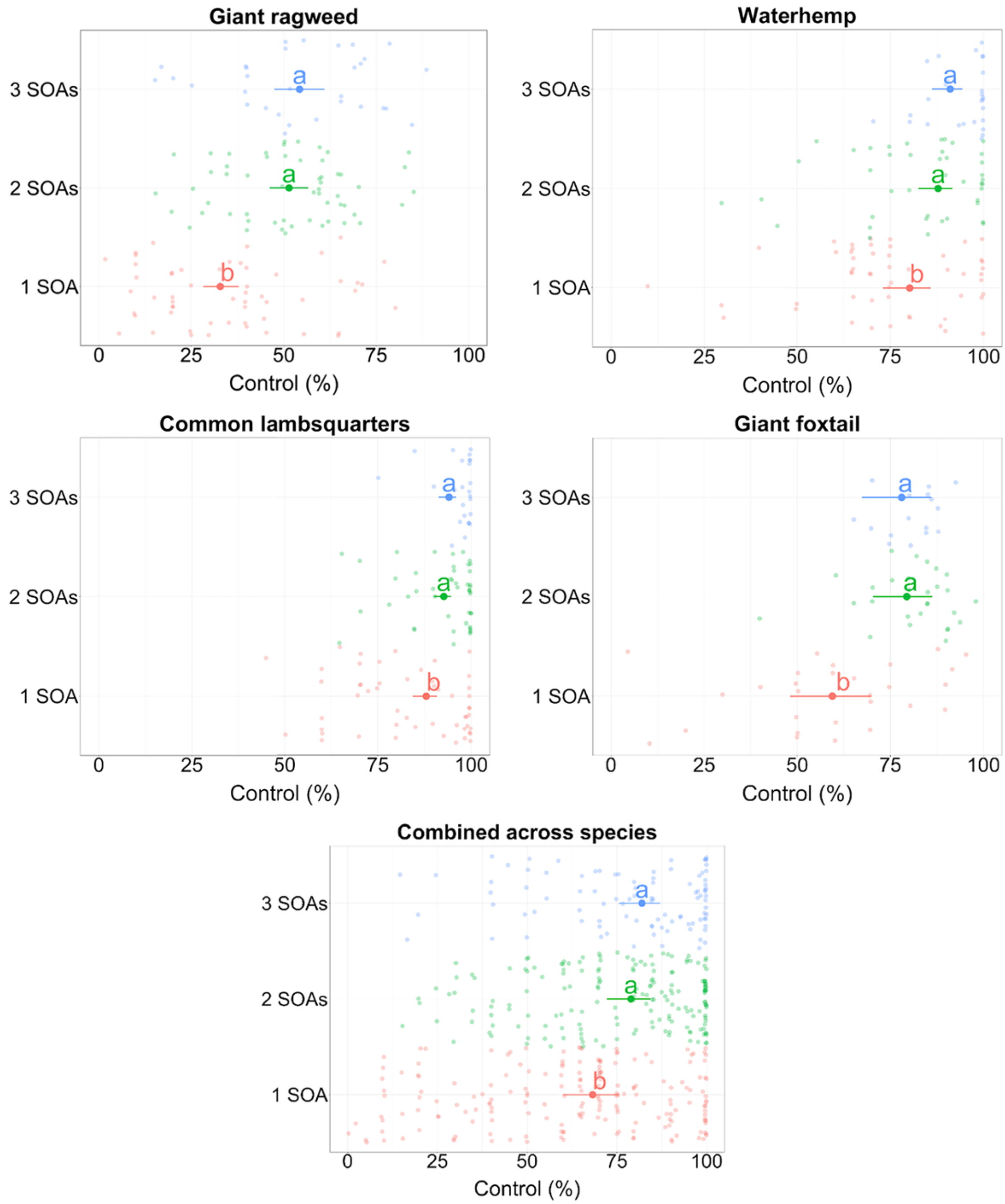

Figure 3. Control (% of nontreated control) of giant ragweed at the Janesville site (6 wk after treatment [WAT] in 2021 and 4 WAT 2022), waterhemp (2021 and 2022), common lambsquarters (2021 and 2022), and giant foxtail (2022) at the Lancaster, Wisconsin site (6 WAT), and all data combined across species based on herbicide treatments with a single, two, and three sites of action applied PRE in corn.

improved giant ragweed control and biomass reduction compared with acetochlor (58% and 27%), or S-metolachlor (8% and 3%; Figure 2), which have a single active ingredient. Acetochlor or S-metolachlor in premixes with atrazine (atrazine + acetochlor and atrazine + S-metolachlor) provided similar giant ragweed control (<50%) when compared to each active ingredient sprayed separately. The thiencarbazone-methyl + isoxaflutole premix also increased giant ragweed control (40%) compared to isoxaflutole applied alone (26%).

At Janesville-2022, the PRE herbicide treatment effect was significant for control ($P < 0.01$) and biomass reduction ($P < 0.01$), but none of the treatments provided ≥70% giant ragweed control and biomass reduction 4 WAT. Similar to Janesville-2021 results, the premix S-metolachlor + bicyclopyrone + mesotrione provided greater giant ragweed control (53%) and biomass reduction (56%) compared to S-metolachlor applied alone (<20%; Figure 2). The other herbicide premixes provided similar giant ragweed control compared to each active ingredient applied separately. Surprisingly, dicamba alone provided the greatest level of giant ragweed control (≥60%; Figure 2) compared to the NTC.

