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Inter-row cultivation timing effects on waterhemp (*Amaranthus tuberculatus*) control and sugarbeet yield and quality

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Research Article

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Abstract

The invasion of waterhemp into northern sugarbeet growing regions has prompted producers to re-integrate inter-row cultivation into weed management programs, as no currently registered herbicides can control glyphosate-resistant waterhemp POST in crop. Inter-row cultivation was a common weed control practice in sugarbeet until the release of glyphosate-resistant sugarbeet cultivars in 2008 made the use of inter-row cultivation unnecessary. In the late 2010s, producers began again to use inter-row cultivation to remove weeds that glyphosate did not control, but producers need information on the effectiveness and safety of inter-row cultivation when used with soil-residual herbicide programs. Efficacy and tolerance field experiments were conducted in Minnesota and North Dakota from 2017 to 2019. Results from the efficacy experiment demonstrated that cultivation improved waterhemp control 11% and 12%, 14 and 28 d after treatment, respectively. Waterhemp response to cultivation was dependent on crop canopy and precipitation after cultivation. Cultivation had minimal effect on waterhemp density in three environments, but at one environment, near Galchutt, ND in 2019, waterhemp density increased 600% and 196%, 14 and 28 d after treatment, respectively. Climate data indicated that in 2019 Galchutt, ND received 105 mm of precipitation in the 14 d following cultivation and had an open crop canopy that probably contributed to further weed emergence. Results from the tolerance experiment demonstrated that root yield and recoverable sucrose were not affected by cultivation timing or number of cultivations. In one environment, cultivating reduced sucrose content by 0.8% regardless of date or cultivation number, but no differences were found in four environments. Damage/destruction of leaf tissue from in-season cultivation is probably responsible for the reduction in sucrose content. Results indicate that cultivation can be a valuable tool to control weeds that herbicide cannot, but excessive rainfall and open crop canopy following cultivation can create an environment conducive to further weed emergence.

Introduction

Weeds have been a major production challenge for sugarbeet since the crop was first widely grown in Europe in the late 1700s (Schweizer and May 1993). Weed management in sugarbeet is especially challenging because of its low growth habit, slow canopy development, and limited POST herbicide options (Bollman and Sprague 2007). Inter-row cultivation and hand-weeding were the primary weed control methods prior to the development of herbicides, but these methods took on a lesser role in sugarbeet weed management as more herbicides were developed. Desmedipham and phenmedipham were the primary herbicides used to control *Amaranthus* and *Chenopodium* species in sugarbeet from the 1970s to 2000s (Dale et al. 2006; Dexter 1977, 1994), with inter-row cultivation to supplement their use. The chloroacetamide herbicides *S*-metolachlor and dimethenamid-*P* were registered for sugarbeet in the mid-2000s, which led to their brief use with desmedipham and phenmedipham before the commercialization of glyphosate-resistant (GR) sugarbeet (Bollman and Sprague 2007).

The commercialization of GR sugarbeet cultivars in 2008 resulted in a sweeping change in sugarbeet weed management. Glyphosate became the primary tool used for weed control, as it was cheaper, safer, and more effective than desmedipham, phenmedipham, and inter-row cultivation. Guza et al. (2002) reported that greater than 95% redroot pigweed (*Amaranthus retroflexus* L.) and common lambsquarters (*Chenopodium album* L.) control could be achieved with two POST applications of glyphosate in sugarbeet. Dexter and Luecke (2000) reported that glyphosate improved sugarbeet tolerance and weed control compared to the conventional micro-rate program, which contributed to significantly greater root yield. Other research suggested that inter-row cultivation for controlling weeds was unnecessary and possibly detrimental to yield (Dexter et al. 2000). Survey data from 2007 indicated that

99% of North Dakota and Minnesota sugarbeet hectares were inter-row cultivated (Carlson et al. 2008), but only 11% of hectares were cultivated in 2011 following the release of GR cultivars (Stachler et al. 2011). Unfortunately, GR weeds, including waterhemp, had already migrated into the upper Midwest by the time GR sugarbeet cultivars were released and have become progressively more problematic in recent years. Weed control trials in 2016 reported that glyphosate-only treatments in sugarbeet controlled only 30% to 40% of waterhemp by late August (Peters et al. 2017). In addition to the diminishing effectiveness of glyphosate, the label registrations for desmedipham and phenmedipham were not renewed in the mid-2010s (EPA 2014), leaving sugarbeet producers with even fewer POST control options.

Use of the chloroacetamide herbicides *S*-metolachlor, dimethenamid-*P*, and acetochlor applied early POST has increased from 15% in 2014 to 91% in 2018, according to surveyed producers in regions where producers identify waterhemp as their primary production challenge (Carlson et al. 2015; Peters et al. 2020). Chloroacetamide herbicides are activated into soil solution by rainfall and provide residual control of emerging small-seeded broadleaf weeds, including *Amaranthus* species. The current recommendation to Minnesota and North Dakota producers for waterhemp control in sugarbeet is to apply *S*-metolachlor and/or ethofumesate PRE followed by layered applications of a chloroacetamide herbicide early POST (Peters et al. 2017). Layering residual chloroacetamide herbicides throughout the season will prevent weed emergence until the sugarbeet crop canopy provides shade to suppress further weed growth. Chloroacetamide herbicides require 10 to 20 mm of precipitation for activation into soil solution and do not control already emerged weeds (Anonymous 2014, 2017). Herbicide-resistant weed escapes are a concern when limited rainfall results in poor herbicide activation or when excessive rainfall makes timely herbicide applications challenging. Many sugarbeet producers have used inter-row cultivation to remove glyphosate-resistant weeds that escaped the residual chloroacetamide herbicide layer.

