Weed Technology

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Research Article

Cite this article: Singh N, Peters TJ, Naeve SL, Nicolai DA, Miller RP, Sarangi D (2025) A system approach for waterhemp (*Amaranthus tuberculatus*) management in soybean–sugar beet rotation. Weed Technol. **39**(e104), 1–12. doi: 10.1017/wet.2025.10058

Received: 28 June 2025
Revised: 16 September 2025
Accepted: 17 October 2025

Associate Editor:
Vipan Kumar, Cornell University

Nomenclature:
Acetochlor; flumioxazin; glufosinate; glyphosate; lactofen; 2,4-D; waterhemp; *Amaranthus tuberculatus* (Moq.) Sauer; soybean; *Glycine max* (L.) Merr; sugar beet; *Beta vulgaris* L.

Keywords:
Canopy cover; harvest weed seed control; integrated weed management; row spacing; soybean yield; waterhemp seed production

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A system approach for waterhemp (*Amaranthus tuberculatus*) management in soybean–sugar beet rotation

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Abstract

Effective waterhemp management in crop rotations that include sugar beet requires a proactive approach, starting with robust weed management in the preceding crop. Sugar beet is vulnerable to weeds due to its poor competitiveness during its early growth stages and a limited availability of effective herbicide options within this rotation. This research aimed to evaluate multi-tactic weed management strategies, including planting soybean in narrow rows with low- and high-input treatments, and a high-input treatment plus harvest-time weed seed control (HWSC) simulation, on waterhemp control and seed production in soybean, and their effects on waterhemp density in the following sugar beet crop. Field experiments were conducted from 2021 to 2023 in Franklin, Moorhead, and Rosemount, Minnesota. Soybean planted in narrow rows closed the canopy earlier at Franklin in 2021 and at Moorhead in 2022. Soybean row spacing did not affect waterhemp control, density, biomass, or seed production at any site-year. A high-input treatment consisting of flumioxazin applied preemergence followed by (fb) an early postemergence application of lactofen + acetochlor fb a late-postemergence application of 2,4-D + glyphosate provided ≥95% waterhemp control at harvest at all site-years and seed production was reduced to 0 seeds m^{-2} at Franklin and Rosemount. At those locations, waterhemp control at harvest was comparable among all high-input herbicide treatments. Soybean planted in narrow rows yielded 9.4% and 18.5% more than soybean planted in wide rows at Franklin and Rosemount, respectively, while no yield difference was observed at Moorhead. Waterhemp emergence in the subsequent season's sugar beet crop fell by 72% to 92% at the Franklin site in 2022, Moorhead in 2023, and Rosemount in 2023 after high-input herbicide treatments. However, adding HWSC to a high-input treatment did not result in a further reduction of waterhemp density. In this research, 1 yr of effective waterhemp control with high-input herbicide treatments in soybean reduced waterhemp emergence in the following season's sugar beet crop.

Introduction

Soybean and sugar beet are two important agronomic crops with 5.3 and 0.3 million hectares planted area, respectively, in Minnesota and North Dakota combined in 2022 (USDA-NAAS 2022a). In 2022, Minnesota accounted for one-third of the total sugar beet production in the United States (USDA-NAAS 2022b). Soybean and sugar beet crops are commonly grown in rotation with corn (*Zea mays* L.) and small grains (Overstreet et al. 2007; Sims 2007). Soybean–sugar beet rotation is becoming increasingly popular in Minnesota due to higher soybean grain and sugar prices in recent years, improved sugar beet varieties, and effective fungicide options. However, weed management is a significant challenge in this crop rotation. Soltani et al. (2017, 2018) reported that weeds can cause up to 52% and 70% yield losses in soybean and sugar beet, respectively.

In a survey conducted by the Weed Science Society of America, waterhemp [*Amaranthus tuberculatus* (Moq.) J.D. Sauer] was identified as the most troublesome weed of soybean and sugar beet in Minnesota and North Dakota (Van Wychen 2019). Season-long interference from eight waterhemp plants per meter of row length reduced soybean yield by 56.2% (Bensch et al. 2003). When growing with crops, waterhemp can produce more than 30,000 seeds per female plant (Hartzler et al. 2004; Uscanga-Mortera et al. 2007), leading to a rapid increase in the weed seedbank. Additionally, a recent report suggested that farmers in Minnesota have limited postemergence herbicide choices due to the frequent occurrence of multiple herbicide–resistant waterhemp (Singh et al. 2024).

A limited number of effective herbicide options are available to control waterhemp in sugar beet crops (Beiermann et al. 2021). Implementing aggressive waterhemp management strategies during the soybean phase can help reduce the weed seedbank, leading to fewer waterhemp plants in the subsequent sugar beet crop. Application of an effective preemergence herbicide is a crucial step in waterhemp control in soybean (Sarangi et al. 2017; Singh et al. 2025); however, a majority of soil residual herbicides commonly used on soybean can carry over to the sugar beet crop in the following season, further limiting the number of herbicide options for soybean. Given the limited herbicide options for the soybean–sugar beet rotation, multi-tactic approaches that integrate cultural and mechanical management tactics with chemical weed control are essential.

Planting soybean in narrow rows as a cultural management practice promotes earlier canopy closure compared with 76-cm row spacing. Arsenijevic et al. (2022) reported that soybean planted in 38-cm rows achieved 90% green canopy cover 4 to 7 d earlier than when rows were spaced 76 cm apart. Steckel and Sprague (2004) reported that in Illinois, waterhemp emergence fell by ≥50% after the V2 stage when soybean was planted in 19-cm rows compared with 76-cm rows. Similarly, several studies conducted in the midwestern United States reported that planting soybean in narrow rows had a positive effect on weed control and weed density (Singh et al. 2023). Although narrow-row spacing can reduce weed density in soybean, it is often not sufficient as a stand-alone weed control measure and needs to be integrated with other weed management techniques (Schultz et al. 2015).

Weed seed production within the field is the primary source for weed seedbank replenishment (Buhler et al. 1997). Although studies have reported that the majority of waterhemp seeds lose their viability after 4 yr of being buried in the soil (Egley and Chandler 1983; Korres et al. 2018; Sosnoskie et al. 2013), between 1% and 3% of seeds can remain viable after 17 yr of burial (Burnside et al. 1996). Therefore, any control measures that reduce waterhemp seed production and seedbank replenishment should be adopted for better weed control in a cropping system. Harvest-time weed seed control (HWSC) in row-crop production systems provides an opportunity to target herbicide-resistant weed seeds by either collecting or destroying the seeds when the crop is harvested (Walsh et al. 2018). One of the HWSC techniques involving the use of cage mills (in Harrington Seed Destructor [iHSD] or Redekop Seed Control Unit [SCU]) is becoming popular for herbicide-resistant weed management in row crops. Shergill et al. (2019) reported that iHSD lethally damaged >95% waterhemp seeds that passed through the combine. Waterhemp retained 70% to 100% of seeds at the time of soybean maturity (Bennett 2021; Schwartz et al. 2016), suggesting the potential benefit of using HWSC techniques.

The efficacy of weed management interventions is often reflected in changes to the weed seedbank (Norsworthy et al. 2018). Studies that include narrow-row spacing herbicide applications as an integrated weed management strategy in soybean often do not estimate the change in the seedbank and weed emergence in subsequent seasons. No information is available on waterhemp management in soybean–sugar beet rotation. Thus, the objectives of this experiment were to 1) evaluate the effects of weed management programs and soybean row spacing on waterhemp control, density, seed production, and soybean yield; and 2) evaluate waterhemp emergence in the subsequent sugar beet crop in response to multi-tactic management in the preceding soybean crop. We hypothesized that combining narrow-row soybean spacing with high-input herbicide treatments would enhance waterhemp control, reduce seed production, and increase soybean yield. Furthermore, integrating HWSC simulation treatment to a high-input herbicide treatment and narrow soybean rows would further reduce waterhemp emergence in the subsequent sugar beet crop.