The relatively high level of giant ragweed control observed in 2021 for the PRE herbicide premixes (S-metolachlor +

bicyclopyrone + mesotrione, atrazine + S-metolachlor + bicyclopyrone + mesotrione, and clopyralid + acetochlor + mesotrione) compared with acetochlor or S-metolachlor, which have a single active ingredient, may be a result of the different SOA combinations in these mixtures. These different SOAs can complement each other under a range of environmental conditions, thus providing more consistent weed control (Barbieri et al. 2022; Bollman et al. 2006). Striegel et al. (2021a) reported high (95%) giant ragweed control at this experimental location (Rock County Farm, Janesville, Wisconsin) using herbicide premixes that contain mesotrione (clopyralid + acetochlor + mesotrione and S-metolachlor + bicyclopyrone + mesotrione).

The large giant ragweed population and lack of timely rainfall for herbicide activation in the soil might be two of the factors that led to poor giant ragweed control (≤70%) at the Janesville location in 2022. The lower amount of accumulated rain during the first (9 mm) and second weeks (21 mm) after PRE herbicide application was probably not adequate to dissolve the herbicide into the soil-water solution that provides weed control (Figure 1). In 2022, the amount of rain between application and 15 DAT was only half the amount that fell in 2021 (21 mm vs. 40 mm; Figure 1). According to Landau et al. (2021a), 50 to 100 mm of total rain in the first 15 d, depending on the herbicide and weed species, is typically required to prevent losses in control efficacy due to poor activation of PRE herbicides.

The greater control of giant ragweed in 2022 by dicamba confirms the extended residual activity of this herbicide when rain is limited (21 mm within 15 DAT; Figure 1). This would be associated with a reduction in microbial degradation under dry conditions and reduced leaching, which means that more dicamba is available to control sensitive broadleaf weeds such as giant ragweed (Cahoon et al. 2015b). Dicamba is highly soluble in water (4,500 mg L^{-1} at 25 C), thus the little rain that fell in 2022 can explain the greater dicamba residual activity 4 WAT (Shaner 2014). Although dicamba PRE activity did not result in giant ragweed control >70% in this study, the residual activity of dicamba appears to improve early season giant ragweed control in dry spring seasons. Mundt et al. (2022) also observed that residual weed control is extended if the rainfall accumulation is not enough to leach dicamba molecules through the crop residue and soil profile.

Another reason for reduced giant ragweed control in 2022 compared with 2021 was the high degree of weed seedling emergence (24 ± 2 plants m^{-2} in 2021 [6 WAT] compared with 104 ± 4 plants m^{-2} in 2022). A previous study also reported low giant ragweed control by PRE herbicides due to the high giant ragweed seedling density at the Janesville site in 2018 (Striegel et al. 2021a). No cases of giant ragweed resistance have been documented in Wisconsin for the PRE herbicides tested in this study (Heap 2022).

Waterhemp Control

At the Lancaster-2021 site, the PRE herbicide treatment effect was significant for control ($P < 0.01$) and biomass reduction ($P < 0.01$); most PRE herbicides provided ≥90% waterhemp control and biomass reduction 6 WAT, other than atrazine, dicamba, and flumetsulam + clopyralid (<45%; Figure 4). At the Lancaster-2022 site, the PRE herbicide treatment effect was significant ($P < 0.01$), and the herbicides isoxaflutole, dicamba, atrazine, and simazine (all with a single SOA) and the premix flumetsulam + clopyralid (all with two SOAs) provided poor waterhemp control (≤70% control and biomass reduction; Figure 4). Atrazine + acetochlor, atrazine + S-metolachlor, and atrazine + S-metolachlor + bicyclopyrone + mesotrione premixes controlled waterhemp by 98%, 92%, and 80%, respectively, and reduced waterhemp biomass by 96%, 84%, and 87%, respectively, compared to atrazine alone (66% of control and 56% of biomass reduction) in 2022; however, waterhemp control and biomass reduction were similar to that achieved with acetochlor or S-metolachlor applied alone (Figure 4). Herbicide premixes with more than one SOA provided relatively better waterhemp control than herbicides with a single SOA (Figure 3).

The low degree of waterhemp control provided by the PRE herbicide premix flumetsulam + clopyralid and atrazine may be related to waterhemp resistance to herbicides that inhibit acetolactate synthase (ALS) (Faleco et al. 2022b) and photosystem II (PS II), respectively (Faleco et al. 2022a, 2022b). ALS- and PS II-resistant waterhemp has been widely reported across the midwestern United States (Evans et al. 2019; Heap 2022; Vennapusa et al. 2018). The ineffective waterhemp control provided by atrazine may also be a result of reduced residual activity caused by repeated use of atrazine over the years (Mueller et al 2017). According to previous studies, atrazine microbial degradation is enhanced in soils with repeated atrazine use compared with soils that have not been treated with the herbicide (Mueller et al 2017; Shaner and Henry 2007).

Reduced residual waterhemp control provided by simazine in 2022 may be due to the rapid dissipation of this herbicide. Although simazine is considered moderately persistent in soil with an average half-life of 60 d (Shaner 2014), persistence is affected by edaphoclimatic conditions and history of use with a wide half-life range (16 to 186 d). Abit et al. (2012) observed a range of simazine half-life of 21 to 158 d in California vineyards, and the residual weed control was reduced in the site-years where simazine had dissipated more quickly due to rapid microbial degradation.

The effective control of waterhemp in the premixes containing atrazine may be attributed to the shared active ingredients mesotrione (Group 27), acetochlor (Group 15), and S-metolachlor (Group 15), which are recommended for small-seeded broadleaf control (DeWerf et al. 2023). Therefore, despite considered the most troublesome weed in Wisconsin cropping systems and across U.S. corn production (Van Wychen 2020; Werle and Oliveira 2018), multiple effective PRE herbicide options exist for waterhemp management.

