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Dicamba; glufosinate; glyphosate; broadleaf signalgrass, *Urochloa platyphylla* (Munro ex C. Wright) R.D. Webster; morningglory, *Ipomoea* spp.; Palmer amaranth, *Amaranthus palmeri* S. Watson; purslane, *Portulaca* spp.; soybean, *Glycine max* (L.) Merr.

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Comparing herbicide application methods with See & Spray™ technology in soybean

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Abstract

New machine-vision technologies like the John Deere See & Spray™ could provide the opportunity to reduce herbicide use by detecting weeds and target-spraying herbicides simultaneously. Experiments were conducted for 2 yr in Keiser, AR, and Greenville, MS, to compare residual herbicide timings and targeted spray applications versus traditional broadcast herbicide programs in glyphosate/glufosinate/dicamba-resistant soybean. Treatments utilized consistent herbicides and rates with a preemergence (PRE) application followed by an early postemergence (EPOST) dicamba application followed by a mid-postemergence (MPOST) glufosinate application. All treatments included a residual at PRE and excluded or included a residual EPOST and MPOST. Additionally, the herbicide application method was considered, with traditional broadcast applications, broadcasted residual + targeted applications of postemergence herbicides (dual tank), or targeted applications of all herbicides (single tank). Targeted applications provided comparable control to broadcast applications with a ≤1% decrease in efficacy and overall control ≥93% for Palmer amaranth, broadleaf signalgrass, morningglory species, and purslane species. Additionally, targeted sprays slightly reduced soybean injury by at most 5 percentage points across all evaluations, and these effects did not translate to a yield increase at harvest. The relationship between weed area and targeted sprayed area also indicates that nozzle angle can influence potential herbicide savings, with narrower nozzle angles spraying less area. On average, targeted sprays saved a range of 28.4% to 62.4% on postemergence herbicides. On the basis of these results, with specific machine settings, targeted application programs could reduce the amount of herbicide applied while providing weed control comparable to that of traditional broadcast applications.

Introduction

Producers face economic and environmental pressure to reduce herbicide use, and the increasing occurrence of herbicide-resistant weeds threatens the options for successful chemical control. Weeds compete with crops for resources, reducing yield and harvest efficiency (Klingaman and Oliver 1994; Spitters and Van Den Bergh 1982). Palmer amaranth has become the most troublesome weed for row-crop producers across the United States (Van Wychen 2020, 2022). A single Palmer amaranth plant per meter of row reduced soybean yield by 32% and can produce up to 600,000 seeds (Keeley et al. 1987; Klingaman and Oliver 1994). Additionally, Palmer amaranth has evolved resistance to nine different sites of action, seven of which are utilized for postemergence (POST) control of the weed (Brabham et al. 2019; Foster and Steckel 2022; Heap 2023; Jones 2022; Priess et al. 2022a; Randell-Singleton et al. 2024). Additionally, ensuring that weeds do not set seed by the end of the season is paramount to preventing the evolution of herbicide resistance (Bagavathiannan and Norsworthy 2012; Norsworthy et al. 2012).

The spatial distribution of weeds is not uniform across agricultural fields (Cardina et al. 1997; Metcalfe et al. 2019; Rew and Cousens 2001; Stafford and Miller 1993; Wiles et al. 1992). Often weeds emerge in clumps or patches, creating an opportunity to target herbicide applications to the patches or individual weeds, reducing the amount of chemical applied to a field and thereby improving environmental stewardship. In the United States, from 2017 to 2022, the total cost of production for row-crop farms increased by 26.6%, and chemicals accounted for an average of

Table 1. Site-specific information and management.[a]

Location	Year	Texture	OM	Variety	Planting date	Application date (growth stage)		
						PRE	EPOST	MPOST
		% sand, silt, clay						
NEREC	2021	17, 34, 49	2.2	Beck's 4885XF0	15 Jun	15 Jun	22 Jul (V4)	4 Aug (R1)
	2022	1, 41, 50	2.8	Beck's 4885XF0	6 Jun	6 Jun	30 Jun (V4)	21 Jul (R1)
SRD	2021	35, 56, 9	0.8	LS4606XF	31 May	1 Jun	24 Jun (V4)	3 Jul (R1)
	2022	35, 56, 9	0.8	AG48XF2	1 Jun	1 Jun	23 Jun (V3)	7 Jul (R1)

[a] Abbreviations: EPOST, early postemergence; MPOST, mid-postemergence; NEREC, Northeast Research and Extension Center, Keiser, AR; OM, organic matter; PRE, preemergence; SRD, Stoneville R&D, Greenville, MS.

7.7% of the total cost (Foreign Agriculture Service 2023). With the increasing cost of production, producers are seeking technologies to reduce costs and improve profitability.

Over the past few decades, some of the primary limitations in developing machine vision technologies for weed detection have included the lack of robust computer processing and the environmental variability in production systems, where plant morphology and the environment are dynamic and weeds can often be occluded by crops (Fernandez-Quintanilla et al. 2018; Franz et al. 1991; Munier-Jolain et al. 2014). Recently, lettuce (*Lactuca sativa* L.) thinners have utilized machine vision, reducing labor by ~13 hr ha^{-1} compared to hand thinning (Mosqueda et al. 2017). One of the technologies evaluated by Mosqueda and others was developed by Blue River Technology, now a subsidiary of Deere & Company. In 2020, John Deere publicly announced the development of See & Spray™ for row-crop production sprayers.