Inter-row cultivation mid-season has benefits and drawbacks. The greatest benefit is nonselective removal of weeds between crop rows that herbicides did not or cannot control. Other benefits include drying and loosening of the soil and incorporation of fertilizer and soil-active herbicides. In some weed species, disturbance of the soils by tillage can increase the germination and emergence of weed seeds in the seed bank; in other species, tillage reduces emergence (Egley and Williams 1990). Over a 5-yr average, however, Egley and Williams (1990) concluded that tillage or tillage depth did not significantly affect weed emergence for numerous species including redroot pigweed. Weed dormancy and emergence is a complex interaction of soil moisture, temperature, and light exposure (Alm et al. 1993; Baskin and Baskin 1990; Kemp 2000). For many weed species, especially small-seeded broadleaves, tillage has limited effects on weed emergence. Oryokot et al. (1997) reported that tillage had minimal effect on redroot pigweed emergence. Soil samples taken to a 2.5-cm depth on plots with and without tillage indicated that tillage did not change soil temperature or soil moisture. This incidence is due to a relationship between the top 2.5 cm of soil and the atmosphere that creates an equilibrium of temperature and moisture. *Amaranthus* species are physiologically limited to germination within the top 2.5 cm of soil as a result of the seed's small endosperm, explaining tillage's limited effect on redroot pigweed emergence (Oryokot et al. 1997). Exposure of weed seeds to light during tillage can also affect weed emergence. Buhler (1997) reported that common lambsquarters emergence increased nearly 250% when tillage was performed in the light compared to the dark, demonstrating the influence of infrared light on weed dormancy and germination.

Numerous studies have evaluated the effect of inter-row cultivation on sugarbeet yield and quality. Results of these studies generally demonstrate that early-season cultivation has little effect on recoverable sucrose yield, but cultivation later in the season is detrimental to yield and quality (Dexter et al. 2000). Dexter (1983) reported that sugarbeet yield tended to increase with up to three cultivations but decreased after four cultivations. Giles et al. (1987) reported increasing cultivation number from one to four numerically reduced yield in one of two environments. Giles et al. (1990) reported that one to three cultivations had no effect on sugarbeet yield, but there was an increasingly negative effect on sugarbeet yield as cultivation number increased from four to seven in one of two environments.

Root yield loss from inter-row cultivation later in the season is probably due to two factors: physical damage to the sugarbeet plant tissue and increased infection of *Rhizoctonia solani* (Kühn), the causal agent of *Rhizoctonia* crown and root rot. Giles et al. (1990) excavated roots in mid-July and observed less root development in the area from surface to 7 cm deep of soil in treatments receiving a large number (four to seven) of cultivations. The physical act of driving a mechanical implement between crop rows can also crush beet leaves that extend across field rows. The trend for reduced yield could also be related to soil-borne diseases. Cultivation when the sugarbeet plants are near canopy closure may deposit soil on the crown of the sugarbeet roots, potentially moving pathogens nearer their host. Schneider et al. (1982) reported that covering sugarbeet roots with soil (hilling) in mid-August caused a significant increase of root rot from *R. solani*. However, hilling did not cause greater disease pressure in all location-years, suggesting that environmental factors may also contribute to disease severity. Cultivation at reduced ground speeds is recommended to reduce the chance of *R. solani* infection due to soil hilling near the sugarbeet crown (Schneider et al. 1982; Windels and Lamey 1998).

Sugarbeet producers in the late 2010s frequently applied glyphosate and chloroacetamide herbicides in layers until crop canopy closure. Inter-row cultivators are used after herbicide application to remove herbicide-resistant weed escapes or to control weeds when inconsistent control occurs with herbicides. Producers have inquired whether inter-row cultivation is a viable tool to remove weeds that glyphosate did not control. They are also interested in knowing whether or not a delayed cultivation will expose weed seeds in untreated soil, resulting in additional weed seed germination and emergence. Many producers are also concerned that inter-row cultivation will reduce sugarbeet yield and quality because of the results of earlier research by Dexter and Giles (Dexter 1983; Dexter et al. 2000; Giles et al. 1987, 1990). Most producers consider one to two cultivation passes mid-season a "rescue" strategy rather than a contributor to an integrated weed management strategy. Therefore, two experiments were developed to address these concerns: (1) "delayed-cultivation efficacy" and (2) "cultivation tolerance." The objectives of the "delayed-cultivation efficacy" experiment were to evaluate (1) the effectiveness of cultivation at removing herbicide-resistant weeds and (2) the effect of delayed cultivation on weed emergence. The objective of the "cultivation tolerance" experiment was to evaluate the effect of inter-row cultivation timing and number on sugarbeet yield and quality.

Table 1. Soil description across environments including series, texture, subgroup, organic matter (OM) and pH; 2017, 2018, and 2019.

	Soil series and texture	Soil subgroup	OM	pH
Delayed cultivation efficacy				
Renville-2017	Mayer silty clay loam	Typic Endoaquolls	7.7	7.9
Nashua-2018	Croke sandy loam	Oxyaquic Hapludolls	3.5	7.2
Lake Lillian-2019	Normania silt loam	Aquic Hapludolls	6.5	6.9
Galchutt-2019	Mantador-Delamere-Wyndmere sandy loam	Pachic Hapludolls-Typic Endoaquolls-Aeric Calciaquolls	1.9	8.1
Cultivation tolerance				
Amenia-2018	Bearden-Lindaas silty clay loam	Aeric Calciaquolls-Typic Argiaquolls	3.9	8.0
Hickson-2018	Fargo silty clay	Typic Epiaquerts	6.0	7.5
Glyndon-2018	Wyndmere fine sandy loam	Aeric Calciaquolls	2.6	8.2
Amenia-2019	Bearden-Lindaas silt loam	Aeric Calciaquolls-Typic Argiaquolls	3.6	7.7
Hickson-2019	Fargo silty clay	Typic Epiaquerts	6.4	7.6
Galchutt-2019	Mantador-Delamere-Wyndmere sandy loam	Aquic Pachic Hapludolls-Typic Endoaquolls-Aeric Calciaquolls	2.4	8.3

Table 2. Description of treatments applied in the delayed cultivation efficacy experiment; timing of cultivations and herbicide treatments applied to 8- to 10-cm weeds at Renville-2017, Nashua-2018, Lake Lillian-2019, and Galchutt-2019.

