CULTIVATION TO SUPPLEMENT RESIDUAL HERBICIDES IN SUGARBEET

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

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ABSTRACT

The migration of waterhemp (*Amaranthus tuberculatus*) into northern sugarbeet (*Beta vulgaris*) growing regions has prompted sugarbeet producers to utilize inter-row cultivation in their weed management program as no currently registered herbicides can control glyphosate-resistant waterhemp postemergence. Field experiments were conducted to evaluate cultivation efficacy on waterhemp and common lambsquarters (*Chenopodium album*) and to evaluate cultivation safety on sugarbeet. Cultivation efficacy experiments demonstrated cultivation removes 65% of waterhemp and has no effect on further waterhemp emergence, but can be deleterious to common lambsquarters control if cultivation is timed before sugarbeet canopy closure. The ideal time to implement inter-row cultivation in sugarbeet is after sugarbeet canopy is closed and can suppress further weed emergence. Cultivation safety experiments demonstrated three cultivations as late as August 16 had no effect on sugarbeet yield and quality. Cultivation is a valuable tool to control glyphosate-resistant weeds with no deleterious effects if used correctly.

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TABLE OF CONTENTS

LIST OF TABLES

CHAPTER 1. REVIEW OF LITERATURE

Characterization of Sugarbeet

Sugarbeet (*Beta vulgaris spp. vulgaris*) is an agricultural crop grown for the production of white sucrose. Sugarbeet is a member of the *Betoidae* subfamily with the *Amaranthaceae* botanical family (Müller and Borsch 2005). The mature sugarbeet plant consists of two main parts: a compressed stem comprised of multiple rosette leaves on the upper portion known as the crown, and a series of cambial rings on the lower portion known as the root (Artschwager 1926; Milford 2006). Its vegetative growth is indeterminate, but the plants early season is primarily leaf/shoot growth, while the later season (early July to October in North Dakota) is primarily root growth. The root contains 16 to 20% sugar in the lower root portion, 13 to 15% in the lower crown/hypocotyl, and 7 to 9% in the upper portion of the crown (Milford 2006). As a biennial, plant vegetation will grow until cold vernalization triggers stem elongation and floral development. In the US, seed companies produce sugarbeet seed primarily in the Willamette Valley of Oregon due to mild winters that allow vernalization with minimal damage to young plants. Sugarbeet grown in the western hemisphere for sucrose production are primarily grown in northern temperate regions of the US where seeds are sown in early spring (March-April) and harvested in mid-fall (October).

Sugarbeet is a relatively new world food crop that was likely domesticated from wild sea beet (*Beta vulgaris spp. maritima)* which originated from areas surrounding the Mediterranean Sea (Francis 2006). Beets were grown mainly as vegetable and fodder crops until selection for higher sugar content started in the 1780s. Early beet selection efforts were led by a scientist named Franz Carl Achard whose work resulted in the world's first sugarbeet factory in the Prussian province of Lower Silesia (modern day Poland) being built in 1801 (Francis 2006). In the following years, global disputes over Caribbean sugarcane producing regions led to numerous sugarbeet factories being built across Europe.

The first sugarbeet factory in North America was built in Massachusetts in 1838, but the factory could not fulfill its financial obligations which led to an early shutdown in 1840 (Harris 1919). Other attempts were made to establish American sugarbeet factories in subsequent years, but none were truly successful until the construction of the factory in Alvarado, California in 1870 (Francis 2006). The factory in Alvarado produced sugar almost annually until its shutdown in 1967. The first sugarbeet hectares in the Red River Valley of North Dakota and Minnesota were grown as early as 1872 (Shoptaugh 1997). Sugarbeet would continue to be grown occasionally in the Red River Valley for the next 50 years and processed in southern Minnesota and Nebraska. The first sugarbeet factory constructed in the Red River Valley was in East Grand Forks, MN in 1926 under the American Beet Sugar Company.