Currently, John Deere offers three systems for targeted applications: Select, Premium, and Ultimate (John Deere, n.d.; Lazaro et al. 2024). The Select system is factory purchased and designed for "green on brown" or fallow/burndown applications, targeting any growing vegetation in the field. The Premium system can be purchased new or retrofitted to specific models 2018 and newer with BoomTrac™ Pro 2.0 (Deere & Company, Moline, IL, USA) and the ExactApply™ (Deere & Company) nozzle body system. The Ultimate platform is factory purchased and performs like the Premium system but has a dual tank, boom, and pumping system that allows simultaneous broadcast and targeted applications. All systems utilize machine vision with cameras, vision-processing units, and height sensors mounted along the boom. Additionally, See & Spray™ Select uses machine learning with a proprietary algorithm with any vegetation and trigger applications (Lazaro et al. 2023). Premium and Ultimate utilize deep learning and can perform targeted applications in fallow, corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean, while Select can be utilized only in fallow scenarios.

One of the primary concerns with machine-vision, targeted applications is the potential for Type I error, or how many weeds were incorrectly considered not a weed. Currently, See & Spray™ allows operators to adjust the detection sensitivity setting, which dictates the confidence of the algorithm that what the cameras "see" is a weed (Lazaro et al. 2023). Additionally, operators can change the coverage buffer from small, medium, or large, which changes how many and for how long nozzles are triggered. Preliminary research has shown that targeted applications can reduce soybean response to herbicides and provide comparable weed control to traditional herbicide applications (Patzoldt et al. 2022). Also, John Deere claims that See & Spray™ can reduce herbicide use and provide weed control comparable to that of conventional broadcast applications (see John Deere, n.d.). Therefore this research aimed to determine the influence of residual herbicide timings and application methods on weed control and herbicide savings with targeted applications compared to traditional broadcast herbicide applications in a soybean production system.

Materials and Methods

Site and Design

Four trials were conducted from 2021 to 2022, with one conducted each year at both Stoneville R&D (SRD) in Greenville, MS, and at the Northeast Research and Extension Center (NEREC) in Keiser, AR (Table 1), for a total of 4 site-years. The experiment was designed as a single-factor randomized complete block design to compare targeted applications with See & Spray™ to traditional broadcast application methods (Table 2). The treatments featured the same herbicide program and differed at PRE by either broadcasting all herbicides or broadcasting the residual herbicides and applying POST herbicides through targeted applications (See & Spray™ Ultimate or two passes with See & Spray™ Premium). At early postemergence (EPOST), treatments diverged by either including or excluding residual herbicides, applying all herbicides through targeted applications (See & Spray™ Premium or combined dual tank with See & Spray™ Ultimate) or broadcasting residual herbicides and targeting POST herbicides (See & Spray™ Ultimate or two passes with Premium). Again, at mid-postemergence (MPOST), treatments deviated by including or excluding residual herbicides and by application method. A nontreated control, PRE herbicide only, and a hand-weeded control were added for comparisons to produce 14 total treatments. Each treatment was replicated four times, and plots were 27.4 m (SRD) or 30.5 m (NEREC) long × 3.8 m wide with four soybean rows.

In both years, a glyphosate/glufosinate/dicamba-resistant soybean variety (XtendFlex®, Bayer Crop Science, St. Louis, MO, USA) was planted on 96.5-cm-wide rows at 346,000 seeds ha^{-1} from the last week of May to the second week of June (Table 1). At NEREC, furrow irrigation was utilized as needed, whereas SRD was watered by natural precipitation. All herbicide sources are listed in Table 3. PRE applications occurred within 24 hr of planting utilizing SF4003 nozzles (Greenleaf Technologies, Covington, LA, USA) and using a prototype 30° rear-incline cap (30RI) at 303 kPa for targeted applications or AIXR 11002 nozzles (TeeJet® Technologies, Glendale Heights, IL, USA) at 283 kPa for broadcast applications. EPOST treatments were applied primarily around 24 d after planting (DAP), with one instance being 37 DAP at NEREC in 2021. Treatments involving dicamba at EPOST were applied with PSLDMQ2004 nozzles (Hypro, Pentair, Minneapolis, MN,

Table 2. Treatments for herbicides, application timing, and application method.[a,b]

	PRE at planting		EPOST		MPOST	
Treatment	BC	TA	BC	TA	BC	TA
Nontreated	—	—	—	—	—	—
PRE only	Paraquat + metribuzin + *S*-metolachlor + NIS	—	—	—	—	—
BC no residual	Paraquat + metribuzin + *S*-metolachlor + NIS	—	Dicamba + clethodim + NIS/VRA/DRA	—	Glufosinate + glyphosate	—
TA no residual	Metribuzin + *S*-metolachlor + NIS	Paraquat + NIS	—	Dicamba + clethodim + NIS/VRA/DRA	—	Glufosinate + glyphosate
BC + residual EPOST	Paraquat + metribuzin + *S*-metolachlor + NIS	—	Dicamba + clethodim + acetochlor + NIS/VRA/DRA	—	Glufosinate + glyphosate	—
TA + TA residual EPOST	Metribuzin + *S*-metolachlor + NIS	Paraquat + NIS	—	Dicamba + clethodim + acetochlor + NIS/VRA/DRA	—	Glufosinate + glyphosate
TA + BC residual EPOST	Metribuzin + *S*-metolachlor + NIS	Paraquat + NIS	Acetochlor + NIS	Dicamba + clethodim + NIS/VRA/DRA	—	Glufosinate + glyphosate
BC + residual MPOST	Paraquat + metribuzin + *S*-metolachlor + NIS	—	Dicamba + clethodim + NIS/VRA/DRA	—	Glufosinate + glyphosate + acetochlor	—
TA residual MPOST + TA	Metribuzin + *S*-metolachlor + NIS	Paraquat + NIS	—	Dicamba + clethodim + NIS/VRA/DRA	—	Glufosinate + glyphosate + acetochlor
BC residual MPOST + TA	Metribuzin + *S*-metolachlor + NIS	Paraquat + NIS	—	Dicamba + clethodim + NIS/VRA/DRA	Acetochlor + NIS	Glufosinate + glyphosate
BC + residual	Paraquat + metribuzin + *S*-metolachlor + NIS	—	Dicamba + clethodim + acetochlor + NIS/VRA/DRA	—	Glufosinate + glyphosate + acetochlor	—
TA + TA residual	Metribuzin + *S*-metolachlor + NIS	Paraquat + NIS	—	Dicamba + clethodim + acetochlor + NIS/VRA/DRA		Glufosinate + glyphosate + acetochlor
BC residual + TA	Metribuzin + *S*-metolachlor + NIS	Paraquat + NIS	Acetochlor + NIS	Dicamba + clethodim + NIS/VRA/DRA	Acetochlor + NIS	Glufosinate + glyphosate +
Hand-weeded check	Paraquat + metribuzin + *S*-metolachlor + NIS	—	Hand weed	Glyphosate	Hand weed	Glyphosate