Cultivation treatments by environment	Cultivation date	Sugarbeet stage at cultivation
Renville-2017	July 10	8- to 10-leaf
Nashua-2018	June 26	6- to 8-leaf
Lake Lillian-2019	July 8	8- to 10-leaf
Galchutt-2019	July 1	6- to 8-leaf
Herbicide treatments[a]	**Trade name**	**Rate (kg ai or ae ha^{-1})**
Glyphosate	Roundup PowerMAX[b]	1.1
Glyphosate + *S*-metolachlor	Roundup PowerMAX + Dual Magnum[c]	1.1 + 1.34
Glyphosate + dimethenamid-*P*	Roundup PowerMAX + Outlook[d]	1.1 + 0.95
Glyphosate + acetochlor	Roundup PowerMAX + Warrant[b]	1.1 + 1.37

[a] All herbicide treatments included ethofumesate at 140 g ai ha^{-1} (Ethofumesate 4SC, Willowood LLC, Roseburg, OR), high-surfactant methylated oil concentrate at 1.75 L ha^{-1} (Destiny HC, Winfield Solutions LLC, St. Paul, MN), and ammonium sulfate liquid solution at 2.5% v/v (N-Pak AMS liquid, Winfield Solutions LLC, St. Paul, MN). Herbicide treatments were applied June 26 at Renville-2017, June 12 at Nashua-2018, June 26 at Lake Lillian-2019, and June 17 at Galchutt-2019.

[b] Monsanto Company, St. Louis, MO.

[c] Syngenta Crop Protection, Greensboro, NC.

[d] BASF Corp., Research Triangle Park, NC.

Materials and Methods

Site Description

Delayed-Cultivation Efficacy

Field experiments were conducted on four environments in grower fields; near Renville, MN (44.78°N, 95.14°W) in 2017, near Nashua, MN (46.05°N, 96.33°W) in 2018, near Lake Lillian, MN (44.88°N 94.98°W) in 2019, and near Galchutt, ND (46.38°N 96.84°W) in 2019. Each site–year combination is considered an environment. All environments were chisel-plowed in the fall and prepared for spring sugarbeet planting with a field cultivator. The environments in this experiment have a history of recurrent glyphosate use and presence of glyphosate-resistant waterhemp. Detailed soil descriptions for each environment can be found in Table 1.

Cultivation Tolerance

Field experiments were conducted on six environments in grower fields; near Glyndon, MN (46.86°N, 96.52°W) in 2018, Galchutt, ND (46.38°N 96.84°) in 2019, Hickson, ND (46.70°N, 96.80°W) in 2018 and 2019, and Amenia, ND (47.00°N, 97.10°W) in 2018 and 2019. Previous crops grown in fields were soybean [*Glycine max* (L.) Merr.], soybean, sugarbeet, and wheat (*Triticum aestivum* L.) at the Glyndon, Galchutt, Hickson, and Amenia sites, respectively. Each site–year combination is considered an environment. All environments were chisel-plowed in the fall and prepared for spring sugarbeet planting with a field cultivator. Detailed soil descriptions for each environment can be found in Table 1.

Experimental Procedures

Delayed-Cultivation Efficacy

The experiment was a 2 × 4 factorial split-block design with four to six replications, depending on environment. Each replication (block) was grid split, where the horizontal factor was cultivation at two levels and the vertical factor was herbicide at four levels. Plots were 3.3 m wide and 9.1 m long. Sugarbeet was planted to a density of approximately 152,000 (± 1,000) seeds ha^{-1} in six rows spaced 56 cm apart, and *S*-metolachlor (Dual Magnum; Syngenta Crop Protection, Greensboro, NC) at 534 g ai ha^{-1} was applied PRE within 48 h after planting in all environments.

Herbicide treatments were applied to 8- to 10-cm weeds with a bicycle wheel-type sprayer with a shielded boom to reduce particle drift at a volume of 159 L ha^{-1} (Table 2). The center four rows of each six-row plot were sprayed using pressurized CO_2 at 241 kPa through 8002XR nozzles (XR TeeJet® Flat Fan Spray Tips; TeeJet® Technologies, Glendale Heights, IL). Half of the plots were cultivated approximately 2 wk after herbicide application using a modified Alloway 3130 cultivator (Alloway Standard Industries, Fargo, ND) with 38-cm sweep shovels spaced at 56 cm with a ground depth of 4 to 5 cm at 6.4 km h^{-1}. Dates of planting, herbicide application, cultivation, and crop stage at herbicide application can be found in Table 2.

Table 3. Numbers and dates of cultivations in cultivation tolerance experiment, Amenia, Hickson, and Glyndon, 2018 and Amenia, Hickson, and Galchutt, 2019.

Treatment	Cultivation number	Cultivation dates[a]
1	Control	Not cultivated
2	Single	June 22
3	Single	July 6
4	Single	July 20
5	Single	August 3
6	Single	August 17
7	Double	June 22 + July 20
8	Double	July 6 + August 3
9	Double	July 20 + August 17
10	Triple	June 22 + July 20 + August 17

[a] Treatments were cultivated within 5 d (±) of date.

Table 4. Planting and harvest dates, previous crop, and sugarbeet population prior to first cultivation treatment in the cultivation tolerance experiment at six environments, 2018 and 2019.