Yield Limiting Factors in Sugarbeet

Yield of sugarbeet is complex and is dependent on numerous factors such as genetic potential, environmental conditions, and abiotic and biotic stress. Sugarbeet yield is measured by three primary components: root yield, percent sugar concentration, and extractable sucrose per hectare. The fresh weight concentration of sugar in a sugarbeet root in the 18th century was 10 to 13%, but breeding and selection has increased that value to 17 to 20% (Draycott 2006; Francis 2006). In North Dakota and Minnesota, a typical sugarbeet root yield is 40 to 80 t ha^{-1}, with 15 to 19% sugar, resulting in 6 to 15 t sucrose ha^{-1} (Milford 2006; T. Peters 2017, personal communication).

Improving crop yield potential by genetic improvement is paramount to agricultural progress, but management of agronomic factors, nutrients, water, diseases, insects, and weeds is essential to help a crop reach that full genetic potential. To maximize sugarbeet yield, one must ensure the crop has optimal light, water, nutrients, and an environment free of diseases and insects that attack sugarbeet tissue. Weeds compete with the crop for light, nutrients, and water, while diseases and insects attack sugarbeet root and leaf tissue, ultimately reducing yield. Fungi, bacteria, nematodes, and viruses can cause diseases of sugarbeet. The most common diseases that infect sugarbeet in North Dakota and Minnesota fields are by the fungi *Rhizoctonia solani, Aphanomyces cochliodies,* and *Cercospora beticola* (Khan et al. 2017). The most common insects that attack North Dakota and Minnesota sugarbeet fields are root maggot (*Tetanops spp.),* springtails (*Collembola spp.*), root aphid (*Pemphigus spp.*), and Lygus bug (*Lygus spp.*). Genetic resistance, cultural practices, crop rotation, and timely applications of fungicide and insecticide control most diseases and insects.

History of Sugarbeet Weed Control

Weeds have been a major production problem for sugarbeet since the crop was first widely grown in Europe in the late 1700s (Schweizer and May 1993). Physical weed control was the primary method of managing weeds prior to the widespread use of herbicide. "Hand-weeding" methods such as hand-pulling or hand-hoeing were the main methods of removing weeds until the 1850s when sugarbeet producers started using livestock-drawn mechanical hoes for cultivation (May and Wilson 2006). Early mechanical machines used for weed control were similar to our modern cultivators in that they disturbed the soil enough to cover the weeds with soil or bring the weeds to the surface where they would desiccate. Physical weed control remained the primary method of weed control in sugarbeet until the 1950s when herbicides became common and reliable (Schweizer and Dexter 1987). Many producers continue to use physical weed control methods.

The widespread adoption of herbicides was inevitable as labor became increasingly scarce and costly due to the onset of World War II. The earliest herbicides used in sugarbeet were inorganic chemicals such as iron sulphate, sulphuric acid, and calcium cyanamide developed by European producers in the 1890s (Schweizer and May 1993; Schweizer and Dexter 1987). Organic herbicides such as endothall, propham, and sodium trichloroacetate applied primarily preemergence (PRE) followed, and were used in sugarbeet in the late 1930s. Postemergence (POST) herbicides such as dalapon were used to control annual grasses in the 1950s. Numerous new herbicides were introduced into sugarbeet fields in the 1960s, some of which are still used today including desmedipham, phenmedipham, cycloate, and trifluralin. Trifluralin and EPTC were among the first herbicides to be applied postemergence to sugarbeet, and preemergence to the weeds (known as layby), and mechanically incorporated into soil to provide residual control of emerging weeds. The combination of hand-weeding, mechanical cultivation, and herbicides applied pre-plant incorporated (PPI), PRE, POST, and layby allowed sugarbeet producers to achieve season-long weed control with an integrated approach of mechanical, cultural, and chemical weed control methods.