Materials and Methods

Experimental Site and Crop Planting Information

Field experiments were conducted in growers' fields in Franklin, Minnesota, in 2021 (44.579°N, 94.875°W); Moorhead, Minnesota, in 2021 and 2022 (46.892°N, 96.756°W); and at the University of Minnesota's Rosemount Research and Outreach Center, near Rosemount, in 2022 (44.712°N, 93.086°W), for a total of 4 experimental site-years. Mean temperature and total precipitation information for all site-years are summarized in Table 1. Daily temperature data for the Franklin, Moorhead, and Rosemount experimental sites were obtained from the weather stations located at Redwood Falls (19 km from the Franklin site), Fargo Hector International Airport (7 km from the Moorhead site), and Rosemount Research and Outreach Center (1 km from the Rosemount site). Data for Moorhead were downloaded from National Oceanic and Atmospheric Administration websites, whereas data for the Franklin and Rosemount sites were sourced from the National Weather Service. Details of soil texture and other soil physical properties for all of the sites are included in Table 2. A natural seedbank of waterhemp that is resistant to herbicides that inhibit acetolactate synthase was present at all of the experiment sites, and populations at the Moorhead and Rosemount sites were segregating for glyphosate resistance. Field observations and previous herbicide performance indicated resistance at these locations, which is further supported by a 2020–2021 statewide survey carried out and reported by Singh et al. (2024) documenting widespread occurrence of resistant waterhemp biotypes throughout Minnesota.

A conventional tillage system was used for field preparation, including chisel plowing to a depth of 20 cm in the fall followed by field cultivation in the spring before soybean planting. Soybean varieties that are resistant to glyphosate, glufosinate, and 2,4-D (Enlist E3) were seeded at 150,000 seeds ha^{-1} at all three sites. Soybean planting dates are listed in Table 2. No fertilizer, insecticide, or fungicide was applied based on soil nutrient testing and pest monitoring following University of Minnesota Extension recommendations. No supplemental irrigation systems were installed in the fields, thus the soybean crops depended on rain for moisture.

Sugar beet was planted the following season in the soybean fields at a seeding rate of 152,000 seeds ha^{-1} at 56-cm row spacing, between May 10 and May 25, depending on the location and year. Shallow tillage (4 cm deep) using a field cultivator was performed in the direction of soybean rows for seedbed preparation prior to sugar beet planting. A starter fertilizer of urea was applied at 145 kg ha^{-1} before planting. No herbicide was applied to sugar beet to evaluate the treatment effects from soybean on waterhemp emergence. The sugar beet crop was terminated after data were collected.

https://doi.org/10.1017/wet.2025.10058

Table 1. Mean monthly air temperature and total precipitation during the 2021 and 2022 growing seasons and their 30-yr averages in Franklin, Moorhead, and Rosemount, Minnesota.[a]

Month	Franklin			Moorhead			Rosemount	
	2021	2022	30-yr average	2021	2022	30-yr average	2022	30-yr average
	Mean air temperature							
	C							
May	14.0	14.5	14.6	13.0	12.8	13.7	14.8	14.5
June	23.2	21.5	20.5	22.0	20.2	19.5	21.2	20.1
July	23.2	23.1	22.5	23.7	22.0	21.7	22.8	22.1
August	22.0	21.6	21.1	22.1	20.2	20.5	20.6	20.8
September	17.5	18.1	16.8	17.9	16.1	15.7	16.9	16.7
October	12.0	10.2	9.1	10.5	8.2	7.7	9.3	9.2
	Total precipitation							
	mm							
May	69	119	100	9	81	76	107	111
June	35	22	118	91	58	107	22	123
July	18	76	91	17	77	76	59	111
August	151	56	107	72	62	66	182	115
September	95	10	76	80	13	67	11	86
October	75	1	59	75	5	54	7	69
Yearly total	606	523	747	488	544	602	657	863

[a]Data for the Rosemount site were obtained from the National Weather Service (NWS). Data for Franklin were acquired from the NWS's Redwood Falls monitoring station. Data for the Moorhead site were obtained from National Oceanic and Atmospheric Administration monitoring station located at Fargo Hector International Airport.

Table 2. Soil characteristics and planting, harvesting, and herbicide application dates for waterhemp management experiments.[a]

Year	Location	Soil characteristics			Plot dimensions[b]	Soybean			Herbicide application dates[c]		
		Texture	OM[d]	pH	m	Planting date	Harvest date	Variety[e]	PRE	EPOST	LPOST
2021	Franklin	Clay-loam	4.8	7.7	3 × 10	May 10	October 7	S17-E3	May 10	June 10	June 23
2021	Moorhead	Silty clay loam	4.3	7.9	3.5 × 12	May 16	October 4	2005E	May 17	June 22	June 29
2022	Moorhead	Silty clay loam	4.3	7.9	3.5 × 12	May 25	October 3	2005E	May 27	June 23	July 5
2022	Rosemount	Silty clay loam	3.8	6.3	3 × 10	May 24	October 10	5PQNK08	May 26	June 23	July 5

[a]Abbreviations: EPOST, early postemergence; LPOST, late postemergence; OM, organic matter, PRE, preemergence.
[b]Plot dimensions are length × width.
[c]EPOST and LPOST applications were made at the V2 and V5 soybean growth stages, respectively.
[d]Percent (%) OM.
[e]Soybean seed suppliers: S17-E3, NK Seeds, Syngenta Seeds Inc, Downers Grove, IL; 2005E, Peterson Farms Seed, Harwood, ND; 5PQNK08, Pioneer Seeds, Johnston, IA.

Treatment Details

The weed management treatments listed in Table 3 were applied to soybean in 2021 and 2022. The treatments were arranged in a split-plot design with four replications. The main plot factor was soybean row spacing, either narrow rows (38 cm at the Moorhead and Rosemount sites, and 30 cm at the Franklin site) or wide rows (56 cm at all sites). In Minnesota, sugar beet is typically planted in rows with 56-cm spacing, and most farmers also plant subsequent crops (such as corn, soybean, and dry bean [*Phaseolus vulgaris* L.]) using the same spacing to maintain the equipment uniformity across multiple crops. The subplot factor included seven weed management programs: two low-input herbicide treatments; two high-input herbicide treatments; one high-input herbicide treatment combined with a HWSC simulation treatment; a nontreated control; and a weed-free control (Table 3). All of the low- and high-input treatments included application of a preemergence herbicide followed by a postemergence herbicide. The high-input treatments involved either one or two passes of postemergence applications, and all early-postemergence applications consisted of a tank-mix of foliar-active and soil residual herbicides, including very-long-chain fatty acid inhibitors. The weed-free control plots received two applications of 2,4-D choline + glufosinate, and any later emerging weed growth was managed through manual weeding as needed. The preemergence, early postemergence, and late-post-emergence herbicides were applied at planting, and at the V2 and V5 growth stages of soybean, respectively. Herbicide application dates are listed in Table 2. All herbicides were applied using a CO_2-pressurized backpack sprayer equipped with AIXR 110015 flat-fan nozzles (TeeJet Technologies, Glendale Heights, IL), calibrated to deliver 140 L ha^{-1} at 276 kPa. In the HWSC simulation treatment, all the waterhemp plants in that particular plot were carefully removed by clipping them at the base and immediately bagging them to prevent seed shattering. This approach simulates waterhemp seed removal by commercial impact mills with a high degree of seed destruction efficiency but does not account for header loss during combine harvest. Plot margins were maintained weed-free to minimize weed seed movement from adjacent areas. The GPS coordinates of the four corners of the entire experimental area were recorded at all sites, and individual soybean plot boundaries were marked with flags to preserve the layout for sugar beet planting in the subsequent season.

