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Evaluating precision sprayers for targeted weed management in corn and soybean

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Abstract

A targeted application of herbicides in commercial crop fields is desirable for reducing chemical inputs and promoting environmental sustainability. Precision sprayers, equipped with cameras and sensors, detect weeds in real-time and apply herbicides only where needed. The objective of this study was to evaluate spot spray (SS) technology compared to the traditional broadcast application for early-postemergence and late-postemergence (L-POST) herbicides for broadleaf and grass weed control in corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) fields. Two precision sprayers were evaluated separately: Greeneye Technology's sprayer in a corn field near Clay Center, NE, in 2022 and John Deere's sprayer in a soybean field near Mead, NE, in 2023. In 2022, Palmer amaranth (*Amaranthus palmeri* S. Watson) and giant foxtail (*Setaria faberi* Herrm.) control was similar between SS (94%–99%) and broadcast (99%) application 21 days after L-POST. In 2023, common lambsquarters (*Chenopodium album* L.), kochia [*Bassia scoparia* (L.) A.J. Scott], and waterhemp [*Amaranthus tuberculatus* (Moq.) J.D. Sauer] control was similar between SS and broadcast 21 days after L-POST. Herbicide savings varied by site years, ranging from 1% to 94%, depending on the level of weed infestation at the time of target herbicide application. Weed infestation during herbicide applications was low in 2022 and high in 2023, influencing the year-to-year variation in herbicide savings. Corn and soybean yield did not differ among broadcast and SS. The results suggest that precision sprayers can provide comparable control to broadcast herbicide applications and would be more rewarding in fields where preemergence herbicide is applied.

1 | INTRODUCTION

Herbicides are commonly used to manage weeds in large-scale crop fields in the United States and several other countries due to their effectiveness, economics, and ease of use (Lyon et al., 1996; Pacanoski, 2007). Herbicides share a significant portion of the input cost in row cropping systems. For example, in 2022, estimated costs for herbicide programs in corn (*Zea mays* L.), cotton (*Gossypium* L.), and soybean (*Glycine max* (L.) Merr.) were \$123, \$206, and \$200 ha^{-1}, respectively (Greogry & Leach, 2022). The effective use of herbicides can increase crop yield by

Abbreviations: E-POST, early-postemergence; fb, followed by; L-POST, late-postemergence; POST, postemergence; SS, spot spray.

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controlling weeds; however, ineffective or overuse of herbicides risks human health and the environment (Damalas & Eleftherohorinos, 2011; Yarpuz-Bozdoğan, 2018). A risk assessment of commonly used herbicides such as atrazine, glyphosate, and dicamba suggests an increasing cause of concern for human health risks due to herbicide exposure (Gammon et al., 2005; Lerro et al., 2020). Considering increased herbicide prices and associated potential risks to humans and the environment, reducing herbicide input would be beneficial.

In recent decades, large broadcast sprayers have been effectively used to apply herbicides in cash crop fields in the United States. Advancements in broadcast sprayers, such as application technology, sprayer size and speed, and tank volume, have made it possible to cover more acres than ever before; however, these advancements come with potential side effects such as the potential for drift. Spray drift is one of the primary mechanisms of pesticide off-target movement (Matthews et al., 2014). Despite the efforts to mitigate spray drift, off-target movement through particle drift remains a concern in the United States (Werle et al., 2018). Moreover, with increasing herbicide regulations, precise and efficient application of herbicides is beneficial considering their wide prevalent use in corn–soybean cropping systems.

Precision sprayers have been developed to help reduce herbicide inputs per area, associated costs, and, subsequently, potential environmental risks associated with the overuse or unnecessary use of herbicides. For example, variable-rate smart sprayers have been shown to reduce herbicide use compared to constant rate, conventional broadcast sprayers (Hussain et al., 2020). Greeneye Technology (Greeneye Technology) and John Deere (Deere & Company) have developed precision sprayers with attached cameras and processing units to identify/detect weeds and spray herbicide in real-time. Both precision sprayers were labeled for 76-cm row spacing at the timing of application in crops such as corn, soybean, and cotton (Cross Implement, 2024; NuWay-K&H Cooperative, 2023).

Greeneye's sprayer system (Greeneye Technology) consists of a boom that can be mounted onto a compatible sprayer. The Greeneye's precision sprayer used in this study had a boom with 24 cameras controlling 144 nozzles spaced 25.4 cm apart (Figure 1). Its dual tank/line allows herbicides from two tanks to remain separate from "tank to tip." The system could detect weeds in real-time at speeds up to 24 km h^{-1}. Sensitivity, the rate at which weeds can be detected, can be changed for the operators' request. The highest sensitivity reported can identify weeds as low as 0.635 cm (T. Khait, personal communication, July 7, 2022). This technology was attached to a Hagie STS12 sprayer in this project. This design differs from John Deere, which has developed an all-in-one precision sprayer (ASABE Staff, 2022). The John Deere's See & Spray Ultimate package is factory-installed on different sprayer models (410R, 412R, 612R, and 616R) (T. Fischer, personal communication, November 2, 2023). The John Deere 612R model used in this study had a 36.6-m long boom with 96 nozzles and 36 cameras (Figure 2). Nozzle spacing of 38 cm included a nozzle directly over the row crop. This system also had a dual tank system: Tank 1 (2839 L) and Tank 2 (1703 L) with separate booms and nozzles. Two large volume tanks can carry a soil residual and non-residual herbicide separately, allowing the application of non-residual foliar-active herbicides when cameras detect weed presence (Vogt, 2022). Further, at the highest sensitivity setting, the system detects weeds that are just 0.635 cm in diameter and 0.635 cm in height (T. Fischer, personal communication, November 2, 2023). The spot spray (SS) system is labeled for application up to 19 km h^{-1} in 2023, with an expected 24 km h^{-1} speed in the next-generation precision sprayers.