Common Lambsquarters Control

At the Lancaster-2021 site, the PRE herbicide treatment effect was significant for control ($P < 0.01$) and biomass reduction ($P < 0.01$), and most PRE herbicides provided ≥90% control of common lambsquarters at 6 WAT. Dicamba provided the least control of common lambsquarters (≤64%). Acetochlor, dicamba, and saflufenacil + dimethenamid-P provided low biomass reduction (≤66%), and the remaining treatments resulted in ≥87% biomass reduction (Figure 5). In 2022, the PRE herbicide treatment effect was significant for control and biomass ($P < 0.01$) reduction ($P < 0.01$); acetochlor, saflufenacil + dimethenamid-P, isoxaflutole, and S-metolachlor resulted in ≤77% of common lambsquarters control and the remaining treatments provided effective control (≥90%). Isoxaflutole, dicamba, acetochlor, S-metolachlor, and saflufenacil + dimethenamid-P resulted in the lowest common lambsquarters biomass reduction (≤68%; Figure 5). The premixes

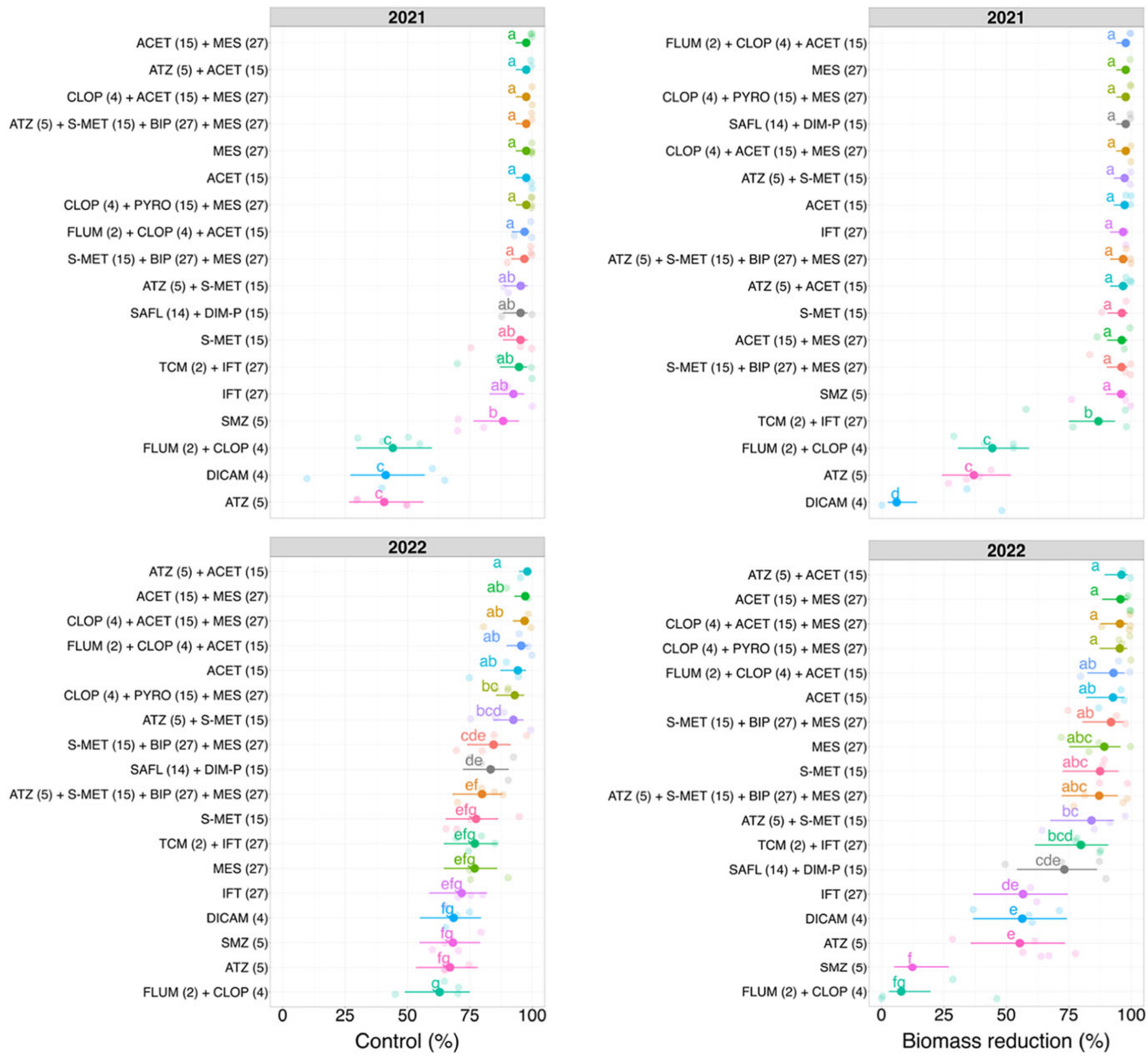

Figure 4. Waterhemp control (% of nontreated control; left) and biomass reduction (% of nontreated control; right) in Lancaster, Wisconsin, 2021 and 2022 at 6 wk after treatment. Jittered points represent replicates, centered solid points denote the means, and error bars represent the upper and lower 95% confidence interval limits. Means were compared using Fisher's LSD, and herbicide treatments with the same letters are not different at $\alpha = 0.05$. Numbers in parentheses in the y-axis represent the site of action of each herbicide. Abbreviations: DICAM, dicamba; ATZ, atrazine; SMZ, simazine; ACET, acetochlor; S-MET, S-metolachlor; IFT, isoxaflutole; MES, mesotrione; TCM, thiencarbazone-methyl; SAFL, saflufenacil; DIM-P, dimethenamid-P; FLUM, flumetsulam; CLOP, clopyralid; BIP, bicyclopyrone; PYRO, pyroxasulfone.

atrazine + acetochlor, atrazine + S-metolachlor, atrazine + S-metolachlor + bicyclopyrone + mesotrione, clopyralid + acetochlor + mesotrione, S-metolachlor + bicyclopyrone + mesotrione, and flumetsulam + clopyralid + acetochlor controlled common lambsquarters to a similar degree when atrazine was applied alone, but control was greater than that provided by acetochlor or S-metolachlor (Figure 5). A similar trend was reported by Jha et al. (2015) who noted that adding pendimethalin to acetochlor improved residual control of common lambsquarters by 40% and 36% at 21 and 35 DAT, respectively.