Soybean Canopy Development Observations

Fractional green canopy cover (FGCC) was estimated in the weed-free control plots to evaluate soybean canopy development using the methodology described by Arsenijevic et al. (2022) and

https://doi.org/10.1017/wet.2025.10058

Table 3. Treatments of soybean for waterhemp control in a soybean–sugar beet rotation in field experiments conducted at the three experimental sites.[a]

Treatment[b]	Treatment type	Herbicide trade name[c]	Herbicide application timing[d]	Herbicide rate
				g ae or ai ha^{-1}
Nontreated control	–	–	–	–
Weed-free control	–	–	–	–
Flumioxazin fb 2,4-D	Low input	Valor SX fb Enlist One	PRE fb LPOST	107 fb 1,060
Dimethenamid-P fb glyphosate	Low input	Outlook fb Roundup PowerMAX II	PRE fb LPOST	736 fb 1,420
Flumioxazin fb lactofen + acetochlor fb 2,4-D + glyphosate	High input	Valor SX fb Cobra + Warrant fb Enlist One + Durango	PRE fb EPOST fb LPOST	107 fb 220 + 1,260 fb 1,060 + 1,420
Saflufenacil + dimethenamid-P fb glufosinate+ acetochlor	High input	Verdict fb Liberty 280 SL + Warrant	PRE fb EPOST	23 + 201 fb 656 + 1,260
Saflufenacil + dimethenamid-P fb glufosinate + acetochlor fb HWSC simulation	High input + HWSC	Verdict fb Liberty 280 SL + Warrant	PRE fb EPOST	23 + 201 fb 656 + 1,260 fb –

[a]Abbreviations: EPOST, early postemergence; fb, followed by; HWSC, harvest-time weed seed control; LPOST, late postemergence; PRE, preemergence.
[b]Ammonium sulfate at 25 ml L^{-1} was added to glufosinate and glyphosate applications; crop oil concentrate at 12.5 ml L^{-1} was added when lactofen was applied.
[c]Herbicide manufacturers: Cobra and Valor SX, Valent USA, Walnut Creek CA; Durango and Enlist One, Corteva Agriscience, Indianapolis, IN; Outlook, Liberty 280 SL, and Verdict, BASF Corporation, Research Triangle Park, NC; and Roundup PowerMAX II and Warrant, Bayer CropScience, St. Louis, MO.
[d]EPOST and LPOST herbicides were applied at the V2 and V5 soybean growth stages, respectively.

Govindasamy et al. (2022). Ground-based color images (a single image per plot) were collected from the weed-free control plots at 10-d intervals, starting from 28 d after soybean planting until 95% canopy cover. Images were taken using a digital camera (Canon PowerShot SX730 HS; Canon U.S.A., Melville, NY) mounted on an inverted Z-shaped wooden structure. The camera was paired with an iPhone 11 telephone (Apple Inc., Cupertino, CA) using the Canon Camera Connect Application (v.2.7.30; Canon) and Bluetooth connectivity. The wooden structure helped to maintain a constant height above the ground. The FGCC was evaluated by processing the images using MATLAB software (MathWorks, Natick, MA) with a Canopeo software add-on (Oklahoma State University, Stillwater, OK).

Daily growing degree days and a cumulative growing degree days after planting were calculated for each site using a base temperature of 10 C in the equations below (McMaster and Wilhelm 1997):

$$\mathrm{GDD} = \left[\left(\frac{T_{max} + T_{min}}{2}\right) - 10\right] \quad [1]$$

where GDD is growing degree days, T_{max} is the maximum temperature, and T_{min} is the minimum temperature of the day; and

$$\mathrm{cGDD} = \sum\nolimits_{i=1}^{n} GDD \quad [2]$$

where $cGDD$ represents cumulative growing degree days, and n is the total number of days after planting.

Waterhemp Control, Density, Seed Production, and Soybean Yield Data Collection

Waterhemp control in soybean was visually assessed at 21 ± 3 d after a preemergence herbicide was applied, 28 ± 3 d after a late-postemergence application, and at harvest on a scale of 0% to 100%, where 0% represented no control and 100% represented complete control. Waterhemp density was recorded at 28 ± 3 d after late-postemergence herbicides were applied and at soybean harvest by counting the number of plants in two 0.25-m^2 quadrats in Franklin and Rosemount, and in four 0.25-m^2 quadrats in Moorhead placed randomly at the center of each plot and adjusting weed density data to number plants per square meter. Aboveground biomass for waterhemp was collected by clipping the plants at the base in one quadrat (0.25 m^2 in Franklin and Rosemount, and 1 m^2 in Moorhead) per plot at 35 d after late-postemergence herbicides were applied. Biomass samples were oven-dried at 60 C for 4 d and then weighed.

Five random female waterhemp plants from each plot were hand-harvested to estimate their seed production at physiological maturity at the Franklin and Rosemount sites. The seeds were threshed in a laboratory and cleaned using a seed blower (Seedburo Equipment, Des Plaines, IL) and bagged separately for each plot. All of the seeds from each plot were weighed, and the value was divided by five to determine the average seed weight per female plant. Three subsamples of 1,000 waterhemp seeds from each site-year were counted using a Diamond counter JR-D (Data Technologies, Kibbutz Tzora, Israel) and weighed to determine the subsample seed weight. The average number of seeds produced by each female waterhemp plant in each plot was estimated as follows:

$$\mathrm{SCP} = \frac{SWP}{SSW} \times 1,000 \quad [3]$$

where SCP is the number of seeds per female plant, SWP is the seed weight per female plant, and SSW is the subsample seed weight.

Finally, the waterhemp seed production (the number of seeds per square meter) at soybean harvest was calculated as:

$$\text{Seed production} = SCP \times waterhemp\ density\ at\ harvest\ (plants\ m^{-2}) \times \frac{1}{2} \quad [4]$$

where SCP is the seed production per female plant, and the waterhemp density data at soybean harvest was is the number of plants per square meter. A male-to-female plant ratio of 1:1 waterhemp plants was assumed for this calculation in this research, but the ratio could vary among waterhemp populations.

Soybean yield was estimated by harvesting a 1.5-m-wide swath from the center of each plot using a plot-combine harvester, and

https://doi.org/10.1017/wet.2025.10058

the grain weight was adjusted to 13% moisture content. In the subsequent sugar beet crop, waterhemp density was recorded approximately 45 d after planting by counting the number of plants in two quadrats (1 m^2) randomly placed in the middle of each plot.

Statistical Analysis

Due to planting issues compounded by dry weather in May at the Moorhead site in 2021, the soybean stand in the narrow-row planting was not uniform; therefore, the effect of row spacing was not included in the data analysis for that particular site-year.