Early herbicide use in sugarbeet had numerous challenges. While they were an invaluable addition to producers' weed control strategies, they had limitations and issues such as crop injury, poor efficacy, and specific precipitation requirements resulting in unpredictable weed control in dry growing seasons. Desmedipham and phenmedipham were two of the most useful POST herbicides for controlling broadleaf weeds in the 1970s (Dexter 1977). Early adopters of desmedipham and phenmedipham often faced issues of moderate to severe sugarbeet injury when applying the labeled rates of 1.1 to 1.7 kg ha^{-1}. Varying weather conditions contributed most to the unpredictable nature of desmedipham and phenmedipham. This crop injury incidence lead to the development of split applications (later termed “micro-rate”), where a half-labeled rate of 0.56 to 0.84 kg ha^{-1} was separated by approximately five to seven days apart (Dexter 1994). Research demonstrated splitting herbicide applications reduced crop injury and improved weed control (Dexter and Schroeder 1978). As the micro-rate program evolved, a majority of sugarbeet producers used combination of desmedipham, phenmedipham, clopyralid, triflusulfuron, various grass herbicides, and methylated seed oil (MSO) adjuvant at reduced rates and up to four applications per growing season (Dexter and Luecke 1999). The reduced herbicide use in the micro-rate program gave producers lower herbicide costs per hectare, less crop injury, and greater flexibility in application timing (Bollman and Sprague 2007; Wilson et al. 2001).

Monsanto Company developed crop cultivars genetically engineered to be resistant to glyphosate in the mid-1990s. Glyphosate resistant (GR) cultivars of sugarbeet were approved by the United States Department of Agriculture (USDA) and Food and Drug Administration (FDA) in 2005 and became commercially available to sugarbeet producers in 2008 (USDA-APHIS 2018). GR sugarbeet cultivars accounted for roughly 95% of the United States sugarbeet hectarage in the 2009-2010 growing season. This shift in the sugarbeet cultivar selection triggered a massive change to sugarbeet weed control strategies. Glyphosate became the primary herbicide used in US sugarbeet production, as it was the safest and most effective at controlling weeds. Guza et al. (2002) reported greater than 95% redroot pigweed (*Amaranthus retroflexus)* and common lambsquarters (*Chenopodium album)* control could be achieved with two glyphosate applications postemergence in sugarbeet. Dexter and Luecke (2000) reported glyphosate improved crop safety and weed control compared to the conventional micro-rate program, which contributed to significantly greater crop yield. Other research evaluating GR sugarbeet cultivars suggested inter-row cultivation for controlling weeds was unnecessary and possibly detrimental to yield (Dexter et al. 2000). Survey data from 2007 indicated 99% of ND and MN 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).

Continuous use of GR cultivars in major crops such as corn, soybean, and sugarbeet has led to a shift in weed populations that have evolved resistance to glyphosate. There was approximately 20 confirmed weed species resistant to glyphosate in 2009 including waterhemp (*Amaranthus tuberculatus)*, common ragweed (*Ambrosia artemisiifolia)*, kochia (*Bassia scoparia syn. Kochia scoparia)*, and horseweed (*Conyza canadensis)* (Heap 2018). That number increased to 42 confirmed species in 2018. Weed control trials in 2016 reported glyphosate-only treatments in sugarbeet gave only 30 to 40% waterhemp control by late August (Peters et al. 2017). Postemergence weed control options also became limited in the mid-2010s because Bayer CropScience elected not to renew the registration of desmedipham and phenmedipham in sugarbeet (EPA 2014).