Core Ideas

- Weed control was similar to broadcast applications when using targeted precision sprayers.
- Herbicide savings were primarily driven by weed pressure present at the time of target herbicide application.
- Precision sprayers could help reduce herbicide use in row crops.

Depending on the weed infestation, precision sprayers can reduce the amount of non-residual herbicides sprayed postemergence (POST) in cash crop fields (Spaeth et al., 2024). Avent et al. (2024) reported average POST herbicide savings of 28%–62% with See & Spray technology in dicamba/glufosinate/glyphosate-resistant soybean experiments in Arkansas and Mississippi. Precision sprayers have been commercialized but not extensively tested for their performance in large-scale field experiments. Therefore, it is crucial to evaluate weed control with precision sprayers compared to traditional broadcast sprayers in row crops such as corn and soybean. If effective, precision sprayers are considered beneficial for the growers and the environment as they reduce herbicide use and, consequently, potentially reduce negative environmental impacts, crop injury, and drift. The hope for herbicide savings through patch or site-specific applications has been widely discussed (Donald et al., 2004; Luck et al., 2011; Miller, 2003). Furthermore, SS may reduce runoff depending on the herbicide applied (Melland et al., 2016). These positive findings reaffirm that financial and environmental benefits are at play. SS technology can be potentially used in multiple crops; for example, it is also being tested in wheat with varying amounts of postharvest stubble (Genna et al., 2021). Advances in other site-specific weed management approaches are opening the door for alternative weed



FIGURE 1 Greeneye Technology precision sprayer used in spot spray experiment conducted in a corn field near Clay Center, NE, in 2022. This system can be retrofitted on compatible sprayers (Photo by Adam Leise).



FIGURE 2 John Deere's See & Spray machine with boom (a) folded and (b) unfolded (36.6 m wide boom) before herbicide application in spot spray experiment conducted in a soybean field near Mead, NE, in 2023 (Photos by Adam Leise).

control methods (Gerhards et al., 2022). The future of targeted spray technology is promising enough to test this technology in various crops, cropping systems, and environments.

The objective of this study was to evaluate precision sprayers' broadleaf and grass weed control efficacy and herbicide savings in spot (targeted) versus broadcast applications. We hypothesized that SS technology would perform similarly to traditional broadcast setup at various weed infestation levels. Additionally, we hypothesized that SS would reduce herbicide input costs at low weed infestation levels if combined with a residual herbicide.

2 | MATERIALS AND METHODS

2.1 | Experimental site

Field experiments were conducted in 2022 at the University of Nebraska-Lincoln's South-Central Agricultural Laboratory (SCAL) near Clay Center, NE (40.52° N, 98.05° W), to test Greeneye Technology's precision sprayer, and in 2023 at the Eastern Nebraska Research Extension and Education Center (ENREC) near Mead, NE (41.8° N, 96.29° W), in 2023 to test John Deere's precision sprayer. Experiments were set up in

TABLE 1 Herbicides, application rates, trade names, and application techniques used for early-postemergence (E-POST) and late-postemergence (L-POST) applications using a precision sprayer in a corn field experiment conducted near Clay Center, NE, in 2022.

	Tank 1[a,b]			Tank 2[a,c]		
Application timing	Herbicide	Rate (g a.i. ha^{-1})	Trade name[a]	Herbicide	Rate (g a.i./a.e. ha^{-1})	Trade name[a]
E-POST	Acetochlor/atrazine + mesotrione	4033 + 165	Harness Xtra + Callisto	Dicamba + glyphosate	350 + 945	DiFlexx + Roundup PowerMax
L-POST	Acetochlor/atrazine + atrazine + mesotrione	1344 + 488 + 105	Harness Xtra + AAtrex 4L + Callisto	Dicamba/diflufenzopyr + glyphosate	196 + 945	Status + Roundup PowerMax

Treatment	Tank 1 application technique	Tank 2 application technique
1	Broadcast	N/A
2	Broadcast	Spot spray
3	Broadcast	Broadcast

Abbreviations: a.e., acid equivalent; a.i., active ingredient.

[a]Manpufacturer: Harness Xtra; Bayer Crop Science; Callisto; Syngenta Crop Protection; AAtrex 4L; Syngenta Crop Protection; DiFlexx; Bayer Crop Science; Roundup PowerMax; Bayer Crop Science; Status; BASF Agriculture.

[b]Included 2.5% v/v ammonium sulfate (AMS) and 1% v/v crop oil concentrate (COC) for both E-POST and L-POST applications.