Environment	Planting date	Harvest date	Previous crop	Sugarbeet population
				No. plants per 30-m row
Amenia-2018	May 14	September 18	Wheat	182
Hickson-2018	May 7	September 11	Sugarbeet	187
Glyndon-2018	May 3	September 17	Soybean	150
Amenia-2019	May 17	November 1	Wheat	159
Hickson-2019	May 14	September 24	Sugarbeet	187
Galchutt-2019	May 11	September 18	Soybean	216

Table 5. Weekly and monthly rainfall in delayed cultivation efficacy experiment conducted in four environments compared with 30-yr averages, 2017, 2018, and 2019.[a]

Week	Renville-2017 8-E[b]	Nashua-2018 4-NW	Lake Lillian-2019 0-N	Galchutt-2019 14-E	30-yr average[d]
	mm				
May 8	–	(0)[c]	–	–	
May 15	48	1	–	(4)	
May 22	0	16	–	22	
May 29	0	21	–	1	
May total	(48)	(24)	–	(26)	81
June 5	25	49	(1)	3	
June 12	14	33	14	19	
June 19	4	0.0	13	39	
June 26	29	10	50	6	
June total	71	97	(62)	67	83
July 3	19	18	62	105	
July 10	5	12	0	32	
July 17	4	97	9	19	
July 24	28	–	56	4	
July 31	27	–	0	26	
July total	56	(138)	142	160	81
August 7	(0)	–	0	–	
Season total	202	258	204	253	

[a] Nashua and Galchutt climate data collected by the North Dakota Agricultural Weather Network (NDAWN); Renville climate data collected from Olivia, MN airport (NWS); Lake Lillian climate data collected from on-site weather station operated by Southern Minnesota Beet Sugar Cooperative (SMBSC).

[b] Distance (km) and direction of weather station from trial site.

[c] Rainfall data in parentheses are within the accumulation period between planting and last evaluation.

[d] 30-yr average is National Weather Service (NWS) average at Wahpeton, ND.

Cultivation Tolerance

The experiment was a randomized complete block with four replicates. Plots were 3.3 m wide and 9.1 m long. Treatments were applied on 14-d intervals throughout the growing season starting June 22 and ending August 17. Treatments were a combination of the cultivation date, number of cultivations, and an untreated control (Table 3). Cultivation date and frequency were reflective of current grower practices (Peters et al. 2018). Inter-row cultivation was performed using a modified Alloway 3130 cultivator (Alloway Standard Industries, Fargo, ND) with 38-cm sweep shovels spaced at 56 cm with a ground depth of 4 to 5 cm at 6.4 km h^{-1}.

The sugarbeet cultivar ‘Crystal 355RR’ (American Crystal Sugar Company, Moorhead, MN) was planted approximately 3 cm deep to a density of approximately 152,000 (± 1,000) seeds ha^{-1} in six rows spaced 56 cm apart (Table 4). Sugarbeet seeds were treated with penthiopyrad (Kabina ST; Sumitomo Corp., New York, NY) at 14 g per 100,000 seeds, hymexazol (Tachigaren 45; Mitsui Chemicals Agro, Tokyo, Japan) at 45 g per 100,000 seeds, and clothianidin and beta-cyfluthrin (Poncho Beta; Bayer Crop Science, Research Triangle Park, NC) at 60 g and 8 g per 100,000 seeds, respectively. Nitrogen, phosphorus, and potassium fertilizer was applied based on spring soil tests and incorporated prior to planting. Weeds and disease were controlled so that crop injury from cultivation could be detected without interference from other yield-limiting factors. Weeds were controlled using glyphosate (Roundup PowerMAX; Monsanto Company, St. Louis, MO) at 1.26 kg ae ha^{-1}. One to three glyphosate applications were made at each environment, and herbicide-resistant waterhemp plants were removed by hand-weeding. Root disease pressure from *R. solani* was controlled with two soil-applied applications of azoxystrobin (Quadris; Syngenta Crop Protection, Greensboro, NC) at Amenia and Hickson. Disease pressure from *Cercospora beticola* was controlled with season-long foliar applications of triphenyltin hydroxide (Super Tin 4L; United Phosphorus, Inc., King of Prussia, PA), thiophanate methyl (Topsin 4.5FL; United Phosphorus, Inc., King of Prussia, PA), prothioconazole (Proline; Bayer CropScience LP, Research Triangle Park, NC), and difenoconazole/propiconazole (Inspire XT; Syngenta Crop Protection, Greensboro, NC).

Data Collection and Analysis

Delayed Cultivation Efficacy

Percent visual waterhemp control was evaluated 14 and 28 (± 3) d after the cultivation treatment (DAC). Evaluation was on a scale of 0% (no control) to 100% (complete control) relative to the untreated check rows between treatments. Waterhemp in the 2.2-m by 9.1-m treatment area of each 3.3-m by 9.1-m plot was counted 14 and 28 DAC at the Renville-2017 and Nashua-2018 environments because of low weed pressure, whereas a 0.25-m^2 quadrat, placed twice between the two middle plot rows, three paces apart, was used at Lake Lillian-2019 and Galchutt-2019, where weed pressure was greater. Rainfall data were collected from nearby weather stations operated by the North Dakota Agricultural Weather Network (NDAWN), National Weather Service (NWS), and Southern Minnesota Beet Sugar Cooperative (SMBSC) and are presented in Table 5.

Data were subjected to analysis using the GLIMMIX procedure in SAS (v. 9.4, SAS Institute, Cary, NC) to test for treatment effects and significant interactions. Data were analyzed as a split-block randomized complete block design with expected means squares as recommended by Carmer et al. (1989). Significantly different

Table 6. Monthly rainfall, cultivation tolerance experiment, 2018 and 2019.[a]

	Amenia-2018	Hickson-2018	Glyndon-2018	Amenia-2019	Hickson-2019	Galchutt-2019	
Month	1-W[b]	21-N	10-SW	1-W	21-N	14-E	30-yr average[d]
				mm			
May total	(41)[c]	(44)	(14)	(66)	(63)	(63)	71
June total	79	123	148	122	83	67	99
July total	65	81	117	156	121	160	71
August total	79	101	92	102	90	64	65
September total	(30)	(15)	(14)	148	(78)	(73)	65
October total	–	–	–	88	–	–	55
Season total	294	364	385	682	435	427	