Soybean green canopy cover percentage data from the weed-free controls were modeled using a four-parameter Weibull 2 model using the DRC package in R (R Core Team 2020; Ritz and Strebig 2015). The FGCC percent data (the response variable) were regressed over cGDD from planting until the day of image acquisition (the explanatory variable) using Equation 5:

$$y = c + (d - c)\left(1 - \exp\{-\exp[b(\log x - \log e)]\}\right) \quad [5]$$

where y is the average soybean green canopy cover, b is the slope around the inflection point, c is the lower limit, d is the upper limit, e is the inflection point, and x represents cGDD after planting (Ritz and Strebig 2015). The lower limit was fixed at zero. Root mean-square error (RMSE) was estimated to assess model fit using Equation 6 (Sarangi et al. 2016):

$$\mathrm{RMSE} = \left[\frac{1}{n}\Sigma_{i=1}^{n}(P_i - O_i)^2\right]^{\frac{1}{2}} \quad [6]$$

where P_i denotes the predicted value, O_i represents the observed value, and n is the total number of observations.

The cGDD required to achieve 90% soybean canopy cover (known as G_{90}) was estimated using the *ED* function, and G_{90} values for narrow and wide rows within a site-year were compared based on a t-test using the *EDcomp* function in the DRC package.

Based on the significant site-by-herbicide program and site-by-row spacing interactions, data from all the experimental sites were analyzed separately. Replications were considered random effects, whereas row spacing, weed management treatment, and interactions were considered fixed effects in the models separated by experimental sites. Generalized linear mixed models were fit to waterhemp control data using a “beta” distribution and *logit* link function with the GLMMTMB package in R (Brooks et al. 2017). Weed density data were also subjected to a generalized linear mixed model using a Poisson distribution and *log* link function. Poisson distribution models were evaluated for overdispersion using nonparametric dispersion tests from the DHARMa package (Hartig 2022); if overdispersion was detected, weed density data were modeled using a negative binomial distribution and *log* link function. Assumptions for generalized linear models were verified by plotting simulated residuals and evaluating model goodness-of-fit using the DHARMa package (Hartig 2022). Similarly, linear mixed models were fit to waterhemp biomass, seed production, and soybean yield data using the LME4 package (Bates et al. 2021). Assumptions of homogeneity of variance and normality for linear models were assessed using the Bartlett and Shapiro-Wilk tests, respectively. The ANOVA was conducted using Type III Wald chi-square tests and Type III F-tests with Satterthwaite’s method for approximating degrees of freedom for the generalized mixed models and linear mixed models, respectively. Mean separation using Fisher’s protected LSD at $P < 0.05$ and pairwise comparisons were conducted using the EMMEANS (Lenth 2021) and MULTCOMP (Hothorn et al. 2008) packages, respectively, in R.

Table 4. Estimates of regression parameters, model goodness of fit, and cumulative growing degree days required to achieve 90% soybean green canopy cover at the three experimental sites.[a]

Site-year	Row spacing	Regression parameter[b] b	Model goodness of fit RMSE	Predicted GDD[b] G_{90}	P-value[c]
Franklin 2021	Narrow	2.6 (±0.2)	6.4	687 (±27)	<0.001
	Wide	2.4 (±0.2)	7.3	893 (±31)	
Moorhead 2022	Narrow	2.5 (±0.4)	10.8	737 (±34)	0.002
	Wide	2.9 (±0.2)	6.7	875 (±32)	
Rosemount 2022	Narrow	2.7 (±0.1)	4.7	846 (±33)	0.05
	Wide	2.6 (±0.1)	6.2	939 (±44)	

[a]Abbreviations: b, slope around inflection point; GDD, growing degree days; G_{90}, cumulative GDD required for 90% soybean green canopy cover; RMSE, root-mean-square error; SEM, standard error of the mean.

[b]Regression parameter and predicted GDD values are ±SEM.

[c]G_{90} values were compared based on t-test using the *EDcomp* function in the DRC package with R software.

Results and Discussion

Mean air temperatures were slightly above the 30-yr average in most site-years, while total seasonal precipitation was 10% to 30% below the long-term average (Table 1). Despite the below-normal amount of spring rain in 2021 and 2022, intermittent rain during this period helped with the effectiveness of soil residual herbicides for waterhemp control.

Soybean Canopy Development

Site-by-row spacing interaction was significant for soybean green canopy cover; therefore, canopy cover data are presented by site. The slopes (b) around the inflection points of the regression curves ranged between 2.4 and 2.9 for both of the row spacings in all site-years (Table 4). The lower RMSE values (≤10.8) show a good fit of the models. At the Franklin site, narrow-row soybean reached 90% green canopy cover (G_{90}) by accumulating 206 fewer GDDs than wide-row spacing (687 ± 27 for narrow rows and 893 ± 31 for wide rows) (Table 4, Figure 1). In 2022, soybean in narrow rows required 138 units less cGDD than in wide rows for G_{90} in Moorhead, whereas cGDD requirements for G_{90} were comparable at Rosemount (Table 4, Figure 1). Differences in G_{90} between narrow- and wide-row spacings corresponded to 15 and 12 d in Franklin 2021 and Moorhead 2022, respectively (data not shown). Several previous studies reported similar observations, wherein soybean planted with 19- to 38-cm row spacing closed the canopy earlier than soybean planted at 76-cm spacing (Dalley et al. 2004; Harder et al. 2007; Mickelson and Renner 1997; Nelson and Renner 1998). Earlier canopy closure reduces the availability of photosynthetically active radiation, lowers red-to–far red light, and decreases soil thermal amplitudes, factors known to inhibit germination of *Amaranthus* spp. (Gallagher and Cardina 1998; Jha and Norsworthy 2009; Leon and Owen 2006; Norsworthy 2004; Sattin et al. 1994).

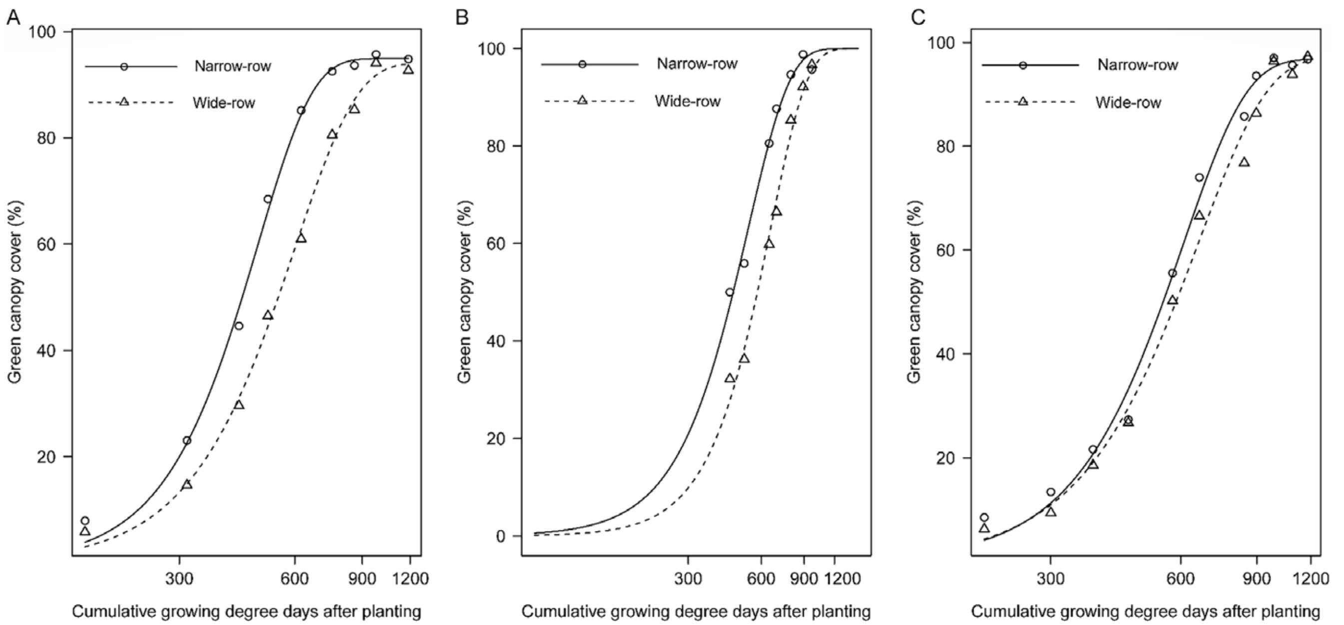

Figure 1. Effect of row spacing on soybean green canopy cover (%) in weed-free controls in field experiments conducted in (A) Franklin, Minnesota, in 2021; (B) Moorhead, Minnesota, in 2022; and (C) Rosemount, Minnesota in 2022. A narrow row represents soybean planted in 38-cm rows at the Moorhead and Rosemount sites and 30-cm rows at the Franklin site, Wide-row spacing represents soybean planted at 56 cm in all the experimental site-years. The soybean green canopy cover represents the fractional green canopy cover (FGCC) estimated through analysis of ground-based color images using the Canopeo application. The FGCC data were regressed over cumulative growing degree days using Weibull 2 functions.