For the current study, the premixes, except saflufenacil + dimethenamid-P, resulted in effective control and biomass reduction of common lambsquarters (≥90%; Figures 3 and 5), similar to atrazine, simazine, and mesotrione when applied alone. Although ranked in the top five most problematic weeds in U.S. corn production (Van Wychen 2020), results of this study demonstrate that several PRE herbicides can be effective for common lambsquarters control.

Giant Foxtail Control

Giant foxtail control data were collected at the Lancaster-2022 site only (this species was not present at the Lancaster-2021 field study location). The PRE herbicide treatment effect was significant for control ($P < 0.01$) and biomass reduction ($P < 0.01$), and only atrazine + acetochlor resulted in >90% control of giant foxtail 6 WAT (Figure 6). The premixes performed better than the herbicides with a single SOA (Figures 3 and 6), except for acetochlor (≥87%)

https://doi.org/10.1017/wet.2023.45 Published online by Cambridge University Press

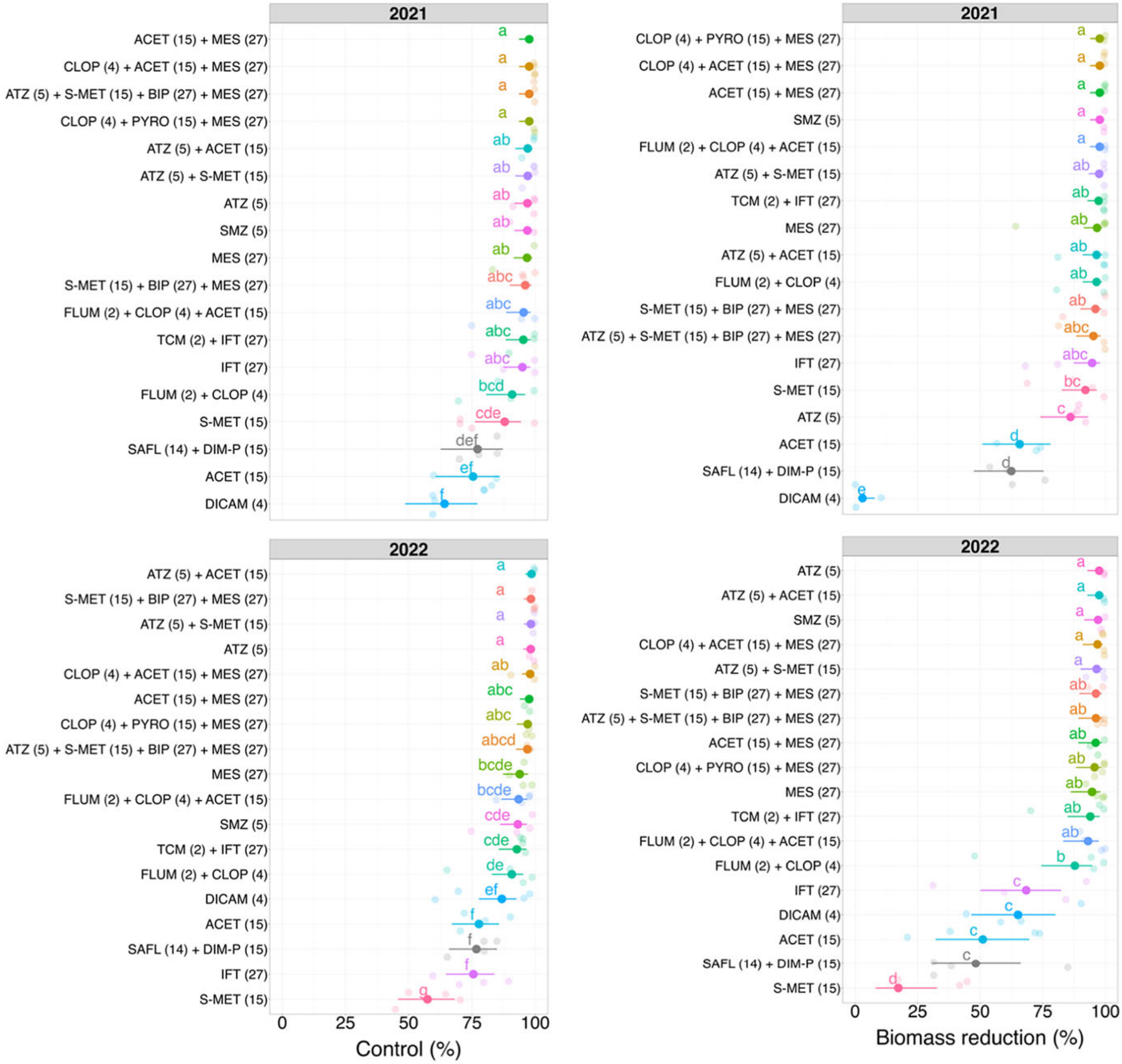

Figure 5. Common lambsquarters control (% of nontreated control; left) and biomass reduction (% of nontreated control; right) in Lancaster, Wisconsin, 2021 and 2022 at 6 wk after treatment. Jittered points represent replicates, centered solid points denote the means, and error bars represent the upper and lower 95% confidence interval limits. Means were compared using Fisher's LSD, and herbicide treatments with the same letters are not different at α = 0.05. Numbers in parentheses in the y-axis represent the site of action of each herbicide. Abbreviations: DICAM, dicamba; ATZ, atrazine; SMZ, simazine; ACET, acetochlor; S-MET, S-metolachlor; IFT, isoxaflutole; MES, mesotrione; TCM, thiencarbazone-methyl; SAFL, saflufenacil; DIM-P, dimethenamid-P; FLUM, flumetsulam; CLOP, clopyralid; BIP, bicyclopyrone; PYRO, pyroxasulfone.

and S-metolachlor (≥74%), which provided an effective level of giant foxtail control, and the premix flumetsulam + clopyralid, which provided a low level of giant foxtail control (≤68%; Figure 6). The biomass reduction followed a similar trend: the PRE herbicides with a single active ingredient (simazine, isoxaflutole, dicamba, mesotrione, and atrazine) resulted in low levels of giant foxtail biomass reduction (≤48%), except S-metolachlor and acetochlor (≥75%), which both provided an effective reduction in biomass, similar to that of the premixes (Figure 6).