The presence of GR weed species led sugarbeet producers to use herbicides from the chloroacetamide family including S-metolachlor, dimethenamid-P, and acetochlor. Chloroacetamide herbicides are only effective at controlling emerging weed seedlings after being activated by moisture in the soil due to their mechanism of action. Because of this, chloroacetamide herbicides are applied either PRE or layby to provide residual control of emerging weeds mid-season. Chloroacetamide herbicides are used in many crops to control annual grasses, but they also have activity on small-seeded broadleaf weeds, including *Amaranthus* species. S-metolachlor and dimethenamid-P were registered for use in sugarbeet in the early-2000s and were used as PRE and POST in the micro-rate system (Bollman and Sprague 2007). Guza et al. (2002) in Oregon reported dimethenamid-P with a single application of glyphosate resulted in 11 to 22% greater redroot pigweed control compared to glyphosate alone preharvest. The use of chloroacetamide herbicides for weed control became unnecessary once GR sugarbeet cultivars were released commercially. However, many producers renewed their use of chloroacetamide herbicides POST as supplement to glyphosate because of the migration of GR waterhemp into eastern North Dakota and Minnesota. From 2014 to 2017, use of chloroacetamide herbicides applied early postemergence increased from 15 to 70% according to surveyed producers (Carlson et al. 2015; Peters et al. 2018). Peters et al. (2017) in Minnesota reported including a chloroacetamide herbicide with glyphosate improved season-long waterhemp control by over 40% compared to glyphosate only treatments. Applying S-metolachlor PRE followed by two applications of glyphosate plus a chloroacetamide herbicide resulted in excellent (90-100%) waterhemp control.

Chloroacetamide Herbicides: History and Mode of Action

Herbicides including acetochlor, S-metolachlor, and dimethenamid-P are members of the chloroacetamide chemical family. Chloroacetamide herbicides have been commercially used in agriculture for 60 years (Hamm 1974) and are still used in numerous crops including sugarbeet, corn, and soybean. The mode of action of chloroacetamide herbicides is known to be inhibition of lipid biosynthesis; specifically, very long chain fatty acid biosynthesis (Böger et al. 2000). Very long chain fatty acids (VLCFA) are fatty acids with akyl chains longer than 18 carbons (Cobb and Reade 2010). In plants, VLCFAs are important components of epicuticular waxes and cutin that form the leaf cuticle, but also serve as components of waxes that make up the extracellular pollen coat (Trentkamp et al. 2004). Plant cuticles coat plant leaves and stems and essentially serve as the first line of defense against the surrounding atmosphere. In addition to defense against herbivores and disease, the hydrophobic cuticle is also responsible for regulating the diffusion of water, which helps plants tolerate drought. Chloroacetamide herbicides are applied to soil and once activated, form a herbicide barrier on the soil to inhibit development of emerging weeds. Seeds usually germinate in soil but chloroacetamide herbicides quickly penetrate the plant mesocotyl and inhibit lipid synthesis in the young seedling. Affected seedlings will die once their fatty acid reserves are depleted (Cobb and Reade 2010).

The site of action of chloroacetamide herbicides has been a mystery for the majority of their agricultural use, but now most researchers believe they are inhibitors of VLCFA elongases, which occur in the endoplasmic reticulum, Golgi apparatus, and plasma membrane of the plant cell (Cobb and Reade 2010). Trentkamp et al. (2004) reported at least six VLCFA elongases in *Arabidopsis thaliana* were inhibited by the chloroacetamide herbicide allidochlor. Trentkamp states resistance to VLCFA-elongase-inhibiting herbicides might be rare because several elongases, each with varying functions, are inhibited simultaneously (Trentkamp et al. 2004).

Weed Interference in Sugarbeet

Weeds are a major production issue for sugarbeet producers in eastern North Dakota and Minnesota. The most problematic weeds in this region in 2016 included waterhemp, common ragweed, common lambsquarters, and redroot pigweed (Peters et al. 2018). Weeds compete with sugarbeet for light, space, essential nutrients, and moisture. Light competition is the main cause of yield reduction in irrigated or high rainfall cropping systems (Dawson 1965). Early season emerging weeds deliver the most economical damage because the sugarbeet’s low growth profile combined with slow canopy development allow weeds to quickly overtake the crop. Weeds left uncontrolled will significantly reduce sugarbeet root yield and extractable sucrose per hectare. Brimhall et al. (1965) reported high densities of redroot pigweed and green foxtail (*Setaria viridis*) reduced sugarbeet root yields by up to 85% compared to a weed-free control. Numerous studies have been done to determine the specific densities of weeds required to significantly reduce sugarbeet yield. Common sunflower (*Helianthus annus)* in Colorado has reduced yield at densities as low as one plant per 30m of crop row (Schweizer and Bridge 1982). Regarding other weeds, densities as low as four kochia plants, four to six common lambsquarters plants, and three to six redroot pigweed plants per 30m of row have reduced root yield (Schweizer 1973; Schweizer 1981; Schweizer 1983). Velvetleaf (*Abutilon theophrasti)* required 9 to 12 plants and Powell amaranth (*Amaranthus powellii)* required 9 to 11 plants per 30m of row to reduce yield (Schweizer and Bridge 1982; Schweizer and Lauridson 1985). One lanceleaf sage (*Salvia reflexa)* and one Venice mallow (*Hibiscus trionum*) plant per meter of row in Wyoming reduced yield by 3% and 6%, respectively (Odero et al. 2010; Odero et al. 2009). These studies also concluded weeds only affect sugarbeet root yield and not percent sucrose.