[c]Included 2.5% v/v AMS and 0.25% v/v nonionic surfactant (NIS) for both E-POST and L-POST applications.

a randomized complete block design. For the feasibility of applying herbicides with larger commercial sprayers, the plot size was 18 m × 45 m at Clay Center, NE, in 2022 and 18 m × 76 m at Mead, NE, in 2023. In 2022, three treatments were replicated three times. Because each plot measured either 45 or 76 m in length, it was subsampled four times during data collection. These subsamples, which were drawn from the same plot and lacked independence, are referred to as pseudo-replicates. Treatments comprised of different application techniques consisting of Broadcast only (using Tank 1 only), Broadcast (Tank 1) + SS (Tank 2), and Broadcast (Tank 1) + Broadcast (Tank 2). For each application technique, herbicides were applied as an early-postemergence (E-POST) and a late-postemergence (L-POST) (Table 1). In 2023, four herbicides, each applied as broadcast and SS, comprised eight treatments replicated twice, with four pseudo-replicates in each replication. Herbicides were applied E-POST and L-POST (Table 2). The broadcast application of each herbicide was placed directly beside the SS to have a similar weed infestation for both applications.

In 2022, glufosinate/glyphosate-resistant corn (DKC60-87RIB RR/LL; Dekalb Genetics Crop) was planted in 76 cm rows on April 28 in a field with irrigated, ridge-till conditions. Flumioxazin (Valor SX; Valent USA) at 71 g a.i. ha^{-1} was applied in the fall of 2021 after the soybean harvest, which provided control of winter annual weeds. Tank 1 was activated 100% of the time (Table 1). For the "Broadcast only" treatment, the SS feature (Tank 2) was deactivated for both E-POST and L-POST applications. The AIXR 11005 flat fan nozzles (TeeJet Technologies; Spraying Systems Co.) were used for Tank 1 applications, while custom-made DG4003 large droplet nozzles (TeeJet Technologies) were used for Tank 2 applications to reduce dicamba drift (Sousa et al., 2017).

Enlist E3 soybean (Stine 32EE21; Stine Seed Company), which is resistant to 2,4-D choline, glufosinate, and glyphosate, was planted in 76-cm spaced rows on May 9, 2023, in a field with no-till, rainfed conditions. To fully determine SS's effectiveness and push the technology's boundaries with high weed infestation, no herbicide with residual activity was applied in this application. The PSLDMQ2006 low-drift nozzles (John Deere) were used for broadcast applications, and AIXR 11004R4 nozzles (TeeJet Technologies) for SS applications. The specific herbicides applied in both E-POST and L-POST applications are listed in Table 2. Due to the higher pressure of taller weeds at the time of L-POST application, the glufosinate rate was increased to 881 g a.i. ha^{-1}. During the L-POST application, acetochlor (Warrant; Bayer Crop Science) at 1513 g ha^{-1} was broadcast in the entire field in a separate tank to provide residual weed control coupled with the non-residual herbicides.

2.2 | Weed size and environmental conditions

In 2022, weed sizes ranged from cotyledon to 3 cm tall at the time of E-POST application, and wind speed was 3–10 km h^{-1}. During the L-POST application, weed sizes ranged from 3 to 15 cm tall, and the average wind speed was 15 km h^{-1}. Weed pressure was minimal at the time of L-POST application due to a solid residual herbicide program in the

TABLE 2 Herbicides, application rates, and trade names for early-postemergence (E-POST) and late-postemergence (L-POST) applications using a precision sprayer in a soybean field experiment conducted near Mead, NE, in 2023.

Herbicide[a]	Timing	Rate (g a.i./a.e. ha^{-1})	Trade Name	Manufacturer[b]
2,4-D choline fb glufosinate	E-POST fb L-POST	1284 fb 881	Enlist One fb Liberty	Corteva Agriscience fb BASF Corporation Research
Glyphosate fb lactofen	E-POST fb L-POST	1091 fb 168	Roundup PowerMax fb Cobra	Bayer CropScience fb Valent USA Corporation
Glufosinate fb glyphosate	E-POST fb L-POST	655 fb 1091	Liberty fb Roundup PowerMax	BASF Corporation Research fb Bayer CropScience
Saflufenacil fb 2,4-D choline	E-POST fb L-POST	21 fb 1284	Sharpen fb Enlist One	BASF Corporation Research fb Corteva Agriscience

Note: Each treatment was applied separately as broadcast and spot (targeted) spray.

Abbreviations: a.e., acid equivalent; a.i., active ingredient; fb, followed by.

[a]Besides 2,4-D choline, 3% v/v ammonium sulfate (AMS) was mixed with each herbicide treatment. Glyphosate and lactofen included 0.25% v/v nonionic surfactant (NIS), and saflufenacil included 1% v/v methylated seed oil (MSO).

E-POST application that was broadcasted in 100% of the experimental site. The E-POST and L-POST herbicides were applied on May 17 and June 13, respectively. The average sprayer speed was 13 km h^{-1} and the spray volume was 187 L ha^{-1}. The air temperature was 27°C at the time of the L-POST application. The sensitivity of the machine was at the default setting, recognizing weeds at 2.5 cm in diameter.