The premix flumetsulam + clopyralid and atrazine + S-metolachlor + bicyclopyrone + mesotrione provided low giant foxtail biomass reduction (≤42%). The low biomass reduction by atrazine + S-metolachlor + bicyclopyrone + mesotrione suggests that not all herbicide premixes with multiple SOAs may provide effective weed control. The lower rate of S-metolachlor applied in this premix (1,498 g ai ha^{-1}) compared to S-metolachlor alone (1,791 g ai ha^{-1}) may have contributed to the lower giant foxtail biomass reduction in the premix treatment. Thus, it is important to consider the application rate of each active ingredient in a premix and how that compares to the same herbicide applied alone. Besides containing multiple SOAs at appropriate rates, premixes or herbicide mixtures should contain active ingredients that have similar efficacy and persistence in soil to act simultaneously on the same spectrum of weeds (Norsworthy et al. 2012).

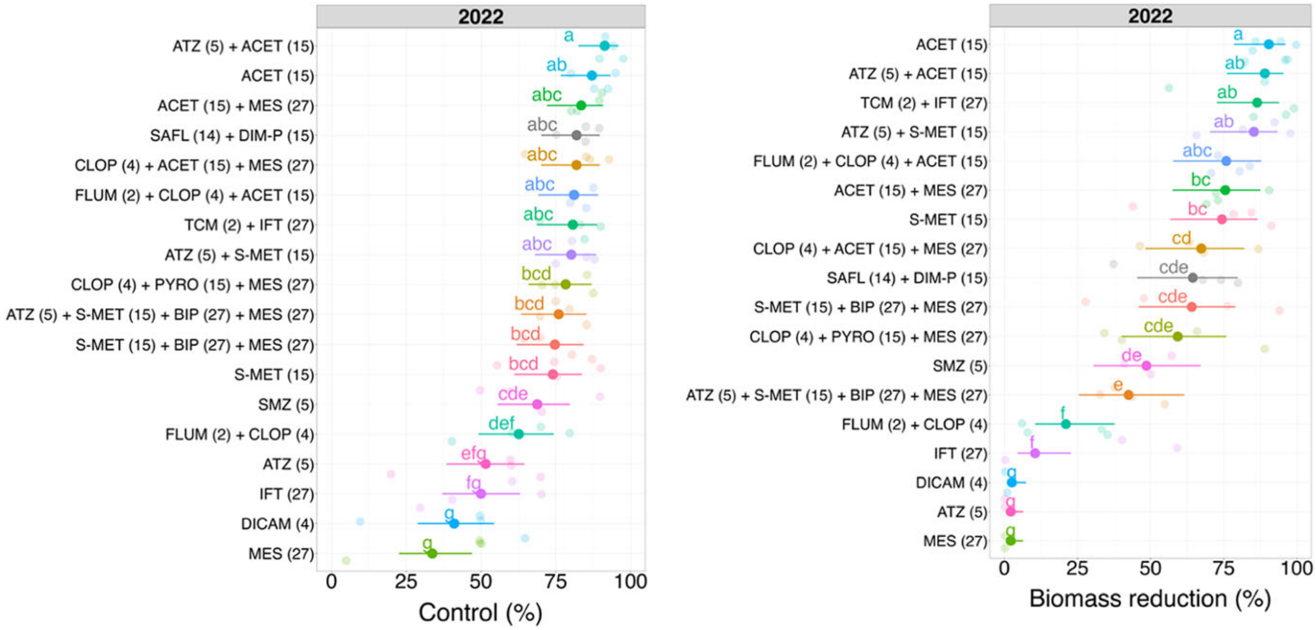

Figure 6. Giant foxtail control (% of nontreated control; left) and biomass reduction (% of nontreated control; right) in Lancaster, Wisconsin, 2022 at 6 wk after treatment. Jittered points represent replicates, centered solid points denote the means, and error bars represent the upper and lower 95% confidence interval limits. Means were compared using Fisher's LSD, and herbicide treatments with the same letters are not different at $\alpha = 0.05$. Numbers in parentheses in the y-axis represent the site of action of each herbicide. Abbreviations: DICAM, dicamba; ATZ, atrazine; SMZ, simazine; ACET, acetochlor; S-MET, S-metolachlor; IFT, isoxaflutole; MES, mesotrione; TCM, thiencarbazone-methyl; SAFL, saflufenacil; DIM-P, dimethenamid-P; FLUM, flumetsulam; CLOP, clopyralid; BIP, bicyclopyrone; PYRO, pyroxasulfone.

Corroborating the visual control results, acetochlor and atrazine + acetochlor provided the greatest reduction in giant foxtail biomass (≥90%; Figure 6). The high degree (≥87%) of giant foxtail control with acetochlor, atrazine + acetochlor, and the relatively effective (≥70%) control with the other acetochlor premixes, S-metolachlor alone, and S-metolachlor premixes might be due to the action of herbicides that inhibit very-long-chain fatty acids (e.g., acetochlor or S-metolachlor) since the premixes did not provide a reduction in giant foxtail biomass that was different from that provided by acetochlor or S-metolachlor applied alone.