[a] Climate data collected by instrumentation managed by the North Dakota Agricultural Weather Network.
[b] Distance (km) and direction of weather station from trial site.
[c] Rainfall data in parentheses are within the recorded period between planting and harvest.
[d] 30-yr average is National Weather Service (NWS) average at Fargo, ND.

treatment means were separated using the Tukey-Kramer procedure at the $P \leq 0.05$ level. Waterhemp control data were arc sine square-root transformed $\{\arcsin[(Y/100)^{1/2}]\}$, and waterhemp density data were square-root transformed ($[Y+0.5]^{1/2}$) to better fit assumptions of the model analysis, and untransformed means are presented. The cultivation and herbicide treatment factors were considered fixed effects, whereas replicate, environment, and interactions containing replicate and environment were considered random effects. Results from Levene's test for homogeneity found that waterhemp control data could be combined across four environments (P values = 0.141 and 0.408, 14 and 28 DAC), but waterhemp density data required separate analysis for each environment. Only main effects are presented, as no significant cultivation-by-herbicide interactions were detected.

Cultivation Tolerance

Sugarbeet density was collected in the center two rows prior to the start of cultivation treatments and prior to harvest to determine percent stand mortality throughout the season (Equation 1). At harvest, sugarbeet was defoliated and harvested mechanically from the center two rows of each plot and weighed. A sample weighing approximately 10 kg was collected from each plot and analyzed for sucrose content and sugar loss to molasses by American Crystal Sugar Company (East Grand Forks, ND). Sugarbeet roots were visually analyzed for *Rhizoctonia* root and crown rot, but no visible infection was observed. Root yield (kg ha^{-1}), purity (%), and recoverable sucrose (kg ha^{-1}) were calculated using Equations 2, 3, and 4, respectively. Monthly rainfall data were collected for each environment by NDAWN and are presented on Table 6.

$$\text{Stand mortality} = \left[1 - \left(\frac{\text{Density prior to harvest}}{\text{Density prior to cultivation}}\right)\right] \times 100 \quad [1]$$

$$\text{Root yield (kg/ha)} = \frac{\text{Harvested plot weight (kg)}}{\text{Hectare area of harvested plot}} \quad [2]$$

$$\text{Purity (\%)} = \frac{\text{\% Sucrose content} - \text{\% sugar loss to molasses}}{\text{\% Sucrose content}} \times 100 \quad [3]$$

$$\text{Recoverable sucrose (kg/ha)} = \left(\frac{[(\text{\% Purity} / 100) \times \text{\% sucrose content}]}{100}\right) \times \text{root yield} \quad [4]$$

Data were subjected to analysis using the GLIMMIX procedure in SAS (v. 9.4, SAS Institute, Cary, NC) to test for treatment effects, and means were separated using the Tukey-Kramer procedure at $P \leq 0.05$. Cultivation treatment was considered a fixed effect, whereas environment and replicate were considered random effects. Single degree-of-freedom contrasts were used to compare the effect of cultivation number on sugarbeet density and yield components. Levene's test for homogeneity was conducted to determine which environments could be combined for each independent variable at the $P \leq 0.05$ level.

Results and Discussion

Delayed Cultivation Efficacy

Waterhemp Control

Visual waterhemp control data were analyzed across environments, but data from each environment are also reported (Table 7). Cultivation significantly improved waterhemp control 11% and 12%, 14 and 28 DAC, respectively, across environments (Table 7). Herbicide treatment did not affect waterhemp control, nor was there any interaction between herbicide and cultivation treatments (Table 7). A cultivator removes about two-thirds of weeds in fields with 56-cm crop spacing (38-cm shovels cover 68% of area in 56-cm rows). One of the major drawbacks of inter-row cultivation is that it removes only the weeds in between rows (VanGessel et al. 1998), necessitating the use of other means to remove the remaining weeds. Hand-weeding to remove weeds that escaped inter-row cultivation was a common strategy prior to the development of GR sugarbeet in 2008. Cultivation may have reduced herbicide efficacy on waterhemp control in this experiment, as previous research demonstrated improved waterhemp control from a chloroacetamide plus glyphosate treatment as compared to glyphosate alone (Peters et al. 2017).

Waterhemp Density

Data were not combined across environments based on Levene's test and were analyzed by environment. Density of waterhemp was relatively low (<2 plants m^{-2}) at the Renville-2017 and Nashua-2018 environments, and plants were counted on a per-plot basis, whereas a 0.25-m^2 quadrat was used at Lake Lillian-2019 and Galchutt-2019 to measure waterhemp density. Results from Renville-2017 indicated that cultivation reduced waterhemp density 63% and 53% 14 and 28 DAC, respectively (Table 8).

Table 7. Waterhemp control in response to cultivation and herbicide treatment, 14 and 28 d after cultivation treatment (DAC).[a]

Main effects	Renville-2017 14 DAC	Renville-2017 28 DAC	Nashua-2018 14 DAC	Nashua-2018 28 DAC	Lake Lillian-2019 14 DAC	Lake Lillian-2019 28 DAC	Galchutt-2019 14 DAC	Galchutt-2019 28 DAC	Average 14 DAC	Average 28 DAC
Cultivation[b]					%					
With cultivation	86 A	80 A	91	88	90	88	78 A	72 A	86 A	82 A
No cultivation	72 B	62 B	88	83	85	80	57 B	54 B	75 B	70 B
Herbicide[c]										
Glyphosate	83 a	77 a	88	86	85	85	56 c	54	78	76
Glyphosate + *S*-metolachlor	70 b	61 b	91	87	87	83	62 bc	58	77	72
Glyphosate + dimethenamid-*P*	83 a	77 a	88	81	86	81	77 a	69	84	77
Glyphosate + acetochlor	80 a	69 a	91	88	91	88	73 ab	72	84	79
ANOVA			P value					P value		
Cultivation	0.006	0.004	0.400	0.379	0.259	0.146	0.004	0.013	0.038	0.030
Herbicide	0.001	0.005	0.934	0.762	0.737	0.808	0.042	0.259	0.266	0.503
Cultivation × herbicide	0.700	0.575	0.426	0.650	0.827	0.806	0.681	0.687	0.527	0.942

[a] Numbers within a main effect and environment column followed by different letters are statistically different at $P \le 0.05$ (Tukey's test).
[b] Cultivation was approximately 2 wk after spray treatment.
[c] All herbicide treatments included ethofumesate (140 g ai ha^{-1}), high-surfactant methylated oil concentrate (1.8 L ha^{-1}), and liquid ammonium sulfate at 2.5% v/v.
[d] Evaluation on scale of 0% (no control) to 100% (complete control).