[a] Abbreviations: BC, broadcast; DRA, drift-reducing agent; EPOST, early postemergence; MPOST, mid-postemergence; NIS, nonionic surfactant; PRE, preemergence; TA, targeted application; VRA, volatility-reducing agent.

[b] Herbicide rates for the Northeast Research and Extension Center, Keiser, AR, and Stoneville R&D, Greenville, MS: paraquat, 547 g ai ha^{-1}; metribuzin, 368 g ai ha^{-1}; *S*-metolachlor, 1,552 g ai ha^{-1}; dicamba, 560 g ae ha^{-1}; clethodim, 102 g ai ha^{-1}; acetochlor, 1,260 g ai ha^{-1}; glufosinate, 657 g ai ha^{-1}; glyphosate, 870 g ae ha^{-1}; nonionic surfactant, 0.25 %v/v; volatility-reducing agent, 1 %v/v; drift-reducing agent, 0.21 %v/v.

Table 3. Herbicides and adjuvants used in the experiment

Common name	Trade name	Manufacturer
Metribuzin *S*-metolachlor	Boundary® 6.5 EC	Syngenta Crop Protection, Greensboro, NC
Paraquat	Gramoxone® SL 3.0	Syngenta Crop Protection
Nonionic surfactant	Preference®	Winfield Solutions, St. Paul, MN
Dicamba	Engenia®	BASF, Research Triangle Park, NC
Clethodim	Select Max®	Valent USA, San Ramon, CA
Drift-reducing agent	UltraLock™	Winfield Solutions
Volatility-reducing agent	Volt-Edge™	Winfield Solutions
Acetochlor	Warrant®	Bayer Crop Science, St. Louis, MO
Glufosinate	Liberty® 280 SL	BASF
Glyphosate	Roundup PowerMAX® 3	Bayer Crop Science

USA) with the 30RI cap at 207 kPa, whereas broadcast residual applications were applied with AIXR 11002 nozzles. The MPOST applications occurred 9 to 21 d after the EPOST treatments and utilized PSGAT1003 nozzles (Pentair) for broadcast applications at 283 kPa, PS3DQ0004 nozzles (Pentair) that were all aligned rearwardly for targeted applications at 296 kPa, and AIXR 11002 nozzles for broadcast residual applications. All nozzles were calibrated for 12.9 kph to deliver 140 L ha^{-1}, except for any application using AIXR nozzles, which applied 94 L ha^{-1}.

The rearward inclination of nozzles for targeted applications allows more time between detection and decision, improving the accuracy and efficiency of the system (WLP, personal communication, 2021). Different nozzles were selected for different application timings owing to the herbicides being applied and because the nozzles were characterized for targeted application accuracy. Prior to use with targeted applications, nozzles must be characterized to ensure the accuracy of spray deposition. Some of the factors that would likely be considered are droplet velocity, droplet size, and fan pattern angle, to ensure that droplets deposit where weeds are detected (Giles et al. 2002). Additionally, venturi (air-inducted) nozzles can cause issues with technologies that signal solenoid valve activation, as indicated by pulse-width modulation research by Butts et al. (2019).

At the PRE application timing, the AIXR 11002 nozzles were utilized for both broadcast and broadcast residual applications to keep residual coverage uniform. Additionally, at the time of experiment initiation in 2021, AIXR nozzles were not characterized for targeted applications, but SF4003 nozzles were, hence the utilization at the PRE timing. At EPOST, dicamba was applied, and to maintain applicable results for producers utilizing this technology, nozzles that were characterized for targeted applications were selected. PSLDMQ nozzles are labeled for use with Engenia® (BASF, Research Triangle Park, NC, USA) when using the 06 orifice size (Anonymous 2024); however, given the speed of 12.9 kph, a 06 orifice size would not have been applicable, and a 04 orifice size was utilized instead. For glufosinate applications at MPOST, guardian air twin nozzles were used for the standard broadcast treatments. In contrast, the 3DQ nozzles provide a similar droplet spectrum but are naturally inclined and could be utilized for targeted applications, while PSGAT nozzles cannot be used because of the air induction and rearward inclination requirement for targeted applications. The rearward inclination of PSGAT nozzles would result in one of the fans depositing along the boom architecture, disrupting the overall spray pattern.

All herbicides were applied at 12.9 kph, and nozzles applying herbicides through the targeted spray boom were rearward inclined by 30°, except the PS3DQ nozzle, which is naturally inclined by 38°. The fallow/bareground model was utilized for PRE applications. POST treatments occurred using the crop model for soybean. The soybean crop model differentiates between soybean and weeds and triggers any nozzle that can contribute to the targeted deposition area. POST applications were triggered when new weeds emerged (<10 cm) to simulate when producers would initiate herbicide applications. All herbicides were applied through a refinement prototype mounted to the front-end loader of a tractor.