Pearson's Correlation

A strong positive correlation was detected between overall visual weed control and biomass reduction ($R = 0.88$; $P < 0.001$; Figure 7). Despite the potential subjectivity of visual weed control ratings, the strong correlation detected herein indicates that such assessments can be a reliable assessment of weed control efficacy. Visual weed control and weed biomass reduction are important measurements in determining PRE herbicide efficacy, but often researchers will collect only visual weed control ratings. According to our results, high-quality visual weed control data can be used as indicators of PRE herbicide efficacy when biomass data are not available. In general, less work is required to collect visual weed control data, which allows for a rapid quantitative evaluation of herbicide efficacy. Despite that, biomass data are commonly required in the weed science literature to support weed control results and can be used to estimate weed seed production if such correlations (biomass and seed production) are available in the literature (Chauhan and Johnson 2010; Schwartz et al. 2016; Wilson et al. 1995).

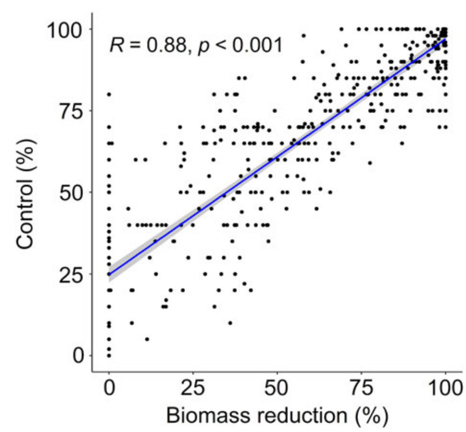

Figure 7. Pearson's linear correlation between weed control (% of nontreated control) and weed biomass reduction (% of nontreated control) for giant ragweed, waterhemp, common lambsquarters, and giant foxtail at the Janesville and Lancaster locations in 2021 and 2022 combined. The correlation (*R*) is 0.88 (lower confidence interval [CI] 0.86 to upper CI 0.89) with P-value < 0.001. The blue line represents the linear trend and the shaded area the 95% CI.

Weed Control by the Number of Active Ingredients

The PRE herbicide comparison by the number of SOAs concluded that PRE herbicide premixes (two and three SOAs) tended to result in greater control of giant ragweed, waterhemp, common lambsquarters, and giant foxtail than herbicides with a single SOA (Figure 3). The overall weed control across site-years followed the same trend, wherein PRE herbicides with two (78%) and three (81%) SOAs provided greater weed control than PRE herbicides with a single SOA (68%) (Figure 3).

https://doi.org/10.1017/wet.2023.45 Published online by Cambridge University Press

Supporting our weed control and biomass reduction findings, these results indicate that at least two SOAs are needed in a premix to achieve greater weed control with PRE herbicides; however, more SOAs may not further improve the weed control. In this study there was no difference in weed control efficacy between the premixes with two and three SOAs (Figure 3). Nevertheless, the strategic selection of premixes with at least two SOAs considering the weed seed bank community composition and the predicted environmental conditions following application can improve the diversity of the weed management program and may delay the evolution of resistance because of reduced selection pressure on single PRE and POST herbicides (Norsworthy et al. 2012). With limited rainfall as occurred at the Janesville-2022 experimental site, the PRE herbicide premixes still performed better than most PRE herbicides with a single SOA (Figures 1 and 2).

Considering that more variable weather conditions and future weed resistance problems are likely to occur across the Midwest United States (Landau et al. 2021a; Westwood et al. 2018), the use of strategically selected herbicide premixes should become a standard management practice for more effective early season weed control in corn crops. Premixes add to the diversity of SOAs and contribute to a more sustainable and effective corn PRE herbicide program by offering a broader spectrum weed control and reducing the reliance on single PRE and POST herbicides.

Practical Implications

The results of this study provide insight into PRE herbicide options to improve early season weed control in conventional tillage corn crops. PRE herbicide premixes containing at least two SOAs provided more reliable and improved weed control compared to herbicides with a single SOA, but dominant weed species and rainfall amount and pattern are still essential factors to be considered when selecting a PRE herbicide premix. These results will support Wisconsin farmers and others who must select or recommend PRE herbicides for weed control in corn production while also considering the soil seedbank weed community composition and anticipated environmental conditions.

Acknowledgments. We thank the University of Wisconsin–Madison Lancaster Agricultural Research Station and the Rock County Farm staff, and the University of Wisconsin–Madison Cropping Systems Weed Science members for their technical assistance in conducting this research. Tatiane Severo Silva's graduate research assistantship was partially sponsored by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES), Finance Code 001. The authors acknowledge Drs. Alexandre Tonon Rosa (Bayer Crop Science), Luis Antonio de Avila (Mississippi State University), Ahmadreza Mobli (University of Wisconsin–Madison), Christopher A. Proctor (University of Nebraska–Lincoln), and John M. Wallace (Pennsylvania State University) for their contributions to the manuscript. No conflicts of interest have been declared. This research received no specific grant from any funding agency, commercial, or not-for-profit sectors.