Table 8. Waterhemp density in response to cultivation and herbicide treatment, 14 and 28 d after cultivation treatment (DAC).[a]

Main effects	Renville-2017 14 DAC	Renville-2017 28 DAC	Nashua-2018 14 DAC	Nashua-2018 28 DAC	Lake Lillian-2019 14 DAC	Lake Lillian-2019 28 DAC	Galchutt-2019 14 DAC	Galchutt-2019 28 DAC
Cultivation[b]		No. plants per plot				No plants m^{-2}		
With cultivation	7.1 A	9.5 A	4.0	3.5	1.8	2.1 A	241 B	53 B
No cultivation	19.2 B	20.3 B	1.8	1.8	4.0	5.3 B	34 A	18 A
Herbicide[c]								
Glyphosate	8.1 a	9.3 a	1.3	1.3	2.8	2.5	171	31
Glyphosate + *S*-metolachlor	20.6 b	22.8 b	1.8	2.2	1.9	3.1	115	35
Glyphosate + dimethenamid-*P*	8.7 a	11.2 a	2.9	4.1	3.0	4.3	127	35
Glyphosate + acetochlor	15.3 ab	16.3 ab	2.8	2.9	3.9	4.9	136	40
ANOVA				P value				
Cultivation	0.004	0.007	0.404	0.213	0.096	0.026	0.007	0.022
Herbicide	0.043	0.038	0.826	0.697	0.937	0.738	0.394	0.962
Cultivation × herbicide	0.887	0.745	0.561	0.827	0.693	0.175	0.812	0.280

[a] Numbers within a main effect and environment column followed by different letters are statistically different at $P \le 0.05$ (Tukey's test).
[b] Cultivation was approximately 2 wk after spray treatment.
[c] All herbicide treatments included ethofumesate (140 g ai ha^{-1}), high-surfactant methylated oil concentrate at 1.8 L ha^{-1}, and liquid ammonium sulfate at 2.5% v/v.

Waterhemp density at Nashua-2018 was not affected by cultivation. Results from Lake Lillian-2019 indicated no effect of inter-row cultivation 14 DAC, but cultivation reduced waterhemp density 59% 28 DAC (Table 8). Inter-row cultivation increased waterhemp density 600% and 196% at Galchutt-2019 14 and 28 DAC, respectively (Table 8). Herbicide treatment did not affect waterhemp density at three of four environments (Table 8), but the effect of herbicide at Renville-2017 was not meaningful, as recorded plants were already emerged at time of herbicide application.

Waterhemp density with and without cultivation is likely due to an interaction between the crop stage and canopy at the time of cultivation and the amount of rainfall received following the cultivation event. Renville-2017 and Lake Lillian-2019 were cultivated with a developed canopy of 8- to 12-leaf and 8- to 10-leaf (10-leaf predominant) sugarbeet (Table 2) that provided natural shade in between the sugarbeet rows and received approximately 9 mm and 11 mm of rainfall in the 14 d following cultivation at Renville-2017 and Lake Lillian-2019, respectively (Table 5). The interaction of a developed canopy and low precipitation following cultivation at Renville-2017 and Lake Lillian-2019 likely made environments nonconducive to further weed germination. Nashua-2018 was cultivated with an underdeveloped canopy of 6- to 8-leaf (8-leaf predominant) sugarbeet (Table 2) and received approximately 28 mm of cumulative rainfall to 14 d following cultivation (Table 5), but rainfall did not trigger further weed emergence. The waterhemp density at Nashua-2018, however, was relatively low compared to the other environments. Galchutt-2019 was cultivated with an underdeveloped canopy of 6- to 8-leaf (6-leaf predominant) sugarbeet (Table 2) and received 105 mm of precipitation in the 14 d following the cultivation event (Table 5). The interaction of an underdeveloped crop canopy that left much soil exposed at the time of cultivation and the 105 mm of precipitation that followed are likely responsible for the explosion of weed emergence following the cultivation.

Cultivation works by stirring soil and carrying plants to the soil surface, where they will ideally die of desiccation. In the case of Galchutt-2019, however, the cultivation on an underdeveloped canopy likely mixed soil, exposing seeds in the seed bank to infrared light that stimulates germination, and subsequent rainfall created an environment conducive to further weed emergence. Furthermore, observations throughout the years have shown that a timely precipitation event following cultivation can result in failed control by causing plants uprooted by cultivation to re-root (Mohler et al. 2016).

Table 9. Sugarbeet stand mortality in response to cultivation timing and number, 2018 and 2019.[a]

	Stand mortality[b]					
Cultivation timing	Amenia-2018	Hickson-2018	Glyndon-2018	Amenia-2019	Hickson-2019	Galchutt-2019
	%					
Control	15	32	−14	−5	7	38
June 22	20	37	−1	5	0	37
July 6	15	37	4	14	7	30
July 20	20	41	−10	−5	6	29
August 3	11	32	−1	11	6	29
August 17	13	30	10	0	4	38
June 22 + July 20	13	31	−7	0	9	51
July 6 + August 3	19	36	4	4	14	37
July 20 + August 17	21	39	7	6	16	31
June 22 + July 20 + August 17	16	37	7	5	0	37
P value	0.075	0.435	0.842	0.295	0.768	0.759
Contrasts						
NC vs. C	0.642	0.329	0.179	0.104	0.987	0.811
NC vs. ST	0.834	0.348	0.226	0.094	0.766	0.592
NC vs. DT	0.385	0.428	0.219	0.174	0.428	0.822
NC vs. TT	0.866	0.331	0.185	0.256	0.496	0.941
ST vs. DT	0.288	0.876	0.895	0.695	0.096	0.253
ST vs. TT	0.993	0.750	0.611	0.813	0.560	0.659
DT vs. TT	0.505	0.687	0.689	0.981	0.110	0.753

[a] Abbreviations: NC, Noncultivated treatment; C, cultivated treatments; ST, single-timing treatments; DT, double-timing treatments; TT, triple-timing treatment.