Agronomy Testing Machine

While commercial machines utilize a 36.6-m boom, Blue River Technology (Santa Clara, CA, USA) provided a research-grade version of these platforms to perform small-plot research. The agronomy testing machine (ATM) is designed to perform every task of a commercial machine and uses the same sensors, cameras, and processors as the marketed product. Four cameras, two vision-processing units, one StarFire™ (Deere & Company) GPS unit, and three boom-height sensors are fitted to the ATM to detect weeds, determine the locations of both the weeds and the nozzles, and trigger applications. The ATM also uses the same nozzle bodies with two solenoid valves, allowing simultaneous broadcast and targeted applications. A total of 10 nozzles are spaced 38 cm apart.

The main difference between the ATM and commercial sprayers is the fluid delivery system; the ATM utilizes two onboard air compressors with pressure regulators, rather than mechanical pressurization, and has the ability to connect two 18.9-L tanks to change between herbicide treatments efficiently. Additionally, the ATM has an external and in-cab control panel to prime and activate the sprayer and an in-cab computer to collect and extract data from the vision-processing units. At the time of each application, the ATM can collect recordings of each plot for later analysis using John Deere's proprietary software for quantitative assessments of weed area, crop area, and sprayed area. The models selected for the applications were based on the model year 2022 with a level 3 detection sensitivity and a small coverage buffer, corresponding with the same buffer but a different detection sensitivity level between medium and high in the model year 2024.

Data Collection and Analysis

Visual weed control by species and crop injury was evaluated at the EPOST application, 7 and 14 days after treatment (DAT) from the EPOST applications, and 14 and 21 DAT from the MPOST applications. Injury and weed control were estimated on a 0% to 100% scale, where 0% represents no injury or weed control and 100% represents complete crop death or no weeds present (Frans and Talbert 1977). The weed, crop, and sprayed areas were collected at each application, and the weed area was recorded again 14 to 21 d after the MPOST application using the ATM. Data collected by the ATM were isolated to the center two rows by cropping to furrows 1 and 3. Additionally, to avoid influence from potential weeds between replicates, the plot recordings were shortened to 24.4 m, creating a subplot sample. After defining the area and recording the data, the weed, crop, and sprayed areas were made relative to the area recorded.

Crop yield was estimated by harvesting the center two rows, adjusted to 13% moisture and made relative to the hand-weeded control. All data collected before or at EPOST applications were analyzed as a pairwise *t*-test based on PRE applications (Table 2). Data collected after the EPOST application were analyzed using a two-factor ANOVA, excluding the nontreated, PRE-only, and hand-weeded controls. Factor A (residual) at EPOST and before MPOST was with or without residual. Factor A after the MPOST application consisted of no residual, residual applied EPOST, residual applied MPOST, or residual applied at both timings. Factor B (application method) was either broadcast, targeted spray only, or broadcast residual + targeted spray. Because a combination of no residual and broadcast residual + targeted spray is not possible, the factorial is incomplete, and the interaction term cannot be included. All ANOVA analyses were considered significant at $\alpha = 0.05$ with means separated by Tukey's HSD ($\alpha = 0.05$). The decision not to analyze the data as a one-way ANOVA was made to highlight differences averaged over residual timings or herbicide application methods rather than each treatment individually.

Site-year was considered a random effect along with block nested within site-year for inference because four total trials were included in this analysis. All data reported hereinafter were evaluated at 2 or more site-years. All data were analyzed using the GLIMMIX procedure in SAS version 9.4 (SAS Institute, Cary, NC, USA) (Gbur et al. 2012). All data except relative yield were bound from 0 to 1; therefore the distributions were assumed beta with a logit link function. Injury residuals with a beta distribution after EPOST applications were heavily skewed due to low injury levels at certain site-years, and Gaussian distributions resulted in near-normal residual distributions. Therefore all injury evaluated after EPOST and before MPOST was analyzed as a normal distribution. Relative yield residuals passed the Shapiro–Wilk's normality test, so the relative yield was analyzed as a normal distribution. Sprayed area P-values are not displayed because the broadcast applications applied herbicide to 100% of the area, resulting in no variance.

To determine the relationship between weed area, crop area, and sprayed area for targeted applications, a regression analysis was performed in the fit curve platform of JMP Pro 17 (SAS Institute). No coefficient of determination between crop area and other responses exceeded 0.5 (Figure 1), but a strong nonlinear relationship was observed with weed area and sprayed area. Application timing was considered a group variable to evaluate the potential differences of each curve with 307 data points. One site in one year was missing data for the weed area in 2021. One plot recording was also corrupted during the MPOST application. Every sigmoidal nonlinear relationship was explored to determine the best-fit model based on the Akaike information criterion. The Weibull growth model was determined to be the best fit, with a reported overall $R^2 = 0.94497$ and RMSE = 8.4763 (Equation 1):

$$\%\ \text{Area sprayed} = \text{Asymptote} * \left(1 - \text{EXP}\left\{-\left[\left(\frac{\%\text{Weed area}}{\text{Inflection point}}\right)^{\text{Growthrate}}\right]\right\}\right) \quad [1]$$

Inverse predictions of weed area by sprayed area were also used to determine differences between application timings.

Results and Discussion

Soybean Response

The crop response to the different application methods did not separate at the EPOST application evaluation ($P > 0.05$), which was expected because the two methods at the PRE timing featured broadcast applications of metribuzin and *S*-metolachlor. Treatments without residuals 7 and 14 d after EPOST reduced soybean injury by 2 percentage points (Table 4). At 14 d after EPOST, treatments with all herbicides applied as targeted sprays caused less soybean injury than treatments that applied acetochlor to the entire area. A similar trend was observed with residual application timings 14 and 21 d after the MPOST application (Table 5). Applying acetochlor at all timings resulted in the greatest injury at 10%, whereas applying acetochlor at only one timing or not at all caused ≤6% injury. Similarly to the EPOST evaluations, applying all herbicides through targeted applications reduced soybean injury by at least 4 percentage points for both evaluations after MPOST.