Waterhemp Control and Density

The Moorhead 2021 site-year was excluded from the analysis of row spacing effects due to planting issues. Soybean row spacing–by–weed management treatment interactions were nonsignificant in all site-years ($P \geq 0.05$); therefore, the main treatment effects are presented. Contrary to our hypothesis and despite the early canopy closure, soybean row spacing did not influence waterhemp control, density, or aboveground biomass in any of the site-years and evaluation timings (Tables 5–8). Previous research has reported variable effects of soybean row spacing on *Amaranthus* spp. control and biomass reduction; for example, Schultz et al. (2015) reported higher waterhemp control and a lower weed density in 38-cm soybean rows compared with 76-cm spacing in a 2-yr experiment in Missouri. In contrast, Lamers (2022) reported similar waterhemp and Palmer amaranth (*Amaranthus palmeri* S. Watson) control in row spacings of 38 and 76 cm in soybean at 4 and 10 wk after postemergence herbicide application. In our experiment, soybean row spacing of 30 or 38 cm was compared to spacing of 56 cm; thus, the smaller difference in row spacing relative to previous studies may have contributed to the lack of a significant effect.

At the Franklin site in 2021, all the herbicide treatments tested in this experiment provided similar waterhemp control ($P \geq 0.05$) at all observation timings (Table 5). Application of preemergence herbicides resulted in ≥90% waterhemp control at 28 d after preemergence application in Franklin, whereas in Rosemount, flumioxazin applied preemergence resulted in 73% waterhemp control compared with ≤55% control achieved with dimethenamid-P or saflufenacil + dimethenamid-P (Table 5 and 8). Differences in waterhemp control between the two sites were likely associated with the differences in waterhemp seedbank size, soil physical properties, and herbicide choices (Table 5 and 8). The Rosemount site had a larger waterhemp seedbank, as indicated by the higher plant density in the nontreated control. Moreover, the soil at Rosemount was silty clay loam with 36% clay content, compared to loam with a clay content of <25% at the Franklin site. Although flumioxazin efficacy is generally unaffected by soil clay content (Glaspie et al. 2021), dimethenamid-P, which has a lower sorption coefficient (K_f), may exhibit reduced activity when applied to soils with higher clay content (Sharipov et al. 2021).

At the Franklin site in 2021, all herbicide treatments provided ≥96% waterhemp control at 28 d after the late-postemergence application and at soybean harvest, and that reduced the density to ≤1 plant m^{-2} compared with 64 plants m^{-2} in the nontreated control (Table 5). The waterhemp biomass at that site-year ranged between 0 and 8 g m^{-2} from all of the herbicide treatments compared with 110 g m^{-2} from the nontreated control (Table 5).

In Moorhead in 2021, a high-input herbicide treatment containing flumioxazin applied preemergence followed by (fb) an application of lactofen + acetochlor early postemergence fb 2,4-D + glyphosate applied late postemergence resulted in 96% and 98% control of waterhemp at 28 d after late-postemergence application and at harvest, respectively. This was similar to waterhemp control (≥94%) obtained with a low-input treatment of flumioxazin applied preemergence fb 2,4-D applied late postemergence (Table 6). When assessed at 35 d after the late-postemergence herbicide application, waterhemp density decreased by >99% with the aforementioned herbicide treatments compared with density in the nontreated control. A similar trend was also observed at Moorhead in 2022, where ≥94% waterhemp control was achieved with these treatments (Table 7). However, another high-input herbicide treatment that included saflufenacil + dimethenamid-P applied preemergence fb glufosinate + acetochlor applied early postemergence also resulted in similar waterhemp control (93%), density (0 plants m^{-2}), and aboveground biomass (9 g m^{-2}) as the aforementioned herbicide treatment at the same site-year.

https://doi.org/10.1017/wet.2025.10058

Table 5. Effect of soybean row spacing and weed management treatment on waterhemp control, density, and aboveground biomass in Franklin, Minnesota, in 2021.[a]

Treatment	Application timing[b]	Treatment type	Control[c,f]			Density[d,f]		Biomass[e,f]
			28 DAPRE	28 DALP	At harvest	28 DALP	At harvest	35 DALP
			%			plants m^{-2}		g m^{-2}
Nontreated control	–	–	0	0	0	64 a	24 a	110 a
Weed-free control	–	–	100	100	100	0	0	0
Flumioxazin fb 2,4-D	PRE fb LPOST	Low input	90 a	96 a	98 a	1 b	0 b	0 b
Dimethenamid-P fb glyphosate	PRE fb LPOST	Low input	91 a	96 a	96 a	1 b	1 b	8 b
Flumioxazin fb lactofen + acetochlor fb 2,4-D + glyphosate	PRE fb EPOST fb LPOST	High input	92 a	97 a	99 a	0 b	0 b	0 b
Saflufenacil + dimethenamid-P fb glufosinate + acetochlor	PRE fb EPOST	High input	91 a	97 a	99 a	0 b	0 b	0 b
Saflufenacil + dimethenamid-P fb glufosinate + acetochlor fb HWSC simulation	PRE fb EPOST	High input + HWSC	94 a	98 a	99 a	0 b	0 b	0 b
P-value			0.71	0.36	0.07	< 0.001	< 0.001	< 0.001
Row spacing								
Narrow			93 a	97 a	98 a	8 a	4 a	23 a
Wide			90 a	97 a	98 a	9 a	4 a	16 a

[a]Abbreviations: DALP, days after late postemergence application; DAPRE, days after preemergence application; EPOST, early postemergence; fb, followed by; HWSC, harvest-time weed seed control; and LPOST, late postemergence; PRE, preemergence.
[b]EPOST and LPOST herbicides were applied at the V2 and V5 soybean growth stages, respectively.
[c]Data were analyzed using a generalized linear mixed model with beta distribution and *logit* link function; interpretations are based on the logit scale; however, back-transformed estimated mean values are presented. The nontreated and weed-free control were excluded from the analysis.
[d]Data were analyzed using a generalized linear mixed model with either negative binomial: quadratic parameterization or Poisson distribution and *log* link function. Interpretations are based on the log scale; however, back-transformed estimated mean values are presented. The weed-free control was excluded from the analysis.
[e]Data were analyzed using a linear mixed model. The weed-free control was excluded from the analysis.
[f]Means within the same column with no common letters are significantly different based on Fisher's protected LSD ($P < 0.05$).