[b] Percent stand mortality is calculated using the ratio of harvest stand and pre-treatment stand.

Cultivation Tolerance

Sugarbeet Stand Mortality

Stand mortality percentage was calculated from the ratio of sugarbeet density before cultivation treatments and at harvest. Inter-row cultivation did not affect sugarbeet stand mortality at any environment in 2018 and 2019 (Table 9). The relatively high stand mortality at Hickson-2018 and Galchutt-2019 probably occurred because sugarbeet and soybean, respectively, were the crop grown on the field sites in the prior year. Planting sugarbeet into sugarbeet residue greatly increases chance of infection from *R. solani*, which can cause significant stand loss (Windels and Brantner 2008).

Harvested sugarbeet roots were visually inspected for root and crown rot from *R. solani*, but no significant infection due to inter-row cultivation was observed at any environment. Damage from *R. solani* in the field primarily manifests in the form of stand mortality (M. Khan 2018, personal communication), which was observed on all treatments at Hickson-2018 and Galchutt-2019. Inter-row cultivation has historically been associated with root and crown rot, because cultivation may physically deposit soil onto a beet crown, moving soil-borne pathogens nearer their host. Schneider et al. (1982) reported that covering sugarbeet roots with soil with a cultivator moving 13 km h^{-1} in mid-August resulted in greater root rot due to *R. solani* in two of three field environments. Windels and Lamey (1998) reported that reducing cultivation ground speed reduces the likelihood of infection from *R. solani*. Some soil movement onto beet crowns was observed in this experiment, but the cultivation speed of 6.4 km h^{-1} used in this experiment may not have been fast enough to cause significantly different root rot infection compared to the untreated control.

Root Yield

Inter-row cultivation did not affect root yield at any environment or environment combination (P values = 0.271 to 0.863) (Table 10). Inter-row cultivation only disturbs soil between the sugarbeet rows and does not significantly affect root growth or yield. Giles et al. (1990) conducted root excavations on sugarbeet in late July and reported less root development and yield with treatments receiving five to seven weekly cultivations throughout the season in one of two environments. Giles et al. (1990) cultivated to a similar depth of 4 to 5 cm, but ground speed was 5 km h^{-1}. Significant root yield reduction was not observed with up to three cultivations in this experiment, cultivating 4 to 5 cm deep and 6.4 km h^{-1}. The yield loss Giles et al. (1990) reported in one of two environments was likely due their five to seven cultivations as compared to one to three implemented in our experiment.

Sucrose Content

Inter-row cultivation timing and number significantly reduced sucrose content at one environment, Hickson-2019 (Table 11). At Hickson-2019, only the June 22 and July 20 single-cultivation treatments had sucrose content similar to the untreated control. Single degree-of-freedom contrasts at Hickson-2019 showed that cultivation reduced sucrose content by an average of 0.8% compared to sugarbeet that were not cultivated (P value = 0.007) (Table 11). A single mid-season cultivation of sugarbeet reduced sucrose by 0.7% (P value = 0.031), two mid-season cultivations reduced sucrose content by 1.0% (P value = 0.004), and three mid-season cultivations reduced sucrose content by 0.9% compared to the control that was not cultivated (P value = 0.010). These data suggest that mid-season cultivation, especially multiple cultivations, can reduce sucrose content of harvested sugarbeet in certain environments. The reason for Hickson-2019 showing these differences and other environments not showing differences is unknown.

We observed on multiple occasions that cultivation at later dates can damage leaf tissue by tearing or ripping leaf tissue from the plant (Figure 1). Sugarbeet plants compensate for the foliar damage by producing new leaves, utilizing sucrose stored in roots as energy source and thus potentially lowering sucrose content. Leaf tissue is the medium by which photosynthesis and sucrose production is conducted in the plant, and cultivation damaging leaf tissue would logically reduce percent sucrose. Three layers of sugarbeet leaf tissue are required for optimal sucrose production in sugarbeet (K. Fugate 2019, personal communication), and we

Table 10. Sugarbeet root yield and recoverable sucrose in response to cultivation timing and number, 2018 and 2019.[a]

	Root yield				Recoverable sucrose			
Cultivation timing	Amenia 2018 and 2019	Hickson 2018 and 2019	Glyndon 2018	Galchutt 2019	Amenia 2018 and 2019	Hickson 2018 and 2019	Glyndon 2018	Galchutt 2019
	kg ha^{-1}				kg ha^{-1}			
Control	87,522	49,537	31,825	41,243	12,424	7,350	4,037	5,903
June 22	91,465	49,149	29,428	45,245	13,379	7,206	3,733	6,445
July 6	88,685	47,650	33,423	44,912	12,634	6,868	4,355	6,539
July 20	93,075	44,933	31,692	52,137	13,069	6,614	3,989	7,366
August 3	88,131	51,422	32,491	49,136	12,164	7,174	4,147	7,189
August 17	87,632	48,922	28,230	49,469	11,977	6,777	3,525	6,969
June 22 + July 20	90,518	49,756	22,104	38,019	12,684	6,898	2,714	5,065
July 6 + August 3	94,909	48,868	26,765	43,022	13,241	6,826	3,406	6,077
July 20 + August 17	90,244	43,205	29,695	46,801	12,838	6,147	3,924	6,483
June 22 + July 20 + August 17	89,299	48,649	26,898	43,244	12,718	6,790	3,496	6,230
P value	0.271	0.732	0.466	0.863	0.193	0.750	0.481	0.847
Contrasts								
NC vs. C	0.194	0.651	0.435	0.478	0.374	0.263	0.507	0.558
NC vs. ST	0.320	0.740	0.838	0.299	0.552	0.391	0.869	0.336
NC vs. DT	0.087	0.529	0.164	0.844	0.219	0.176	0.222	0.979
NC vs. TT	0.540	0.838	0.317	0.815	0.539	0.379	0.429	0.806
ST vs. DT	0.180	0.614	0.062	0.214	0.277	0.356	0.096	0.143
ST vs. TT	0.823	0.945	0.277	0.458	0.843	0.776	0.393	0.516
DT vs. TT	0.285	0.700	0.858	0.928	0.602	0.745	0.791	0.744