In terms of crop area, utilizing residuals reduced soybean area by 1.3 percentage points, where soybean area in the absence of residuals averaged 95.2% across application methods (Table 6). Applying overlapping residuals in all evaluations resulted in greater soybean injury (increased visual malformation) than not applying an overlapping residual or applying an overlapping residual at only one timing (Tables 4 and 5). Still, injury was <11% overall and did not influence relative yield by the end of the season ($P > 0.05$). The reduction in soybean injury from applying all herbicides through targeted applications is likely a function of the reduction in area sprayed at application, whereas the reduction from residual timing is from the reduction in acetochlor-induced leaf malformation. Though the differences are subtle, both effects were observed only in 2 of the 4 site-years of this experiment.

The reduction in injury or improvement in crop area by separating the residuals from the POST herbicides, applying residuals through targeted applications, or not applying residuals at all did not translate to improved crop yield (Table 6). Furthermore, the differences were ≤10 percentage points from the best to worst crop response. Utilizing overlapping residuals is essential to reducing the risk for herbicide resistance and is recommended as a best weed management practice (Norsworthy et al. 2012). Therefore, on the basis of the subtle crop response, the crop health benefits would not outweigh the risk of targeting residual herbicides or excluding the residuals from the herbicide program altogether.

Weed Control

Prior to the EPOST applications, the four weed species evaluated (Palmer amaranth, morningglory species, purslane species, and broadleaf signalgrass) did not differ with the two application methods of broadcast versus broadcast residual + targeted POST herbicides (supplementary data). Overall, weed control within

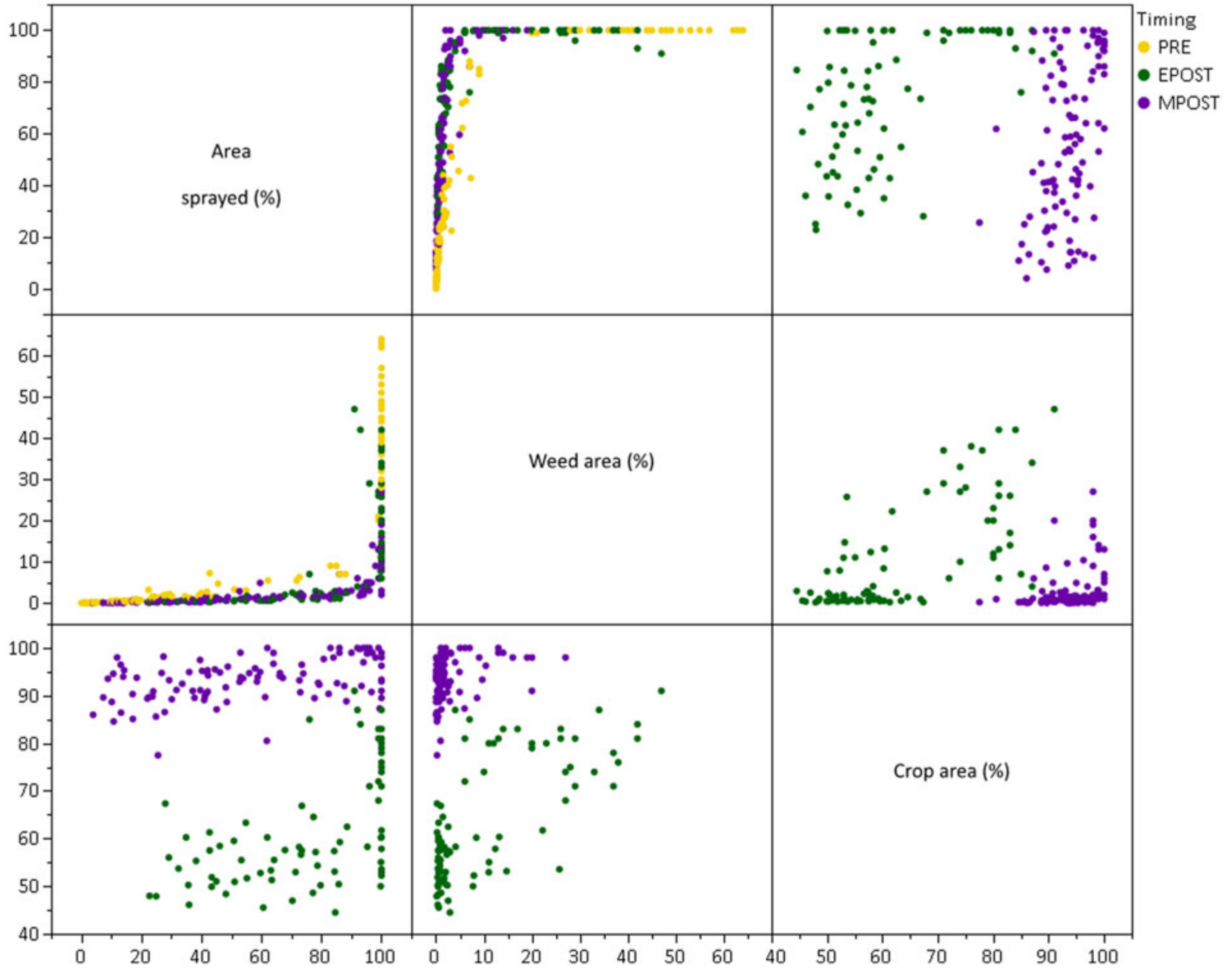

Figure 1. Scatterplot matrix of the relationships between weed area, crop area, and sprayed area. All data were collected by recording each plot at application and estimated using John Deere's software. The graph was made using JMP Pro 17.0 (SAS Institute, Cary, NC, USA) in the multivariate platform.

species ranged from 93% to 99% for the PRE treatments. After the EPOST applications, the only difference occurred 7 DAT, where broadcast residuals + targeted POST herbicides reduced purslane species control by 1 percentage point compared to the other application methods, with overall control of all species ranging from 94% to 99% (Table 7). After the MPOST applications, residual application timing (averaged over the application method) did not result in any biological differences across the weed species: control was ≥98% (Table 8). For the application methods, only one biological difference occurred for the morningglory species 21 DAT. Applying all herbicides as targeted sprays reduced morningglory control to 98%, compared to 99% control with the broadcast application.