References

Abit MJ, Rainbolt CM, Krutz LJ, Shaner DL, Hanson BD (2012) Effects of long-term use on simazine dissipation in central California vineyards Weed Sci 60:531–536

Barbieri GF, Young BG, Dayan FE, Streibig JC, Takano H, Merotto Junior A, Avila LA (2022) Herbicide mixtures: interactions and modeling. Adv Weed Sci 40:e020220051

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

Bell HD, Norsworthy JK, Scott RC, Popp M (2015) Effect of row spacing, seeding rate, and herbicide program in glufosinate-resistant soybean on Palmer amaranth management Weed Technol 29:390–404

Bollman SL, Kells JJ, Penner D (2006) Weed response to mesotrione and atrazine applied alone and in combination preemergence Weed Technol 20:903–907

Brooks ME, Kristensen K, Van Benthem KJ, Magnusson A, Berg CW, Nielsen A, Skaug HJ, Machler M, Bolker BM (2017) glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. R J 9:378–400

Cahoon CW, York AC, Jordan DL, Everman WJ, Seagroves RW, Braswell LR, Jennings KM (2015b) Weed control in cotton by combinations of microencapsulated acetochlor and various residual herbicides applied preemergence. Weed Technol 29:740–750

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

Carneiro GDOP, de Freitas Souza M, Lins HA, das Chagas PSF, Silva TS, da Silva Teófilo TM, Pavão QS, Grangeiro LC, Silva DV (2020) Herbicide mixtures affect adsorption processes in soils under sugarcane cultivation. Geoderma 379:114626

Chauhan BS, Johnson DE (2010) Implications of narrow crop row spacing and delayed *Echinochloa colona* and *Echinochloa crus-galli* emergence for weed growth and crop yield loss in aerobic rice. Field Crops Res 117:177–182

Dewerf R, Bick E, Liesch PJ, Nice G, Renz M, Smith D, Werle R (2023) Pest Management in Wisconsin Field Crops - 2023 (A3646). Madison: University of Wisconsin Extension. https://cropsandsoils.extension.wisc.edu/files/2022/12/A3646_Book_web.pdf. Accessed: December 21, 2022

DeWerff R, Arneson N, Werle R (2022) 2022 Wisconsin Weed Science Research Report. https://wiscweeds.info/reports.html. Accessed: January 16, 2023

Dong F, Mitchell PD, Davis VM, Recker R (2017) Impact of atrazine prohibition on the sustainability of weed management in Wisconsin maize production. Pest Manag Sci 73:425–434

Evans CM, Strom SA, Riechers DE, Davis AS, Tranel PJ, Hager AG (2019) Characterization of a waterhemp (*Amaranthus tuberculatus*) population from Illinois resistant to herbicides from five site-of-action groups. Weed Technol 33:400–410

Faleco FA, Oliveira MC, Arneson NJ, Renz M, Stoltenberg DE, Werle R (2022b) Multiple herbicide resistance in waterhemp (*Amaranthus tuberculatus*) accessions from Wisconsin. Weed Technol 36:597–608

Faleco FA, Oliveira MC, Arneson NJ, Renz M, Stoltenberg DE, Werle R (2022a) Multiple resistance to imazethapyr, atrazine, and glyphosate in a recently introduced Palmer amaranth (*Amaranthus palmeri*) accession in Wisconsin. Weed Technol 36:344–351

Fox J, Weisberg S (2019) An R companion to applied regression, 3rd ed. Thousand Oaks, CA: Sage Publications. 608 p

Glaspie CF, Jones EA, Penner D, Pawlak JA, Everman WJ (2021) Effect of clay, soil organic matter, and soil pH on initial and residual weed control with flumioxazin. Agronomy 11:1326.

Grint K, Arneson NJ, Arriaga F, DeWerff R, Oliveira M, Smith DH, Stoltenberg DE, Werle R (2022a) Cover crops and preemergence herbicides: An integrated approach for weed management in corn-soybean systems in the US Midwest. Front Agron 4:888349

Grint KR, Proctor C, DeWerff R, Smith DH, Arneson NJ, Arriaga F, Stoltenberg D, Werle R (2022b) Low carryover risk of corn and soybean herbicides across soil management practices and environments. Weed Technol 36:160–167

Hay MM, Shoup DE, Peterson DE (2018) Palmer Amaranth (*Amaranthus palmeri*) and common waterhemp (*Amaranthus rudis*) control with very-long-chain fatty acid inhibiting herbicides. Crop Forage Turfgrass Manag 4:1–9

Heap I (2022) The International Herbicide-Resistant Weed Database. https://www.weedscience.org/Pages/Species.aspx. Accessed: October 31, 2022

Janak TW, Grichar WJ (2016) Weed control in corn (*Zea mays* L.) as influenced by preemergence herbicides. Int J Agron 2016:1–9

Jha P, Kumar V, Garcia J, Reichard N (2015) Tank mixing pendimethalin with pyroxasulfone and chloroacetamide herbicides enhances in-season residual weed control in corn. Weed Technol 29:198–206