The critical period of weed control in sugarbeet is dependent on factors such as environmental conditions, crop planting date and emergence, weed species present, row spacing, and crop cultivar. Knowledge of a crop's critical period can help producers decide when to control weeds, but producers still need to consider the target weed and its resistance mechanisms, effects on crop quality and aesthetics, and potential contributions to the weed seed bank (Schweizer and May 1993). The critical period generally lies between sugarbeet emergence and 10 weeks after sugarbeet emergence, or when the sugarbeet reaches the 10- or 12-leaf stage (Dawson 1965). Dawson (1974) divided the sugarbeet production calendar into four distinct periods. Period I is the time from planting to thinning, period II from thinning to last cultivation/layby, period III from lay-by to weed end-point, and period IV from weed end-point until harvest. Weed competition was most harmful to yield in period I and becomes less important as the season approaches period IV (Dawson 1977). Weeds established early in the season become increasingly difficult to control as the season progresses and will damage the crop all season. Sugarbeets are effective at competing with weeds via shade once the canopy closes at the beginning of period III (Dawson 1975), which makes stand establishment important. Weeds are much more troublesome all season long and cause reduced yield in low sugarbeet densities (Dawson 1977). While a poor sugarbeet density does not necessarily translate to lost yield (Khan and Hakk 2016), it can increase the time required to reach canopy closure, which increases the risk for competitive late-emerging weeds.

Yield loss in sugarbeet can be reduced if weeds are controlled for a certain time past emergence. Maintained common lambsquarters control for 0, 10, 21, and 30 days after crop emergence (ACE) in the Netherlands reduced root yields by 79%, 37%, 7%, and 0%, respectively (Kropff 1988; Kropff and Lotz 1992). Sugarbeet root yield in Colorado was not affected by kochia when it was controlled up to four weeks ACE, but was reduced 56% when only controlled up to three weeks ACE (Weatherspoon and Schweizer 1969). Sugarbeet root yield in Washington was maximized when barnyardgrass (*Echinochloa crus-galli)* and common lambsquarters were hand-weeded until approximately 6 weeks ACE (Dawson 1965).

Plant seeds survive naturally in soil seed banks. Most seeds present in soil seed banks lie dormant and emerge once requirements for germination are met. The species of the weed seeds and amounts thereof are often dependent on environmental factors such as cropping system history, soil conditions, annual rainfall, tillage history, landscape position, and herbicide use. Seedbanks of cultivated soils can contain over 200,000 viable weed seeds m^{-2} (Forcella et al. 1992); however, these seed banks typically are dominated by one or two species. Within chisel-plowed or no-till systems, the top five cm of soil contains over 60% of the weed seedbank (Clements et al. 1996). Annual weeds such as waterhemp without competition are capable of producing over one million seeds per plant in a growing season (Heneghan and Johnson 2017). The actual production of weed seeds per plant in a given season is dependent on plant density, time of emergence, herbicide effectiveness, and other environmental conditions. Factors influencing the persistence of seeds in a soil seed bank are mostly dependent upon species, but can also be influenced by soil tillage, weather conditions, and naturally occurring predators such as insects. Most annual weed seeds in sugarbeet persist less than six years in the soil (Schweizer and Zimdahl 1984). Schweizer and Zimdahl (1984) reported diligent control of weeds for six years resulted in a 96% decline of total weed seeds present in the upper 25 cm portion of the soil profile in a production area with redroot pigweed and common lambsquarters. The primary reason for the reduction was the elimination of new weed seeds being introduced into the soil for the 6-year period. Schweizer and Zimdahl concluded an intensive weed management system in the first couple of years of a heavy weed infestation would result in easier control over time, demonstrating weed management is profitable over time.