In 2023, the first application (referred to as E-POST for the sake of consistency) was applied on the day of planting. Weed size ranged from 1 to 7 cm tall at the time of the E-POST application. Wind speed was moderate at 8–15 km h^{-1}, with an air temperature of 26°C During the L-POST application, weed size displayed a high variance between the cotyledon stage to 91 cm. The highest weed height and pressure was from kochia [*Bassia scoparia* (L.) A.J. Scott]. Since no residual herbicide was applied, the escapes from the E-POST application provided high weed pressure. The L-POST was applied on June 20, 2023, with an average sprayer speed of 15 km h^{-1} and a volume of 187 L ha^{-1}. The wind speed was 11–13 km h^{-1}, with an air temperature of 34°C. The sensitivity settings for both E-POST and L-POST were at the highest level, recognizing weeds at 0.635 cm in diameter.

2.3 | Data collection

In 2022, weeds present included Palmer amaranth (*Amaranthus palmeri* S. Watson) and giant foxtail (*Setaria faberi* Herrm.). Palmer amaranth and giant foxtail density before L-POST was 0.1 and 0.2 plants m^{-2}, respectively. In 2023, weeds included common lambsquarters (*Chenopodium album* L.), kochia, and waterhemp [*Amaranthus tuberculatus* (Moq.) J.D. Sauer]. The density of common lambsquarters, kochia, and waterhemp was 2.4, 4.6, and 0.8 plants m^{-2} during E-POST, and 6.8, 18.0, and 4.0 plants m^{-2} during L-POST, respectively. Weed control estimates were taken on a scale of 0% (no control) to 100% (complete control) at 14 and 21 days after L-POST in 2022 and 2023, and 21 days after E-POST in 2023. Weed density was determined by counting plants in two 1-m^2 quadrats side by side in a random and representative area of plots at 14 and 21 days after L-POST in 2022 and 14 days after each application in 2023. The area covered (0%–100%) by herbicide application was determined after each application timing from each machine's data center in both years. Then, the percentage area coverage with SS was converted to percentage herbicide savings by deducting it from 100%, with 0% indicating the SS was active during the entire application and 100% indicating the SS did not spray any herbicide. In 2022, corn was harvested using a John Deere 9570, and in 2023, soybean was harvested using a John Deere S650 combine. Corn and soybean yields were adjusted to a standard moisture content of 15.5% and 13%, respectively. Crop yield maps obtained from the combine were categorized for each treatment using ArcGIS PRO version 3.2 (Ersi GIS Mapping Systems).

2.4 | Data analysis

Data were analyzed using SAS Studio, version 9.4 (SAS Institute). Data were separated by year and analyzed using the PROC GLIMMIX procedure. There was no difference in weed control between the three experiments conducted in 2022; therefore, data were combined. The fixed effect included the application technique for 2022, whereas herbicide and application techniques for 2023. The block and pseudo-replicates were treated as a random effect for both years. Type III tests were conducted to assess fixed effects, and treatment means were separated using LSMEANS with Tukey's test at $\alpha = 0.05$. For 2023, orthogonal contrasts between broadcast and SS were conducted using the CONTRAST statement followed by (fb) the PROC MEANS procedure to find overall means, with significance determined at $\alpha = 0.05$.

TABLE 3 Palmer amaranth and giant foxtail control at 14 and 21 days after application (DAA) of late-post treatments applied using a precision sprayer in a corn field experiment conducted near Clay Center, NE, in 2022.

	Percentage control			
	14 DAA		21 DAA	
Application technique	Palmer amaranth	Giant foxtail	Palmer amaranth	Giant foxtail
Broadcast	94a	80b	93b	77b
Broadcast + spot spray	99a	90ab	99a	94a
Broadcast + broadcast	99a	99a	99a	99a
p-value	0.15	0.07	0.04	0.01

Note: Means separated within each column with no common letter(s) are significantly different according to Tukey–Kramer's least significant difference (LSD) test at $p \leq 0.05$.

3 | RESULTS AND DISCUSSION

3.1 | Weed control

Broadcast + SS provided similar control of Palmer amaranth (99%) and giant foxtail (90%–94%) compared to broadcast + broadcast (99%) 14 and 21 DAA of L-POST herbicide application in corn in 2022 (Table 3). With this, control of Palmer amaranth ($p = 0.15$) and giant foxtail ($p = 0.07$) did not differ from broadcast only at 14 DAA, indicating no significant advantage of non-residual herbicides (Tank 2) because weed infestation was minimal at the time of L-POST herbicide application. At 21 DAA of L-POST, control of giant foxtail and Palmer amaranth with broadcast + SS (94%–99%) was 17% and 6% higher than broadcast only (77%–93%), respectively. Spaeth et al. (2024) found that an SS application resulted in the same weed control 14 DAA as conventional broadcast in corn (98%–100%), while SS saved 20% of herbicide in corn. Palmer amaranth control in broadcast + SS application was 5%–9% higher compared to giant foxtail control in the same treatments at 14 and 21 DAA of L-POST (Table 3). Buzanini et al. (2023) found that grass weeds may be more challenging to identify for SS systems, noting that shadows, weed height, and application timing impact the accuracy of weed identification. This notion that grasses may be harder to identify than broadleaf weeds should be tested in the future.

In 2023, control of common lambsquarters, kochia, or waterhemp did not differ between broadcast and SS applications at 21 DAA of E-POST (Table 4). Among individual herbicide treatments, 2,4-D choline (1284 g a.e. ha^{-1}) was not effective on kochia, providing 30% (broadcast) to 34% (SS) control, similar to glufosinate at 655 g a.i. ha^{-1} (47%–50%). Dhanda et al. (2023) observed 23%–33% kochia control at 14 DAA and 13%–30% at 28 DAA with 2,4-D 538 g a.e. ha^{-1} in Kansas.