[a] Abbreviations: NC, Noncultivated treatment; C, cultivated treatments; ST, single-timing treatments; DT, double-timing treatments; TT, triple-timing treatment.

Table 11. Sugarbeet sucrose content in response to cultivation timing and number, 2018 and 2019.[a]

	Sucrose content				
Cultivation timing	Amenia-2018 and 2019	Hickson-2018	Hickson-2019	Glyndon-2018	Galchutt-2019
	%				
Control	15.8	14.9	17.3 a	13.8	15.7
June 22	16.0	14.6	17.1 ab	13.8	15.0
July 6	15.8	14.7	16.5 bc	14.0	15.9
July 20	15.6	14.8	16.8 abc	13.7	15.5
August 3	15.4	14.3	16.4 c	13.9	15.9
August 17	15.3	14.1	16.3 c	13.6	15.3
June 22 + July 20	15.5	14.3	16.1 c	13.4	14.6
July 6 + August 3	15.6	14.3	16.3 c	13.6	15.5
July 20 + August 17	15.7	14.6	16.5 bc	14.2	15.2
June 22 + July 20 + August 17	15.8	14.2	16.2 c	13.9	15.7
P value	0.544	0.857	0.050	0.100	0.305
Contrasts					
NC vs. C	0.638	0.209	0.007	0.894	0.487
NC vs. ST	0.643	0.290	0.031	0.898	0.703
NC vs. DT	0.567	0.215	0.004	0.903	0.181
NC vs. TT	0.959	0.189	0.010	0.489	0.896
ST vs. DT	0.835	0.700	0.117	0.705	0.124
ST vs. TT	0.597	0.515	0.197	0.445	0.582
DT vs. TT	0.527	0.707	0.822	0.335	0.137

[a] Abbreviations: NC, Noncultivated treatment; C, cultivated treatments; ST, single-timing treatments; DT, double-timing treatments; TT, triple-timing treatment.

observed cultivation causing most damage to the bottom layer. Foliar damage was also noted from the tractor wheels traveling between plot rows. The tractor wheels in this experiment traveled on the outside of the plot area to remove the effect of the wheels on these results. Most producers operate with cultivators the same size as their planter to reduce the amount of unnecessary tire tracks and canopy damage in a field. Further research should determine the correlation between severity and timing of foliar damage and sucrose reduction.

Recoverable Sucrose per Hectare

Inter-row cultivation did not affect recoverable sucrose per hectare (RSH) at any environment or combination of environments (Table 10). RSH is a calculation derived from root yield and sucrose content (Equation 3) and is considered the most important metric in sugarbeet production. No treatment differences were measured in any environment (P values = 0.193 to 0.847). This result was expected, because recoverable sucrose is most heavily weighted by root yield (Equation 3), and the effect of root yield was insignificant.

Practical Implications

These data demonstrate that inter-row cultivation is a valuable tool to remove weeds that herbicide did not/could not control but can cause further weed emergence under certain environmental and crop conditions. Cultivation improved visual waterhemp control by 11% to 12% when performed 2 wk following a POST application, but an increase in waterhemp emergence was observed in one environment with an underdeveloped canopy and excessive precipitation. Inter-row cultivation did not affect sugarbeet stand mortality, root yield, or recoverable sucrose across six environments in 2 yr, but cultivation significantly reduced sugarbeet sucrose content in one environment, which could be attributed to foliar destruction from the cultivator. Although no change in recoverable sucrose (considered the most important yield metric for producers) was observed from cultivation, we caution growers that any operation that damages leaf tissue comes with the risk of reducing sucrose content as the plant seeks to replace damaged leaves. Most producers in 2018 and 2019 used cultivation only to remove weeds that glyphosate did not control, so it is unlikely that any sugarbeet producer would cultivate a field more than three times in one season. Most cultivations in 2018 and 2019 were also

Figure 1. Defoliation of sugarbeet leaf tissues caused by an inter-row cultivation event on August 1, 2018 near Amenia, ND.

done after the sugarbeet canopy closed in mid-July. The effect of inter-row cultivation on yield is likely a complex interaction of cultivation timing, soil type, environmental conditions, disease pressure, cultivation speed, and cultivation equipment.

Sugarbeet producers are concerned about yield loss from inter-row cultivation because of previous research reported by Dexter et al. (2000) and Giles et al. (1990). Although the cultivation methods and procedures used in our experiment were similar to what Dexter and Giles implemented in their experiments, our timing of cultivation differed. Dexter and Giles conducted their cultivations on weekly intervals with the same start date, whereas our cultivations were 2 wk apart with staggered starting dates and timings as late as August 16. Furthermore, certain aspects of sugarbeet production that could affect disease pressure differ from the 1980s and 1990s, such as diploid genetics, seed treatments, and soil-applied applications of azoxystrobin. Our results show that cultivation 4 to 5 cm deep at 6.4 km h^{-1} did not affect recoverable sucrose in 2018 and 2019, but further research is needed in future years with different ground speeds, cultivator configurations, fungicide applications, and environmental conditions to determine how and when cultivation could affect sugarbeet yield.

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