Overall, weed control was ≥98% by the end of the season, and all application methods were comparable to one another. Like previous research conducted in soybean utilizing site-specific management with a direct-injection sprayer, comparable control of weeds and a reduction in herbicide inputs relative to traditional broadcast applications occurred (Goudy et al. 2001). However, results from end-of-season evaluations with targeted applications indicated that none of the herbicide programs achieved 100% control. In the traditional broadcast treatments, escapes generally occurred from weeds that emerged in the furrow through the residual herbicides prior to canopy formation. Although this difference was not captured in the evaluations, a common theme was escaped weeds with targeted applications emerging underneath the crop canopy. During applications, these weeds could be missed or receive a partial dose due to the proximity of adjacent weeds and eventually push through the canopy during soybean senescence. Other experiments with blue dye have indicated that targeted applications can miss weeds near crops (THA and JKN, unpublished data).

Like crop response, subtle differences in weed control occurred when comparing targeted applications to traditional broadcast herbicide applications (Tables 7 and 8). This is further supported by the lack of differences in weed area collected at each application and final evaluation (Tables 6 and 9). However, it is essential to note that both research sites utilize preplant tillage, and all applications occurred to labeled weed sizes with three application timings of differing POST herbicides at labeled maximum use rates. Additionally, dicamba followed by glufosinate was utilized in this program and has been identified as an effective program approach for labeled weed sizes (Priess et al. 2022b). On the basis of these considerations, these results may not translate to all soybean production systems. However, in a robust herbicide program with a medium to high detection sensitivity setting, targeted sprays using the See & Spray™ technology should perform comparably to traditional broadcast applications. The lack of a response from the

Table 4. Evaluations of soybean injury after early postemergence.[a,b,c]

Factor	7 DAT	14 DAT
	%	
Residual		
Without	0 b	1 b
With	2 a	3 a
P-value	0.0044	0.0074
Application method		
BC	2	2 b
TA	1	1 c
BCR + TA	0	3 a
P-value	0.2765	0.0260

[a]Abbreviations: BC, broadcast; BCR, broadcast residual; DAT, days after treatment; TA, targeted application.
[b]P-values were generated using the GLIMMIX procedure in SAS version 9.4 (SAS Institute, Cary, NC).
[c]Differing letters in a column indicate significantly different means based on Tukey's HSD at α = 0.05.

Table 5. Evaluations of soybean response after mid-postemergence applications.[a,b,c]

	Injury		
Factor	14 DAT	21 DAT	Relative yield[d]
	%		
Residual timing			
None	2 c	1 c	97
EPOST	5 b	4 bc	94
MPOST	4 bc	6 b	93
Both	10 a	11 a	91
P-value	<0.0001	<0.0001	0.1814
Application method			
BC	8 a	7 a	92
TA	3 b	3 b	96
BCR + TA	6 a	7 a	95
P-value	<0.0001	<0.0001	0.1547

[a]Abbreviations: BC, broadcast; BCR, broadcast residual; DAT, days after treatment; EPOST, early postemergence; MPOST, mid-postemergence; TA, targeted application.
[b]P-values were generated using the GLIMMIX procedure in SAS version 9.4 (SAS Institute).
[c]Differing letters in a column indicate significantly different means based on Tukey's HSD at α = 0.05.
[d]Yields averaged 2,940 kg ha^{-1} among both locations and years.

Table 6. Evaluations of the sprayed, crop, and weed areas at mid-postemergence application.[a,b,c,d]

	Sprayed area			
Factor	BC	TA	Crop area	Weed area
	%			
Residual timing				
Without	—	64.9	95.2 a	1.5
With	—	62.1	93.9 b	1.7
P-value	0.5815		0.0093	0.3779
Application method				
BC	100	0	93.9	1.3
TA	0	63.6	94.4	1.8
BCR + TA	100	63.4	95.4	1.7
P-value	0.9733		0.0645	0.1133

[a]Sprayed, crop, and weed areas were recordings collected at each application; analysis of sprayed area, crop area, and weed area was performed by John Deere's software.
[b]Abbreviations: BC, broadcast; BCR, broadcast residual; TA, targeted application.
[c]P-values were generated using the GLIMMIX procedure in SAS version 9.4 (SAS Institute).
[d]Differing letters in a column indicate significantly different means based on Tukey's HSD at α = 0.05.

residual timing indicates that without overlapping residuals, high weed control (~99%) can be achieved by the end of the season, but not utilizing overlapping residuals places more selection for resistance on POST herbicides (Bagavathiannan and Norsworthy 2012; Norsworthy et al. 2012).

Area Sprayed with Targeted Applications

Targeting applications did reduce herbicide inputs at each application timing. On average, with 95% confidence, targeted applications reduced herbicides used in targeted applications by 62.4% ± 36.9%, 28.4% ± 18.7%, and 36.5% ± 18.0% for PRE, EPOST, and MPOST applications, respectively. Additionally, a secondary objective of this experiment was to determine which overlapping residual application timing would result in the greatest herbicide savings.

When determining total POST herbicide savings, the broadcast treatments applied herbicide to 100% of the area twice, resulting in 200% total area sprayed. The total area sprayed POST was reduced when treatments utilized overlapping residuals EPOST or at both POST application timings (Table 9). If no overlapping residual was used or if it was applied only at the MPOST timing, targeted herbicides were applied to 140% and 138.9% of the area, respectively. Applying the overlapping residual EPOST or at EPOST and MPOST resulted in 118.5% and 116.6% of the area being sprayed, respectively. On the basis of these results, if an applicator could afford only one POST residual application, the EPOST application timing would result in the highest savings. These results also demonstrate that not utilizing residual herbicides POST results in less herbicide savings, though the savings may not justify the cost of the residual product used EPOST. Future research aims to perform an economic analysis to determine these differences.