Similarly, poor control of kochia (25%–39% at 30–39 DAA) when using 2,4-D has been reported in other studies (Tonks & Westra, 1997; Wolf et al., 2000). Glyphosate and saflufenacil provided ≥94% kochia control 21 DAA. Similarly, Kumar and Jha (2015) reported 82% kochia control with saflufenacil (25 g a.i. ha^{-1}) and 93% with glyphosate (1260 g a.e. ha^{-1}). Higher levels of tall kochia infestation became an issue during L-POST applications. Reduced herbicide efficacy when weeds are taller is well documented (Kouame et al., 2023; Meyer & Norsworthy, 2019). With taller kochia (up to 91 cm) during L-POST applications, the glufosinate application rate was increased from 655 to 881 g a.i. ha^{-1}. Weed size at the time of L-POST exceeded the herbicide label recommendations, which limits the generalizability of the relevant results. Saflufenacil provided 94%–95% control of kochia 21 DAA of E-POST, resulting in minimal infestation for follow-up L-POST application of 2,4-D choline. At 14 and 21 DAA of L-POST, 2,4-D choline had similar kochia control between SS (93%–99%) and broadcast (96%–98%; Table 5). Lactofen provided 9% lower kochia control with SS (62%) than broadcast (71%) 14 DAA of L-POST. However, overall weed control of all species did not differ among broadcast and SS for all herbicides by 21 DAA of L-POST.

Precision sprayers, such as custom builds and alternative algorithms, have been tested in turfgrass system and reported to have high precision in identifying broadleaves such as carpetweed (*Mollugo verticillata* L.), three lobe morningglory (*Ipomea triloba* L.), and common ragweed (*Ambrosia artemisiifolia* L.) (Jin et al., 2023; Yu et al., 2019). These findings suggest that SS systems can have a high accuracy in identifying broad leaves among grass crops. In this study, differences were observed in the efficacy of herbicides for controlling individual weed species; however, no differences were observed in weed control between broadcast and SS after E-POST and L-POST applications, validating that the precision sprayer was able to identify weeds in corn in 2022 and detect and target weeds in soybean in 2023.

3.2 | Weed density

Giant foxtail density was similar at 14 and 21 DAA of L-POST in broadcast + SS (0.3–0.7 plants m^{-2}) compared to broadcast + broadcast (0 plants m^{-2}) in corn in 2022

TABLE 4 Common lambsquarters, kochia, and waterhemp control at 21 days after application (DAA) of early-postemergence treatments applied usinga precision sprayer in a soybean field experiment conducted near Mead, NE, in 2023.

Herbicide	Application technique	Common lambsquarters	Kochia	Waterhemp
		Percentage control		
2,4-D choline	Broadcast	83b	30b	77c
2,4-D choline	Spot spray	89ab	34b	79bc
Glyphosate	Broadcast	96a	97a	93ab
Glyphosate	Spot spray	97a	98a	97a
Glufosinate	Broadcast	36c	50b	94ab
Glufosinate	Spot spray	29c	49b	95a
Saflufenacil	Broadcast	93ab	95a	99a
Saflufenacil	Spot spray	91ab	94a	99a
p-value		0.0001	0.0001	0.014
Broadcast vs. spot spray[b]		77 vs. 76	67 vs. 69	91 vs. 92

Note: Means separated within each column with no common letter(s) are significantly different according to Tukey–Kramer's least significant difference (LSD) test at $p \leq 0.05$.

[b]A significant difference between broadcast and spot spray contrast means at $p \leq 0.05$.

TABLE 5 Common lambsquarters, kochia, and waterhemp control at 14 and 21 days after application (DAA) of late-postemergence treatments applied using a precision sprayer in a soybean field experiment conducted near Mead, NE, in 2023.

Herbicide	Application technique	Common lambsquarters		Kochia		Waterhemp	
		14 DAA	21 DAA	14 DAA	21 DAA	14 DAA	21 DAA
		Percentage control					
Glufosinate	Broadcast	96a	53b	98a	99a	96ab	91b
Glufosinate	Spot spray	96a	53b	97a	99a	99a	96b
Lactofen	Broadcast	77b	49b	71b	93b	91c	73b
Lactofen	Spot spray	77b	64b	62c	94ab	96ab	72b
Glyphosate	Broadcast	99a	99a	95a	98ab	98ab	94a
Glyphosate	Spot spray	99a	97a	96a	98ab	95bc	96a
2,4-D choline	Broadcast	99a	98a	98a	96ab	96ab	96a
2,4-D choline	Spot spray	99a	99a	93a	99a	97ab	98a
p-value		0.0001	0.0001	0.0001	0.25	0.0045	0.61
Broadcast vs. spot spray[b]		93 vs. 93	75 vs. 78	91 vs. 87	97 vs. 98	95 vs. 97	88 vs. 90

Note: Means separated within each column with no common letter(s) are significantly different according to Tukey–Kramer's least significant difference (LSD) test at $p \leq 0.05$.

[b]A significant difference between broadcast and spot spray contrast means at $p \leq 0.05$.