Jha P, Kumar V, Godara RK, Chauhan BS (2017) Weed management using crop competition in the United States: A review. Crop Prot 95:31–37
Jursik M, Soukup J, Holec J, Andr J, Hamouzová K (2015) Efficacy and selectivity of pre-emergent sunflower herbicides under different soil moisture conditions. Plant Prot Sci 51:214–222
Knezevic SZ, Pavlovic P, Osipitan OA, Barnes ER, Beiermann C, Oliveira MC, Lawrence N, Scott JE, Jhala A (2019) Critical time for weed removal in glyphosate-resistant soybean as influenced by preemergence herbicides. Weed Technol 33:393–399
Landau C A, Hager AG, Tranel PJ, Davis AS, Martin NF, Williams MM (2021a) Future efficacy of pre-emergence herbicides in corn (*Zea mays*) is threatened by more variable weather. Pest Manag Sci 77:2683–2689
Landau CA, Hager AG,Williams MM (2021b) Diminishing weed control exacerbates maize yield loss to adverse weather. Glob Chang Biol 27:6156–6165
Lenth R (2022) emmeans: Estimated marginal means, aka least-squares means (R package version 1.8.3). https://cran.r-project.org/web/packages/emmeans/index.html. Accessed: September 20, 2022
Mueller TC, Parker ET, Steckel L, Clay SA, Owen MD, Curran WS, Currie R, Scott R, Sprague C, Stephenson DO, Miller DK (2017) Enhanced atrazine degradation is widespread across the United States. Pest Manag Sci 73:1953–1961
Mundt TT, Carbonari CA, Moisinho IS, de Brito IP, Picoli Junior GJ, Ovejero RF, Velini ED (2022) Dynamics and weed control effectiveness of dicamba herbicide when applied directly on the soil and corn straw in Brazil. J Environ Sci Heal B 57:865–875
Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60(SP1):31–62
Oliveira MC, Feist D, Eskelsen S, Scott JE, Knezevic SZ (2017a) Weed control in soybean with preemergence-and postemergence-applied herbicides. Crop Forage Turfgrass Manag 3:1–7
Oliveira MC, Jhala AJ, Gaines T, Irmak S, Amundsen K, Scott JE, Knezevic SZ (2017b) Confirmation and control of HPPD-inhibiting herbicide–resistant waterhemp (*Amaranthus tuberculatus*) in Nebraska. Weed Technol 31:67–79
Palma-Bautista C, Cruz-Hipólito HE, Alcantara-de La Cruz R, Vázquez-García JG, Yanniccari M, De Prado R (2021) Comparison of premix glyphosate and 2, 4-D formulation and direct tank mixture for control of *Conyza canadensis* and *Epilobium ciliatum.* Environ Pollut 281:117013
Pik AJ, Peake E, Strosher MT, Hodgson GW (1977) Fate of 3,6-dichloropicolinic acid soils J Agric Food Chem 25:1054–1061
[PPDB] Pesticide Properties Database (2022) Hatfield, UK: University of Hertfordshire. http://sitem.herts.ac.uk/aeru/footprint/index2.htm. Accessed: December 20, 2022
Priess GL, Norsworthy JK, Roberts TL, Gbur EE (2020) Weed control and soybean injury from preplant vs. preemergence herbicide applications. Weed Technol 34:718–726
R Core Team (2022). R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org/. Accessed: November 10, 2022
Sarangi D, Jhala AJ (2018) 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. Soil Tillage Res 178:82–91
Schwartz LM, Norsworthy JK, Young BG, Bradley KW, Kruger GR, Davis VM, Steckel LE, Walsh MJ (2016) Tall waterhemp (*Amaranthus tuberculatus*) and Palmer amaranth (*Amaranthus palmeri*) seed production and retention at soybean maturity. Weed Technol 30:284–290
Seefeldt SS, Boydston RA, Kaspari PN (2014) Clopyralid and dicamba residue impacts on potatoes and weeds. Am J Potato Res 91:625–631
Shaner DL (2014) Herbicide Handbook. 10th ed. Lawrence, KS: Weed Science Society of America. 513 p
Shaner DL, Henry WB (2007) Field history and dissipation of atrazine and metolachlor in Colorado. J Environ Qual 36:128–134
Somerville GJ, Powles SB, Walsh MJ, Renton M (2017) Why was resistance to shorter-acting pre-emergence herbicides slower to evolve? Pest Manag Sci 73:844–851
Stewart CL, Nurse RE, Hamill AS, Sikkema PH (2010) Environment and soil conditions influence pre-and postemergence herbicide efficacy in soybean. Weed Technol 24:234–243
Striegel S, DeWerff RP, Arneson NJ, Oliveira MC, Werle R (2021a) Pre-emergence herbicides, not carrier volume, impacted weed management in conventional tillage systems. Crop Forage Turfgrass Manag 7:e20132
Striegel S, Oliveira MC, DeWerff RP, Stoltenberg DE, Conley SP, Werle R (2021b) Influence of postemergence dicamba/glyphosate timing and inclusion of acetochlor as a layered residual on weed control and soybean yield. Front Agron 3:788251
Urach Ferreira PH, Ferguson JC, Reynolds DB, Kruger GR, Irby JT (2020) Droplet size and physicochemical property effects on herbicide efficacy of pre-emergence herbicides in soybean (*Glycine max* (L.) Merr). Pest Manag Sci 76:737–746
[USDA-NASS] U.S. Department of Agriculture–National Agricultural Statistics Service (2022) https://www.nass.usda.gov/index.php. Accessed: January 17, 2023.
[USDA-NASS] U.S. Department of Agriculture–National Agricultural Statistics Service (2023) https://www.nass.usda.gov/Data_Visualization/Commodity/index.php. Accessed: January 17, 2023
Van Wychen L (2020) 2020 Survey of the Most Common and Troublesome Weeds in Grass Crops, Pasture & Turf in the United States and Canada. Westminster, CO: Weed Science Society of America. https://wssa.net/wp-content/uploads/2020-Weed-Survey_grass-crops.xlsx Accessed: January 25, 2022
Varanasi A, Prasad PV, Jugulam M (2016) Impact of climate change factors on weeds and herbicide efficacy. Adv Agron 135:107–146
Vennapusa AR, Faleco F, Vieira B, Samuelson S, Kruger GR, Werle R, Jugulam M (2018) Prevalence and mechanism of atrazine resistance in waterhemp (*Amaranthus tuberculatus*) from Nebraska. Weed Sci 66:595–602
Werle R, Oliveira M (2018) 2018 Wisconsin Cropping Systems Weed Science Survey - Where are we at? Madison: University of Wisconsin, Cropping Systems Weed Science. https://www.wiscweeds.info/post/2018-wisconsin-cropping-systems-weed-science-survey/. Accessed: December 13, 2022
Westwood JH, Charudattan R, Duke SO, Fennimore SA, Marrone P, Slaughter DC, Swanton C, Zollinger R (2018) Weed management in 2050: Perspectives on the future of weed science. Weed Sci 66:275–285
Wilson BJ, Wright KJ, Brain P, Clements M, Stephens E (1995) Predicting the competitive effects of weed and crop density on weed biomass, weed seed production and crop yield in wheat. Weed Res 35:265–278
Zhao N, Zuo L, Li W, Guo W, Liu W, Wang J (2017) Greenhouse and field evaluation of isoxaflutole for weed control in maize in China. Sci Rep 7:1–9