Relationships between Weed, Crop, and Sprayed Area

For the different data collected using the ATM, the relationships between weed area, sprayed area, and crop area were explored (Figure 1). While no transparent relationships exist between the other responses and crop area, a strong nonlinear relationship occurred between weed area and sprayed area. For each application timing, the dependency of weed area and sprayed area on the different application methods and residual timings is also insignificant, allowing the relationship to be defined across the differing treatments (Table 6). The relationship between the sprayed area and the weed area was best fit using a Weibull growth model with application timing as a group variable. Utilizing parameter comparisons, the asymptotes of each curve were similar, with a 99.94% overall mean asymptote (Table 10). The inflection points were significantly different from one another (data not shown), with the value for PRE application being greater than the overall model average of 0.0117, for EPOST being less than the average, and for MPOST being no different than the average (inflection point [PRE > MPOST > EPOST]). These findings indicate a rightward shift at the point where the exponential growth of the curve has reached the maximum growth rate at the corresponding weed area. By that concept, the PRE applications with targeted sprays can apply less herbicide with more weed area than the POST applications, and the same is true for MPOST

Table 7. Evaluations of weed control after early postemergence application.[a,b,c,d]

	Palmer amaranth		Morningglory species		Purslane species		
Treatment	7 DAT	14 DAT	7 DAT	14 DAT	7 DAT	14 DAT	Broadleaf signalgrass, 14 DAT
	%						
Residual timing							
Without	96	95	96	98	98	96 b	96
With	96	95	95	96	99	99 a	96
P-value	0.6279	0.6232	0.6289	0.1052	0.3516	0.0069	0.3399
Application method							
BC	96	95	96	97	99 a	98	97
TA	96	94	96	96	99 a	98	96
BCR + TA	96	95	95	96	98 b	97	96
P-value	0.7580	0.6244	0.8887	0.5298	0.0172	0.4654	0.2651

[a] Abbreviations: BC, broadcast; BCR, broadcast residual; DAT, days after treatment; TA, targeted application.

[b] Morningglory species include ivyleaf (*Ipomoea hederacea* Jacq.), entireleaf (*Ipomoea hederacea* Jacq. var. *integriuscula* A. Gray), and pitted morningglory (*Ipomoea lacunosa* L.); purslane species include common (*Portulaca oleracea* L.) and horse purslane (*Trianthema portulacastrum* L.).

[c] P-values were generated using the GLIMMIX procedure in SAS version 9.4 (SAS Institute).

[d] Differing letters in a column indicate significantly different means based on Tukey's HSD at α = 0.05.

Table 8. Evaluations of visible weed control after mid-postemergence application.[a,b,c,d]

	Weed control after MPOST							
	Palmer amaranth		Morningglory species		Purslane species		Broadleaf signalgrass	
Treatment	14 DAT	21 DAT	14 DAT	21 DAT	14 DAT	21 DAT	14 DAT	21 DAT
	%							
Residual timing								
None	99	99	99	98	99	99	99	99 ab
EPOST	99	99	99	99	99	99	99	99 a
MPOST	99	99	99	99	99	99	99	99 b
Both	99	99	99	99	99	99	99	99 ab
P-value	0.4479	0.1452	0.0991	0.1966	0.5756	0.1545	0.0904	0.0293
Application method								
BC	99 a	99 a	99 a	99 a	99	99 a	99 a	99 a
TA	99 b	99 b	99 b	98 b	99	99 b	99 b	99 b
BCR + TA	99 b	99 b	99 b	99 ab	99	99 a	99 ab	99 a
P-value	<0.0001	<0.0001	0.0018	0.0004	0.6911	<0.0001	0.0024	0.0002

[a] Abbreviations: BC, broadcast; BCR, broadcast residual; DAT, days after treatment; TA, targeted application.

[b] Morningglory species include ivyleaf, entireleaf, and pitted morningglory; purslane species include common and horse purslane.

[c] Differing letters in a column indicate significantly different means based on Tukey's HSD at α = 0.05.

[d] P-values were generated using the GLIMMIX procedure in SAS version 9.4 (SAS Institute).

Table 9. Evaluations of total area sprayed and final weed area from recordings with the sprayer.[a,b,c,d,e]

	Total sprayed area postemergence		
	BC	TA	Weed area at final evaluation
	%		
Residual timing			
None	—	140 a	0.2
EPOST	—	118.5 b	0.4
MPOST	—	138.9 a	0.2
Both	—	116.6 b	0.3
P-value		0.0001	0.1031
Application method			
BC		200	0.2
TA	0	129.8	0.3
BCR + TA	200	127.3	0.3
P-value		0.63964	0.6892

[a] Sprayed and weed areas were recorded at each application; analysis of sprayed area and weed area was performed by John Deere's software.

[b] Total area sprayed postemergence was set to 200% for broadcast applications because the herbicides were applied to 100% of the area twice.

[c] Abbreviations: BC, broadcast; BCR, broadcast residual; EPOST, early postemergence; MPOST, mid-postemergence; TA, targeted application.

[d] P-values were generated using the GLIMMIX procedure in SAS version 9.4 (SAS Institute).

[e] Differing letters in a column indicate significantly different means based on Tukey's HSD at α = 0.05.

Table 10. Model parameters for the Weibull growth model of percent sprayed area predicted by percent weed area.[a,b,c]

	Model parameters				
Application timing	Asymptote	Inflection point	Growth rate	*n*	R^2
PRE	101.172	5.546	79.151	112	0.9450
EPOST	99.346	0.973	60.740	84	—
MPOST	99.629	1.268	77.397	111	—

[a] Abbreviations: EPOST, early postemergence; MPOST, mid-postemergence; PRE, preemergence.