(Table 6). However, it was higher in broadcast only (2.3 plants m^{-2}) than broadcast + broadcast (0 plants m^{-2}) at 21 DAA. This was probably because the "broadcast only" program did not include glyphosate for killing emerged grass weeds. With herbicide programs including residual herbicides, Palmer amaranth was effectively controlled throughout the growing season, resulting in 0 plants m^{-2} 21 DAA of L-POST in broadcast + SS and broadcast + broadcast application. In 2023, common lambsquarters density was higher in broadcast (1.4 plants m^{-2}) than SS (1.0 plants m^{-2}) 14 DAA of E-POST ($p = 0.09$; Table 7). Otherwise, no differences were observed between broadcast and SS for all weed species 14 DAA of E-POST and 14 DAA of L-POST.

3.3 | Herbicide savings

In 2022, SS was activated 6% and 13% of the time for E-POST and L-POST applications, saving 94% and 87% of non-residual herbicides, respectively (Table 8). Herbicide savings were high as weed infestation was minimal due to the application of herbicides with diverse modes of action and residual activity (Table 1; Figure 3a). Buzanini et al. (2024) noted 84% and 54% non-residual herbicide savings when following a previously applied residual herbicide in the fall and spring, respectively, in plasticulture pepper (*Capsicum annuum* 'Jalapeno'). Spaeth et al. (2024) noted 55% herbicide savings in sugar beet (*Beta vulgaris* L.) with similar weed

TABLE 6 Palmer amaranth and giant foxtail density (plants m^{-2}) as affected by application techniques at 14 and 21 days after application (DAA) of late-postemergence treatments applied using Greeneye Technology's precision sprayer in a corn field experiment conducted near Clay Center, NE, in 2022.

	14 DAA (plants m^{-2})		21 DAA (plants m^{-2})	
Application technique	**Palmer amaranth**	**Giant foxtail**	**Palmer amaranth**	**Giant foxtail**
Broadcast	0.2a	1.5a	0.3a	2.3a
Broadcast + spot spray	0a	0.7ab	0a	0.3b
Broadcast + broadcast	0a	0b	0a	0b
p-value	0.42	0.04	0.24	0.03

Note: Means separated within each column with no common letter(s) are significantly different according to Tukey–Kramer's least significant difference (LSD) test at $p \leq 0.05$.

TABLE 7 Broadcast versus spot spray contrast for weed density (plants m^{-2}) at 14 days after application (DAA) of early-postemergence (E-POST) and late-postemergence (L-POST) treatments applied using John Deere's precision sprayer in spot spray experiment conducted in a soybean field near Mead, NE, in 2023.

	14 DAA E-POST (plants m^{-2})		
Application technique	**Common lambsquarters**	**Kochia**	**Waterhemp**
Broadcast	1.4*	3.1	0.3
Spot spray	1.0*	2.4	0.4
	14 DAA L-POST		
Broadcast	0.8	0.6	0.7
Spot spray	1.0	0.3	0.9

*Significant difference between broadcast and spot spray contrast means at $p < 0.1$.

control (95%–100%) between broadcast and SS 14 DAA. Likewise, corn and soybean experiments conducted in Nebraska reported savings of 64% in non-residual herbicides in soybean and 43% in corn while providing similar weed control (Barnhart, 2024). Weed density, growth stage, and species present may directly correlate to SS nozzle activation and herbicide savings (Spaeth et al., 2024; Zanin et al., 2022). Gonzalez de Soto et al. (2016) observed that when weed patches covered 22.6% of the ground surface in wheat (*Triticum aestivum* L.), a custom robotized sprayer applied herbicide to 23.1% of the area.

In 2023, non-residual herbicide savings were low (1.1%–5.4%) for E-POST applications and none for L-POST applications (Table 9). For the E-POST application, the lowest and highest amounts of herbicide savings using SS were 1.1% and 5.4%, with 2,4-D choline and glyphosate sprayed in 98.9% and 94.6% of the total plot area, respectively. The previous weed control history provided a high weed infestation during the E-POST application in 2023. Furthermore, since no residual herbicide was applied at planting/E-POST, weed infestation during the L-POST herbicide application in 2023 was significantly higher than in 2022 field experiments (Figure 3b). Overall, proper herbicide coverage should be the priority before herbicide savings. Villette et al. (2022) found that SS systems with multiple nozzle activation with double overlap provide better herbicide coverage than an increased flow rate per nozzle. Furthermore, activating adjacent nozzles regarding a specific target prevents the under-application of herbicide to weeds. Activating multiple nozzles regarding spray overlap may directly impact herbicide savings, alluding to further testing in this area.

3.4 | Crop yield

In 2022, corn yield in broadcast + broadcast was higher (17,219 kg ha^{-1}) than broadcast only (16,366 kg ha^{-1}; Figure 4). However, broadcast + SS yield (16,867 kg ha^{-1}) was similar to broadcast + broadcast yield. In 2023, soybean yield was lowest in 2,4-D choline fb glufosinate for broadcast and SS applications (4456–4893 kg ha^{-1}), with the yield in SS treatment being similar to those of other herbicide treatments (Figure 5). Soybean yield in 2,4-D choline fb glufosinate was lower than other treatments, probably because of poor kochia control early in the growing season. Kochia's impact on soybean yield in Nebraska was noted by Wicks et al. (1997), who observed that soybean yield will likely decrease for each soybean growth stage if kochia is not controlled. For example, Yadav et al. (2020) reported a 68% yield reduction of soybean with season-long interference of kochia in untreated plots in Kansas. There were no differences in yield between broadcast and SS treatments in all other herbicide combinations, indicating that SS herbicide application was as effective as broadcast for weed control and reducing crop-weed competition.