Waterhemp: Biology and Impact

Waterhemp is an erect, herbaceous, summer annual, dioecious, small-seeded broadleaf weed native to North America (Sauer 1956). Waterhemp can be either the species common waterhemp (*Amaranthus rudis*) or tall waterhemp (*Amaranthus tuberculatus*). As differences between species are indistinguishable, numerous weed scientists have suggested combining them together (Pratt and Clark 2001; Steckel 2007). Waterhemp is a member of the *Amaranthaceae* botanical family and is different from other members of its family by its smooth, waxy, long, and narrow leaves. Another characteristic of waterhemp is its smooth, hairless stems and dioecious reproductive system with only male or female flowers per plant. Waterhemp is visually similar to Palmer amaranth (*Amaranthus palmeri*), but can be identified as waterhemp if the plant has petioles shorter than the leaf blade and female flowers that are soft to the touch. Waterhemp is a weed with a C4 photosynthetic pathway, thus it is better adapted for warm seasons. Waterhemp will begin germinating in the upper Midwest around the middle of May and will continue to emerge in flushes throughout the growing season (Nordby et al. 2007). Because waterhemp emerges throughout the season, it has an ability to interfere with agronomic crops much later than other weeds. It is also common for waterhemp to infest fields of early maturing small grains after harvest and complete its life cycle before winter, thus contributing to the soil seed bank. In North Dakota and Minnesota, waterhemp has commonly been introduced in overland-flooded areas. Some reports would suggest waterhemp prefers a wetter agronomic system. While waterhemp generally germinates in wet soil, it has also demonstrated the ability to survive in dry seasons, likely due to the efficient C4 photosynthetic pathway.

Waterhemp is considered the most troublesome weed for row-crop production in the Midwest. Its ability to emerge and produce seed season-long makes any specific control strategy challenging. Waterhemp also has evolved resistance to at least six herbicide modes of action including ALS inhibitors, PPO inhibitors, HPPD inhibitors, PSII inhibitors, glyphosate, and auxin-type herbicides (Heap 2018). Early germinating waterhemp allowed to grow full-season reduced soybean and corn yields 43% and 74%, respectively (Hager et al. 2002; Steckel and Sprauge 2004). Producers that observe several waterhemp plants in fields are encouraged to hand-remove them to prevent the spread of seed in their field. Waterhemp seeds are typically viable for four to six years, so intensive weed management strategies involving crop and herbicide mode of action rotation for a couple years will greatly reduce the waterhemp pressure. While the majority of seeds are not viable after several years, Buhler and Hartzler (2001) reported waterhemp seed germinated up to 17 years after burial. Kivilaan and Bandurski (1981) suggest seed from redroot pigweed, a close relative of waterhemp, will remain viable up to 40 years after burial.

Cultivation in Sugarbeet

Physical weed control is one component of an integrated weed management strategy (Swanton and Murphy 1996). Physical weed control can include any method of preventing or disrupting unwanted plant growth that leads to prevention or removal. Machines used included inter-row cultivators, tine and disc harrows, rotary hoes, rototillers, electrical discharge systems, flame cultivators, and mowers. Burning, hand-weeding, and mulch are also classified as physical weed control. Physical methods are useful due to the indiscriminate destruction of plants in the non-cropping area of a field. Similarly to chemical weed control, physical weed control is most effective when weeds are small.