Table 6. Effect of waterhemp treatment and aboveground biomass in Moorhead, Minnesota, in 2021.[a]

Treatment	Application timing[b]	Treatment type	Control[c,e]		Biomass[d,e]
			28 DALP	At harvest	35 DALP
			%		g m^{-2}
Nontreated control	–	–	0	0	384 a
Weed-free control	–	–	100	100	0
Flumioxazin fb 2,4-D	PRE fb DALP	Low input	94 ab	96 a	2 c
Dimethenamid-P fb glyphosate	PRE fb DALP	Low input	55 d	27 c	126 b
Flumioxazin fb lactofen + acetochlor fb 2,4-D + glyphosate	PRE fb EPOST fb DALP	High input	96 a	98 a	0 c
Saflufenacil + dimethenamid-P fb glufosinate + acetochlor	PRE fb EPOST	High input	84 c	80 b	27 c
Saflufenacil + dimethenamid-P fb glufosinate + acetochlor fb HWSC simulation	PRE fb EPOST	High input + HWSC	88 bc	80 b	5 c
P-value			<0.001	<0.001	<0.001

[a]Abbreviations: DALP, days after late-postemergence application; EPOST, early-postemergence; fb, followed by; HWSC, harvest-time weed seed control; and LPOST, late-postemergence; PRE, preemergence.
[b]EPOST and LPOST herbicides were applied at the V2 and V5 soybean growth stages, respectively.
[c]Data were analyzed using a generalized linear mixed model with beta distribution and *logit* link function; interpretations are based on the logit scale; however, back-transformed estimated mean values are presented. The nontreated and weed-free control were excluded from the analysis.
[d]Data were analyzed using a linear mixed model. The weed-free control was excluded from the analysis.
[e]Means within the same column with no common letters are significantly different based on Fisher's protected LSD ($P < 0.05$).

In Rosemount in 2022, the high-input treatment of flumioxazin applied preemergence fb lactofen + acetochlor applied early postemergence fb 2,4-D + glyphosate applied late postemergence resulted in 98% waterhemp control and a density of 0 plants m^{-2} at 28 d after the late-postemergence application and at harvest (Table 8). At harvest, another high-input herbicide treatment (saflufenacil + dimethenamid-P applied preemergence fb glufosinate + acetochlor applied early postemergence) also provided a similar level (95%) of waterhemp control. All the high-input treatments and a low-input treatment (flumioxazin applied preemergence fb 2,4-D applied late postemergence) resulted in waterhemp aboveground biomass being reduced to ≤1 g m^{-2} at 35 d after the 2,4-D application, whereas waterhemp biomass in the nontreated control was 64 g m^{-2} (Table 8). Including acetochlor, a soil residual herbicide, in the postemergence tank-mix in the high-input treatments improved waterhemp control. Tank-mixing soil residual herbicides with foliar-active postemergence herbicides is considered an effective strategy for season-long management of *Amaranthus* spp. For example, research conducted in Nebraska showed that including soil residual herbicides that inhibit very-

https://doi.org/10.1017/wet.2025.10058

Table 7. Effect of soybean row spacing and weed management treatment on waterhemp control, density, and aboveground biomass in Moorhead, Minnesota in 2022.[a]

Treatment	Application timing[b]	Treatment type	Control[c,f]		Density[d,f]	Biomass[e,f]
			28 DALP	At harvest	28 DALP	35 DALP
			——%——		plants m^{-2}	g m^{-2}
Nontreated control	–	–	0	0	9 a	147 a
Weed-free control	–	–	100	100	0	0
Flumioxazin fb 2,4-D	PRE fb DALP	Low input	95 ab	94 ab	0 d	0 c
Dimethenamid-P fb Glyphosate	PRE fb DALP	Low input	52 c	50 c	5 b	68 b
Flumioxazin fb lactofen + acetochlor fb 2,4-D + glyphosate	PRE fb EPOST fb DALP	High input	96 a	95 A	0 d	0 c
Saflufenacil + dimethenamid-P fb glufosinate + acetochlor	PRE fb EPOST	High input	93 ab	93 ab	0 d	9 c
Saflufenacil + dimethenamid-P fb glufosinate + acetochlor fb HWSC simulation	PRE fb EPOST	High input + HWSC	91 b	88 b	1 c	6 c
P-value			<0.001	<0.001	<0.001	<0.001
Row spacing						
Narrow			90 a	89 a	3 a	36 a
Wide			91 a	89 a	2 a	41 a

[a]Abbreviations: DALP, days after late postemergence application; EPOST, early postemergence; fb, followed by; HWSC, harvest-time weed seed control; LPOST, late postemergence; PRE, preemergence.
[b]EPOST and LPOST herbicides were applied at the V2 and V5 soybean growth stages, respectively.
[c]Data were analyzed using a generalized linear mixed model with beta distribution and *logit* link function; interpretations are based on the logit scale; however, back-transformed estimated mean values are presented. The nontreated and weed-free control were excluded from the analysis.
[d]Data were analyzed using a generalized linear mixed model with either negative binomial: quadratic parameterization or Poisson distribution and *log* link function; interpretations are based on the log scale; however, back-transformed estimated mean values are presented. Weed-free control was excluded from the analysis.
[e]Data were analyzed using a linear mixed model. The weed-free control was excluded from the analysis.
[f]Means within the same column with no common letter(s) are significantly different based on Fisher's protected LSD ($P < 0.05$).

Table 8. Effect of soybean row spacing and weed management treatment on waterhemp control, density, and aboveground biomass in Rosemount, Minnesota, in 2022.[a]

Treatment	Application timing[b]	Treatment type	Control[c,f]			Density[d,f]		Biomass[e,f]
			28 DAPRE	28 DALP	At harvest	28 DALP	At harvest	35 DALP
			——%——			plants m^{-2}		g m^{-2}
Nontreated control	–	–	0	0	0	179 a	287 a	64 a
Weed-free control	–	–	100	100	100	0	0	0
Flumioxazin fb 2,4-D	PRE fb DALP	Low input	73 a	91 c	94 b	2 c	1 d	1 c
Dimethenamid-P fb glyphosate	PRE fb DALP	Low input	52 b	46 d	56 c	36 b	32 b	29 b
Flumioxazin fb lactofen + acetochlor fb 2,4-D + glyphosate	PRE fb EPOST fb DALP	High input	73 a	98 a	98 a	0 d	0 d	0 c
Saflufenacil + dimethenamid-P fb glufosinate + acetochlor	PRE fb EPOST	High input	49 b	94 bc	95 ab	1 cd	3 c	0 c
Saflufenacil + dimethenamid-P fb glufosinate + acetochlor fb HWSC simulation	PRE fb EPOST	High input + HWSC	55 b	95 b	95 ab	1 cd	0 d	0 c
P-value			<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Row spacing								
Narrow			62 a	92 a	93 a	47 a	56 a	16 a
Wide			60 a	91 a	93 a	29 a	51 a	15 a

[a]Abbreviations: DALP, days after late postemergence application; DAPRE, days after preemergence application; EPOST, early postemergence; fb, followed by; HWSC, harvest-time weed seed control; LPOST, late postemergence; PRE, preemergence.
[b]EPOST and LPOST herbicides were applied at the V2 and V5 soybean growth stages, respectively.
[c]Data were analyzed using a generalized linear mixed model with beta distribution and *logit* link function; interpretations are based on the logit scale; however, back-transformed estimated mean values are presented. The nontreated and weed-free control were excluded from the analysis.
[d]Data were analyzed using a generalized linear mixed model with either negative binomial: quadratic parameterization or Poisson distribution and *log* link function; interpretations are based on the log scale; however, back-transformed estimated mean values are presented. The weed-free control was excluded from the analysis.
[e]Data were analyzed using a linear mixed model. The weed-free control was excluded from the analysis.
[f]Means within the same column with no common letters are significantly different based on Fisher's protected LSD ($P < 0.05$).

long-chain fatty acids (e.g., acetochlor, dimethenamid-P, pyroxasulfone, or *S*-metolachlor) in postemergence applications substantially improved Palmer amaranth control, with the benefits becoming more evident later in the season (Sarangi and Jhala 2019).