4 | CONCLUSIONS

Precision sprayers were evaluated for targeted weed control compared with broadcast application of herbicides in Nebraska's corn and soybean production fields. In 2022, a targeted spray of herbicides provided similar control (90%–99%) of Palmer amaranth and giant foxtail as a broadcast application (99%) in corn field experiments (Table 3),

TABLE 8 Percentage of acreage covered with non-residual herbicides and savings for early-postemergence (E-POST) and late-postemergence (L-POST) treatments applied using Tank 2 of Greeneye's precision sprayer in spot spray experiment conducted in a corn field near Clay Center, NE, in 2022.

Tank 1[a]	Tank 2[b]	Timing	Tank 2[c] (% area covered)	Herbicide savings (%)
Broadcast	N/A	E-POST fb L-POST	0 fb 0	–
Broadcast	Spot spray	E-POST fb L-POST	6 fb 13	94 fb 87
Broadcast	Broadcast	E-POST fb L-POST	100 fb 100	0

Abbreviation: Fb, followed by.
[a]Tank 1 included herbicide with residual activity.
[b]Tank 2 included herbicides with non-residual activity.
[c]Herbicide applied on a scale of 0%–100%, with 100% indicating that spot spray was activated during the entire application.

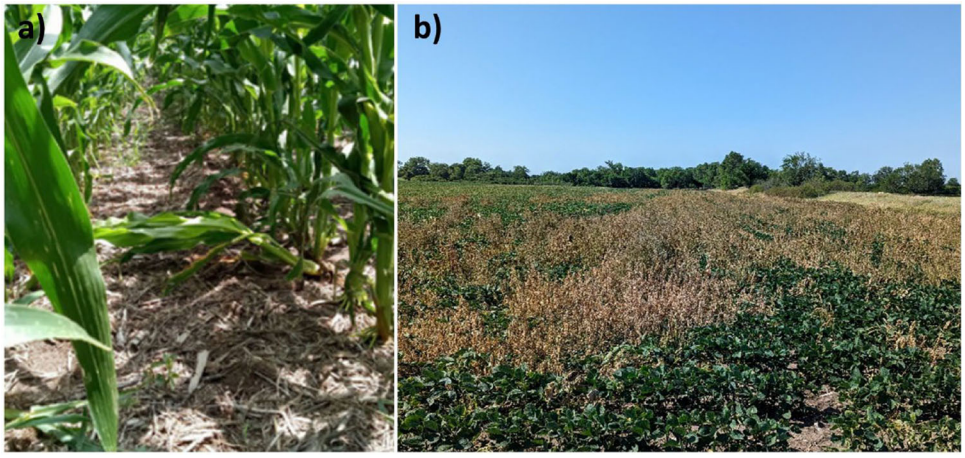


FIGURE 3 (a) Low weed pressure 21 days after late-postemergence herbicide application in a corn field near Clay Center, NE, in 2022, and (b) high weed pressure 7 days after late-postemergence herbicide application in soybean field near Mead, NE, in 2023.

TABLE 9 Percentage of acreage covered with non-residual herbicides and savings for early-postemergence (E-POST) and late-postemergence (L-POST) treatments applied using a precision sprayer in spot spray experiment conducted in a soybean field near Mead, NE, in 2023.

Herbicide	Timing	Rate (g ai/ae ha^{-1})	Area covered[a] (%)	Herbicide savings[a,b] (%)
2,4-D choline fb glufosinate	E-POST fb L-POST	1284 fb 881	98.9 fb 100	1.1 fb 0
Glyphosate fb lactofen	E-POST fb L-POST	1091 fb 128	94.6 fb 100	5.4 fb 0
Glufosinate fb glyphosate	E-POST fb L-POST	655 fb 1091	96.8 fb 100	3.2 fb 0
Saflufenacil fb 2,4-D choline	E-POST fb L-POST	21 fb 1284	98.1 fb 100	1.9 fb 0

Abbreviations: ae, acid equivalent; ai, active ingredient; fb, followed by.
[a]Herbicide applied on a scale of 0%–100%, with 100% indicating that spot spray was activated during the entire application.
[b]Residual herbicide was not applied in the E-POST application.

saving 94% and 87% of herbicide in E-POST and L-POST herbicide applications, respectively (Table 8). Herbicide savings were high because the application of layered residual herbicide provided excellent weed control with minimal infestation. Precision sprayer may allow producers to save a high amount of non-residual herbicides in fields with minimal weed infestation, as observed in 2022. In 2023, control of common lambsquarters, kochia, and waterhemp was mostly similar between broadcast and SS for both E-POST and L-POST herbicide applications in soybean, indicating precision sprayer was very effective at recognizing weeds and applying herbicide. However, herbicide savings ranged from none to 5% because of high weed infestation due to no application of any (preplant/preemergence) residual herbicide. Herbicide savings have been directly linked to weed density, stage, and coverage in fallow and row-crop situations (Esau et al., 2018; Fischer et al., 2020). With this, herbicide savings could be roughly predicted from weed mapping conducted prior to targeted application, among other factors. The benefits of this technology may differ with different cropping systems,