Sugarbeet producers in the US have historically used inter-row cultivators, harrows, rotary hoes, and hand-weeding. Early sugarbeet producers commonly dedicated numerous employees, often migrants, to the task of hand-weeding during the growing season prior to the widespread use of farming machines. Machines such as inter-row cultivators combined with hand-weeding within the cropping rows became the primary weed control method until the adoption of POST herbicides. Inter-row cultivation and hand-weeding remained popular from the mid-1970s until the mid-2000s, despite not being the primary weed control method. Many growers would treat inter-row cultivation as simply routine. “Recreational cultivation” was a term to describe when producers would cultivate, even when the field did not appear to need it (N. Cattanach 2017, personal communication). The use of cultivation as a method of weed control has reduced since the commercialization of GR sugarbeet in 2008. With glyphosate able to adequately control most grass and broadleaf weeds, most farmers only used their inter-row cultivators for thinning field-perimeter rows where double-planting occurred.

Inter-row cultivation within a field mid-season has benefits and drawbacks. The greatest benefit is the use of a non-selective weed control mode of action that weeds will not develop resistance to as herbicides potentially can and have historically. Other benefits include drying/loosening of the soil and incorporation of fertilizer and residual herbicide. Numerous studies have evaluated the effect of inter-row cultivation on sugarbeet yield and quality. Results of these studies generally demonstrate 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 and Luecke (2000) reported cultivation had a negative effect on sugarbeet yield and quality in certain environments. They reported a trend for greater yield with two cultivations compared to no cultivation in certain environments, but they also reported a trend of less yield and quality in three out of ten environments with five cultivations. Dexter (1983) reported 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 one to three cultivations had no effect on sugarbeet yield, but four to seven cultivations had an increasingly negative effect on sugarbeet yield in one of two environments.

The reason cultivation later in the season has a negative effect on yield is likely due to two factors, physical damage to the sugarbeet plant tissue and increased infection of *Rhizoctonia solani* that causes *Rhizoctonia* crown and root rot. Giles et al. (1990) excavated roots in mid-July and observed less root development in the top seven centimeters of soil in treatments that received a large number (4 to 7) 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 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 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 environmental factors may also determine disease severity. Cultivation at reduced ground speeds is recommended to reduce the chance of *R. solani* infection due to soil hilling around the beet crown (Windels and Lamey 1998; Schneider et al. 1982).

Cultivation and Weed Interactions

Weed control by the physical movement of soil affects new weed emergence for some weed species. 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 the emergence (Egley and Williams 1990). Over a five-year average, however, Egley and Williams concluded 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 (Kemp 2000; Alm et al. 1993; Baskin and Baskin 1990). For many weed species, especially small-seeded broadleaves, tillage has limited effects on weed emergence. Oryokot et al. (1997) reported tillage has little effect on redroot pigweed emergence. Soil samples taken at 2.5 cm on plots with and without tillage indicated 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 due to the seed’s small endosperm, which explains why tillage had no 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 common lambsquarters emergence increased nearly 250% when tillage was performed in the light compared to the dark, but this result does not make night tillage a viable option to reduce weed emergence (Kemp 2000).

Shallow tillage has historically been a method of incorporating herbicide (May and Wilson 2006). Mechanical incorporation mixes herbicide into the soil profile, potentially protecting the herbicide from photodegradation and volatilization, increasing herbicide life (Locke and Bryson 1997). Most incorporation has historically been performed with implements such as disk and tine-harrows, but little research has evaluated inter-row cultivation as an incorporation method. Most soil mixing performed by incorporators is done in the top 2.5 to 3.5 cm of soil (Barrentine et al. 1978). Dexter (1978) reported cycloate incorporation to 5 cm provided best weed control, but optimum incorporation depth may vary depending on formulation, solubility, and herbicide mechanism of action. Chloroacetamides are residual herbicides activated by rain and mechanical incorporation is considered unnecessary (Cobb and Reade 2010), but little published research has explored the effect of incorporation on their action and fate, especially when precipitation is limiting.