Waterhemp Seed Production

The row spacing-by–herbicide treatment interactions were not significant at $\alpha = 0.05$; therefore, the main effects are presented. Waterhemp seed production was not evaluated at Moorhead. Soybean row spacing did not affect waterhemp seed production.

https://doi.org/10.1017/wet.2025.10058

Table 9. Effect of soybean row spacing and weed management treatment on waterhemp seed production and soybean yield at the three experimental sites.[a]

Treatment	Application timing[b]	Treatment type	Waterhemp seed production[c,d]		Soybean yield[c,d]			
			Franklin 2021	Rosemount 2022	Franklin 2021	Moorhead 2021	Moorhead 2022	Rosemount 2022
			No. seeds m^{-2}		kg ha^{-1}			
Nontreated control	–	–	522,600 a	151,300 a	1,270 d	570 c	880 d	2,010 c
Weed-free control	–	–	0	0	4,120 bc	2,510 a	3,590 a	3,890 a
Flumioxazin fb 2,4-D	PRE fb LPOST	Low input	0 b	0 c	4,190 abc	2,530 a	3,070 bc	2,920 b
Dimethenamid-P fb glyphosate	PRE fb LPOST	Low input	500 b	43,200 b	4,040 c	1,730 b	2,790 c	2,770 b
Flumioxazin fb lactofen + acetochlor fb 2,4-D + glyphosate	PRE fb EPOST fb LPOST	High input	0 b	0 c	4,170 abc	2,410 a	3,560 a	3,740 A
Saflufenacil + dimethenamid-P fb glufosinate + acetochlor	PRE fb EPOST	High input	0 b	300 c	4,420 a	2,200 ab	3,180 abc	3,940 a
Saflufenacil + dimethenamid-P fb glufosinate + acetochlor fb HWSC simulation	PRE fb EPOST	High input + HWSC	0 b	200 c	4,350 ab	2,320 a	3,270 ab	3,990 a
P-value			<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Row spacing								
Narrow			13,741 a	9,987 a	3,963 a	–	3,048 a	3,603 a
Wide			17,197 a	12,218 a	3,624 b	–	2,764 a	3,041 b

[a]Abbreviations: EPOST, early postemergence; fb, followed by; HWSC, harvest-time weed seed control; LPOST, late postemergence; PRE, preemergence.
[b]EPOST and LPOST herbicides were applied at the V2 and V5 soybean growth stages, respectively.
[c]Data were analyzed using a linear mixed model. The weed-free control was excluded from the analysis of waterhemp seed production data.
[d]Means within the same column with no common letter(s) are significantly different based on Fisher's protected LSD ($P < 0.05$).

When averaged across treatments, seed production in rows with narrow spacing ranged from 9,987 to 13,741 seeds m^{-2}, while wide-row spacing produced 12,218 to 17,197 seeds m^{-2} in all site-years (Table 9). In a field experiment conducted in Minnesota, Flipp (2013) reported a similar trend in waterhemp seed production in soybean crops that were planted with row spacings of 17.5 and 76 cm.

The nontreated control plots produced the highest number of waterhemp seeds, 151,300 and 522,566 seeds m^{-2} at Rosemount and Franklin, respectively (Table 9). In Wisconsin, Striegel et al. (2021) reported that waterhemp in a nontreated control produced up to 511,000 seeds m^{-2}. The low-input herbicide treatment of dimethenamid-P applied preemergence fb glyphosate applied late postemergence produced 43,220 waterhemp seeds m^{-2} in Rosemount in 2022 (Table 9). The presence of glyphosate-resistant waterhemp in Rosemount likely led to lower waterhemp control and greater seed production with this treatment compared with a similar treatment at the Franklin site. The high-input treatment of flumioxazin applied preemergence fb lactofen + acetochlor applied early postemergence fb 2,4-D + glyphosate applied late postemergence resulted in 0 seeds m^{-2} (Table 9). Bell et al. (2015) reported that in Arkansas, *A. palmeri* produced 96,800 to 247,300 seeds m^{-2} in a nontreated control, whereas seed production dropped to 0 seeds m^{-2} in a field of soybean when *S*-metolachlor + metribuzin was applied preemergence fb glufosinate + *S*-metolachlor + fomesafen applied early postemergence fb glufosinate + acetochlor applied late postemergence. Because waterhemp seed production in this research was measured at soybean harvest, it did not account for any seed loss due to preharvest shattering. The estimated seed numbers represent those likely to enter the combine during harvest, making them the primary targets for HWSC strategies. For example, despite an effective high-input herbicide treatment (saflufenacil + dimethenamid-P fb glufosinate + acetochlor), 200 to 300 waterhemp seeds m^{-2} were produced at the Rosemount site in 2022. These seeds were manually removed as part of the HWSC simulation (Table 9). Waterhemp seeds are relatively small, and herbicide-resistant biotypes can spread from one field to another through seed-mediated gene flow during harvest or through the movement of machinery between fields.

Soybean Yield

At 14 d after an early postemergence application of lactofen, 15% to 35% soybean injury was observed in all site-years (data not shown). No preemergence or postemergence herbicides, except for lactofen, caused >8% soybean injury in the site-years.

Row spacing-by-herbicide treatment interaction was not significant in any site-year; therefore, only the main effects are presented. Soybean planted in narrow rows yielded more than soybean spaced in wide rows in Franklin in 2021 (3,963 kg ha^{-1} in narrow rows vs. 3,624 kg ha^{-1} in wide rows) and Rosemount in 2022 (3,603 kg ha^{-1} vs. 3,041 kg ha^{-1}); however, the row spacing did not affect soybean yield in Moorhead in 2022 (Table 9). A slightly earlier canopy closure in narrow-row soybean likely resulted in greater light interception and better soybean growth (Bullock et al. 1998; De Bruin and Pedersen 2008). Although previous research indicated the effect of soybean row spacing on yield could vary depending on the growing environment, most research supported that narrow rows tend to improve soybean yield (Singh et al. 2023). The lack of yield advantage in narrow-row spacing at the Moorhead site was likely due to the incidence of iron deficiency chlorosis (IDC) in soybean; however, the intensity of IDC was not measured in this experiment. Closer planting of soybean seeds within a row (in wide rows) has been reported to enhance synergism between adjacent soybean roots and to improve iron availability to the plants (Wiersma 2007); thus, a more distant arrangement of plants within a row might have increased the intensity of IDC in narrow-row spacing at that site.