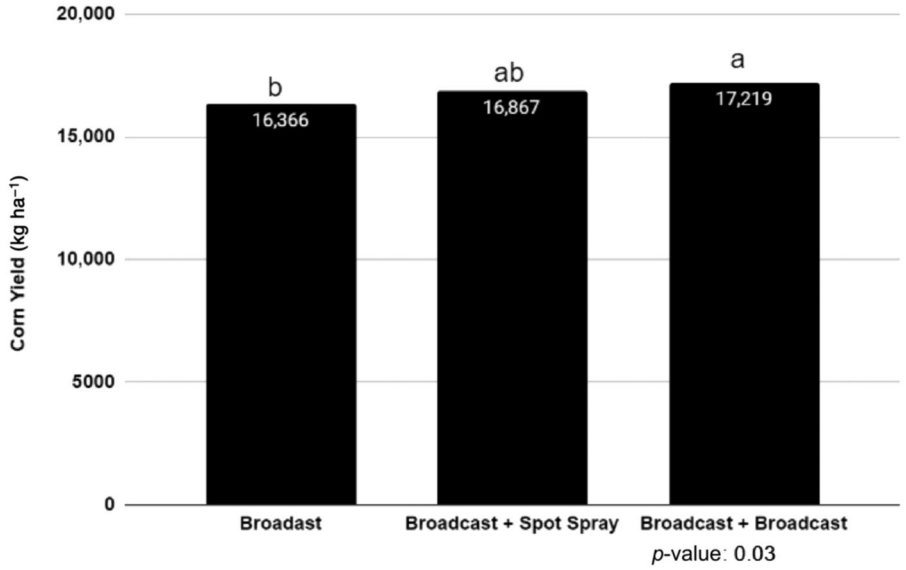


FIGURE 4 Corn yield as affected by application techniques in a Greeneye Technology's precision sprayer field experiment conducted near Clay Center, NE, in 2022.

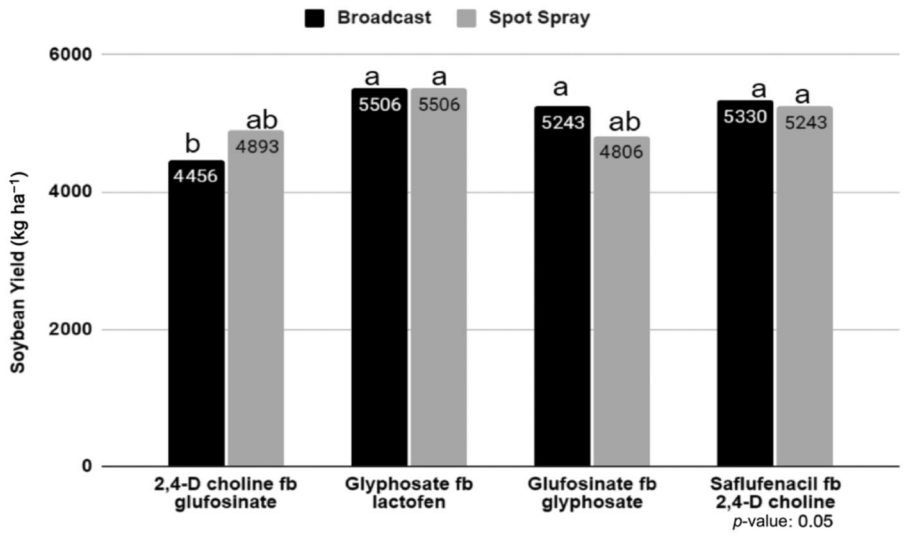


FIGURE 5 Soybean yield as affected by application techniques and herbicide programs in a John Deere's precision sprayer field experiment conducted near Mead, NE, in 2023.

herbicide programs, and level of weed infestation (Avent et al., 2024). Herbicide applicators should carefully assess relevant considerations to determine if it is suitable for their operation. If a producer is focused on maximizing herbicide savings either in season or in future years, they must be diligent in tank mixing the appropriate herbicides to control weeds early (both in season and in the first few years) to limit weed infestation. The introduction of the dual tank system has opened the door for more opportunity and flexibility to ensure this, with the ability to apply chemical combinations simultaneously through separate nozzles. While the advancement of the dual tank system could be beneficial for herbicide use, another benefit is the simultaneous application of other chemicals, such as fungicides and insecticides. Future research of dual tank combinations of herbicides + other pesticides should be considered.

In conclusion, similar levels of weed control when using SS or broadcast are attractive, and SS should be more rewarding in fields with low weed infestation. In some precision sprayers, the sensitivity option may be adjusted per the operator's request to either increase weed detection or allow for more herbicide savings. However, proper herbicide coverage is fundamental and should be emphasized before herbicide savings to reduce weed seed production.

AUTHOR CONTRIBUTIONS

Adam Leise: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; supervision; visualization; writing—original draft; writing—review and editing. **Mandeep Singh**: Writing—review and editing. **Nicolas Cafaro La Menza**: Writing—review and editing. **Stevan Z. Knezevic**: Writing—review and editing. **Amit J. Jhala**: Conceptualization; funding acquisition; methodology; project administration; resources; supervision; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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