[b] All model parameters were significant, χ^2 ($P < 0.0001$).

[c] The Weibull growth model and parameters were determined using JMP Pro 17 with the fit curve platform; only one R^2 is reported, as application timing was considered within the model.

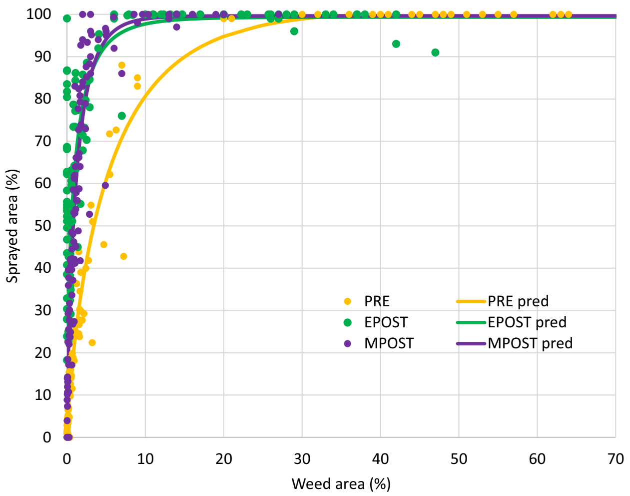

Figure 2. Relationship between sprayed area and weed area with targeted applications. Weed area and sprayed area were collected by recording each plot and estimated using John Deere's software. The predicted lines are based on a Weibull growth model with $R^2 = 0.9450$. Data were analyzed using the fit curve platform of JMP Pro 17 (SAS Institute). Sprayed area and weed area were recorded using the sprayer with a fallow model at preemergence and a soybean model at early and mid-postemergence. Targeted applications with See & Spray™ activate multiple nozzles to apply herbicides. Targeted applications at PRE utilized a 40° fan angle nozzle (SF4003). At the EPOST timing, the nozzles had a 120° angle with PSLDMQ2004. PS3DQ2004 nozzles were used at the MPOST timing and had a 100° fan angle. Abbreviations: EPOST, early postemergence; MPOST, mid-postemergence; PRE, preemergence.

compared to EPOST. The growth rates of each curve were similar, averaging 73.14.

After observing the rightward shift in the curves (Figure 2), inverse predictions of the sprayed area were calculated to determine the predicted weed areas in 10% increments (supplementary material). PRE applications had higher weed area predictions in each specified sprayed area than the other application timings. Additionally, for 10% to 70% of the sprayed area, the predicted weed area for MPOST applications was higher than it was for EPOST applications. This relationship is likely due to the association between targeted applications and the corresponding nozzles used at each application. The See & Spray™ system activates all nozzles that can contribute droplets to a weed, ensuring that the specified rate is applied uniformly to the targeted area (WLP and LMS-L, personal communication, 2022). Additionally, all nozzles require overlap, thus multiple nozzles are activated to spray a single weed. By this design, utilizing narrower nozzle angles would trigger fewer nozzles than a wider nozzle angle for any given weed, hence the greater predicted weed areas for each defined sprayed area from the inverse predictions of the Weibull growth model. SF4003 nozzles, which have a 40° fan pattern, were used at the PRE application; the EPOST targeted application utilized PSLDMQ2004 nozzles, which have a 120° pattern; and the MPOST PS3DQ0004 nozzles had a 100° pattern. Although these are the listed fan angles at 275.8 kPa, each nozzle was operated within its recommended pressure range.

With the machine settings available to change by operators utilizing targeted applications, it is important to note that detection sensitivity may not influence the relationship between sprayed area and weed area, whereas the buffer setting likely would. Detection sensitivity would influence the weeds detected, reducing the detected area and thereby reducing sprayed area. Changing the coverage buffer setting from low to either medium or high would likely cause the curves to shift, as this would dictate the number of nozzles and the length of time nozzles would be activated. Future studies will consider these factors to predict the sprayed area based on weed area.

Practical Implications

Altogether, utilizing multiple sites of action, preplant tillage, a robust herbicide program, and a medium to high detection sensitivity setting, targeted sprays provided (biologically) comparable weed control to that provided by a broadcast herbicide program. By the end of the season, all treatments achieved ≥98% control of the weed species evaluated. Some reductions in crop injury by visual estimation and improved crop area assessments were observed when overlapping residuals were excluded from the herbicide program or applied through targeted applications. However, a reduction in crop response was not observed at all locations, indicating that adopters of this technology should not expect these results to be apparent across all fields. Additionally, there was no yield improvement from using targeted sprays.

Despite achieving high weed control without residual herbicides, best practices for resistant weed management suggest that producers utilizing dual-tank and boom systems should broadcast residuals and benefit from the herbicide savings of the targeted POST applications. For single-tank systems, producers should broadcast residuals and perform a second pass to target POST herbicides, which is likely a major time constraint and will reduce efficiency. In situations where residuals will be applied through targeted applications, producers should utilize a high detection sensitivity, because the long-term impacts of targeted application systems or the detection sensitivity setting within herbicide programs is unknown. Another important consideration is that herbicides are often mixed with plant growth regulators, insecticides, fungicides, or fertilizers. An operator would be forced to broadcast these other components through a dual tank or perform two passes with a single-tank system. However, the targeted applications can be utilized to provide some soybean health benefits, provide comparable control to traditional broadcast applications, and reduce herbicide inputs, improving environmental stewardship and lowering herbicide costs. It is important to note that these results could vary for different production systems and will likely depend heavily on the herbicide program and machine detection sensitivity setting. Additionally, different detection systems from other manufacturers will likely differ in efficacy and potential benefits. Future research will consider these factors, among others.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/wet.2024.70.

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