Table 10. Effect of soybean row spacing and herbicide treatment on waterhemp density in the subsequent season's sugar beet crop in field experiments conducted at the three experimental sites.[a]

Treatment	Application timing[b]	Treatment type	Waterhemp density[c,d]			
			Franklin 2022	Moorhead 2022	Moorhead 2023	Rosemount 2023
			plants m^{-2}			
Nontreated control	–	–	188 a	74 ab	1,128 a	289 a
Weed-free control	–	–	54 b	38 cd	364 bc	8 bc
Flumioxazin fb 2,4-D	PRE fb LPOST	Low input	48 b	40 cd	372 b	54 cd
Dimethenamid-P fb glyphosate	PRE fb LPOST	Low input	39 bc	110 a	995 a	98 b
Flumioxazin fb lactofen + acetochlor fb 2,4-D + glyphosate	PRE fb EPOST fb LPOST	High input	18 d	27 d	287 bc	36 de
Saflufenacil + dimethenamid-P fb glufosinate + acetochlor	PRE fb EPOST	High input	15 d	58 bc	215 c	47 cde
Saflufenacil + dimethenamid-P fb glufosinate + acetochlor fb HWSC simulation	PRE fb EPOST	High input + HWSC	23 cd	46 bc	314 bc	31 e
P-value			<0.001	<0.001	<0.001	<0.001
Row spacing						
Narrow			37 a	–	530 a	75 a
Wide			40 a	–	357 a	58 a

[a]Abbreviations: EPOST, early postemergence; fb, followed by; HWSC, harvest-time weed seed control; and LPOST, late postemergence; PRE, preemergence.
[b]EPOST and LPOST herbicides were applied at the V2 and V5 soybean growth stages, respectively.
[c]Data were analyzed using a generalized linear mixed model with either negative binomial: quadratic parameterization or Poisson distribution and *log* link function; interpretations are based on the log scale; however, back-transformed estimated mean values are presented.
[d]Means within the same column with no common letter(s) are significantly different based on Fisher's protected LSD (P < 0.05).

In all site-years, the nontreated controls yielded 48% to 77% less compared with the weed-free controls (Table 9). At the Franklin site, saflufenacil + dimethenamid-P applied preemergence fb glufosinate + acetochlor applied early postemergence resulted in the greatest soybean yield (4,420 kg ha^{-1}), which was similar to other high-input herbicide treatments and one low-input treatment of flumioxazin fb 2,4-D. At the Moorhead site in 2021, all of the herbicide treatments except for the low-input treatment of dimethenamid-P applied preemergence fb a late-postemergence application of glyphosate provided similar yields (≥2,200 kg ha^{-1}) to that of the weed-free control (Table 9). In Moorhead and Rosemount in 2022, soybean yield in the weed-free controls was 3,590 and 3,890 kg ha^{-1}, respectively, which was similar to the yields obtained with high-input herbicide treatments at those sites. Including herbicides with multiple sites of action and a soil residual herbicide (a very-long-chain fatty acid inhibitor) at early postemergence improved soybean yield in this experiment, and in most cases, was similar to the weed-free controls. In research conducted in Nebraska, Sarangi and Jhala (2019) reported that including a very-long-chain fatty acid inhibitor in a tank-mix of postemergence herbicides improved soybean yield by at least 289 kg ha^{-1} compared to a preemergence fb postemergence treatment with no residual herbicide in the postemergence treatments.

Waterhemp Emergence in the Subsequent Sugar Beet Crop

Consistent with its effect on waterhemp control, density, and seed production during the soybean year, spacing soybean in narrow rows did not affect waterhemp density in the subsequent sugar beet crop (Table 10). Waterhemp density in the subsequent sugar beet crop was largest in the nontreated controls in most site-years (Table 10). Waterhemp density in the nontreated controls (74 and 1,128 plants m^{-2} in 2022 and 2023, respectively) at the Moorhead site was similar to waterhemp density after the low-input treatment of dimethenamid-P fb glyphosate (110 and 995 plants m^{-2}). Mahoney et al. (2021) reported no effect of soybean plant population on Palmer amaranth emergence in a subsequent cotton crop at 3 wk after planting, but Palmer amaranth density in the nontreated control (88 plants m^{-2}) was greater than with herbicide treatments (54 to 66 plants m^{-2}). In Franklin (2022), Moorhead (2023), and Rosemount (2023) sites, high-input herbicide treatments of soybean resulted in a drop in waterhemp density by 72% to 92% in sugar beet compared to the nontreated control (Table 10). The herbicide treatment was the primary factor driving the reduction in waterhemp emergence in the following season. Combining HWSC simulation with high-input treatments did not affect waterhemp density across the site-years (Table 10). The lack of a significant HWSC simulation effect in one year was likely due to the higher efficacy of the high-input herbicide treatment, a relatively large existing seedbank, and the fact that only a small fraction of weed seeds emerges in a given season. Buhler and Hartzler (2001) reported 5% and 7% waterhemp seed emergence from buried seeds at the end of the first and second year, respectively, indicating that a small and relatively consistent portion of the seedbank emerges in the initial years. Furthermore, the HWSC simulation did not account for header losses, suggesting that the actual reduction in germination could be even lower than the observed values.

Practical Implications

Weedy *Amaranthus* spp., including waterhemp and Palmer amaranth, are highly dynamic, characterized by a prolonged emergence window, rapid growth rates, high fecundity, seed viability of at least 4 yr, and strong adaptability to changing environments (Korres et al. 2018; Sarangi et al. 2016, 2021). The rise in herbicide resistance cases, coupled with the absence of new herbicide sites of action, underscores the need for integrated weed management approaches that include nonchemical control methods along with herbicide application (Ervin et al. 2019; Norsworthy et al. 2012; Singh et al. 2024; Tranel 2020). We hypothesized that growing soybean in narrow rows would suppress waterhemp emergence and growth by promoting earlier canopy closure. However, in this study, row spacing did not affect in-season waterhemp control, seed production, or waterhemp density in the following sugar beet crop across the site-years.

This study demonstrated that a single year of effective waterhemp control using high-input herbicide treatments in the preceding crop (here, soybean) substantially reduced waterhemp density in sugar beet compared with density in nontreated control plots. However, despite zero seed production in some high-input soybean herbicide treatments, waterhemp density in plots of sugar beet was not reduced to zero. Given the large existing seedbank at the research sites, a single year of aggressive management was not expected to fully deplete it, consistent with findings that only 5% to 7% waterhemp seeds emerge annually (Buhler and Hartzler 2001). Given the limited early-season competitiveness of sugar beet and few effective herbicide options, it may be advisable to avoid planting it in fields with high waterhemp seedbanks, and instead favor a rotation with more competitive crops such as wheat (*Triticum aestivum* L.) or corn that offer broader weed control options. HWSC may be more effective in reducing the weed seedbank when weed control from herbicides is somewhat limited. In this study, the effect of HWSC simulation in soybean was not evident in waterhemp density in the subsequent sugar beet crop, likely due to the already high efficacy of herbicide treatments, a relatively large existing waterhemp seedbank, and the short duration of the experiment. Walsh et al. (2017) reported a 37% to 90% reduction in rigid ryegrass (*Lolium rigidum* Gaudin) emergence when HWSC was adopted in the previous crop. Similarly, a modeling study by Borger et al. (2021) predicted a 46% reduction in great brome (*Bromus diandrus* Roth) seedbank over 6 yr of HWSC implementation, even with only 20% seed destruction. Future research should evaluate the effect of multi-tactic waterhemp management over a longer period, ideally within at least a 3-yr rotation that includes sugar beet in the third year.

Acknowledgments. We thank Joe Sullivan and the Sullivan Family Farm in Franklin, Minnesota, and American Crystal Sugar Cooperative, Moorhead, Minnesota, for providing the land for on-farm research trials. We appreciate the assistance provided by personnel at the University of Minnesota's Rosemount Research and Outreach Center and the North Dakota State University Sugar Beet Weeds laboratory, including Alexa Lystad, for help in establishing, coordinating, and conducting the experiments. Assistance from members of the University of Minnesota Weeds Laboratory is greatly appreciated. We also thank Steve Quiring for his help in establishing the project and crop harvesting, and Ian Rogers for copyediting the manuscript.

Funding. The research was funded by the Minnesota Soybean Research and Promotion Council.

Competing interests. The authors declare they have no competing interests.

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