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CHAPTER 2. INTER-ROW CULTIVATION IMMEDIATELY FOLLOWING RESIDUAL HERBICIDE APPLICATION IN SUGARBEET

Introduction

Weeds have been a major production challenge for sugarbeet (*Beta vulgaris)* 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 postemergence 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 took a lesser role in sugarbeet weed management as more herbicides were developed. From the 1970s to 2000s, desmedipham and phenmedipham were the primary herbicides used to control *Amaranthus* and *Chenopodium* species in sugarbeet (Dexter 1977; Dexter 1994; Dale et al. 2006), 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 use of glyphosate in sugarbeet (Bollman and Sprague 2007).

The commercialization of glyphosate-resistant (GR) sugarbeet cultivars in 2008 was a drastic change to sugarbeet weed management as glyphosate alone was cheaper, safer, and more effective than desmedipham, phenmedipham, and inter-row cultivation. Guza et al. (2002) reported greater than 95% redroot pigweed (*Amaranthus retroflexus)* and common lambsquarters (*Chenopodium album)* control could be achieved with two glyphosate applications postemergence in sugarbeet. Dexter and Luecke (2000) reported glyphosate improved sugarbeet safety and weed control compared to the conventional micro-rate program, which contributed to significantly greater root yield. Other research suggested inter-row cultivation for controlling weeds was unnecessary and possibly detrimental to yield (Dexter et al. 2000). Survey data from 2007 indicated 99% of ND and MN sugarbeet hectares were inter-row cultivated (Carlson et al. 2008), but only 11% of those were cultivated in 2011 following the release of GR cultivars (Stachler et al. 2011). Unfortunately, GR weeds including waterhemp (*Amaranthus tuberculatus*) 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 glyphosate-only treatments in sugarbeet gave only 30 to 40% waterhemp control 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 postemergence control options.

Use of chloroacetamide herbicides S-metolachlor, dimethenamid-P, and acetochlor applied early postemergence has increased from 15% in 2014 to 70% in 2017 according to surveyed producers (Carlson et al. 2015; Peters et al. 2018). Chloroacetamide herbicides are activated into soil solution by precipitation and provide residual control of emerging small-seeded broadleaf weeds, including *Amarathus* species. The current recommendation for waterhemp control in sugarbeet is to apply S-metolachlor and/or ethofumesate preemergence followed by split applications of a chloroacetamide herbicide early-postemergence (Peters et al. 2017). Stacking residual chloroacetamide herbicides throughout the season will prevent weed emergence until the sugarbeet crop canopy can provide shade to suppress further weed growth. Chloroacetamide herbicides are not perfect, however, as they require 10 to 20 mm precipitation for activation into soil solution and do not control already emerged weeds (Anonymous 2014, 2017). Herbicide-resistant weed escapes are a concern in a season with limited precipitation that results in poor herbicide activation or a year with excessive precipitation that makes timely herbicide applications impossible. Many sugarbeet producers have used inter-row cultivation to remove glyphosate-resistant weeds that escaped the residual chloroacetamide herbicide layer.

Shallow tillage has historically been a method of incorporating herbicide (May and Wilson 2006). Trifluralin and cycloate require immediate incorporation to prevent photodegradation and volatilization. Most incorporation has historically been performed with implements such as disk and tine-harrows, but little research has evaluated inter-row cultivation as an incorporation method. Most soil mixing performed by equipment occurs in the top 2.5 to 3.5 cm of soil (Barrentine et al. 1978). Dexter (1978) reported cycloate incorporation to 5 cm provided the best weed control, but optimum incorporation depth may vary depending on formulation, solubility, and herbicide mechanism of action.

Chloroacetamide herbicides are activated by precipitation and mechanical incorporation is considered unnecessary (Cobb and Reade 2010), but little published research has explored the effect of incorporation on their action and fate. Sugarbeet producers have inquired if inter-row cultivation can be used to incorporate and activate chloroacetamide herbicides in a season devoid of precipitation (T. Peters 2017, personal communication). Producers have inquired how effective cultivation is at removing herbicide-resistant weeds and how it affects subsequent weed emergence. Therefore, the objectives of this experiment were to 1) evaluate the effectiveness of cultivation at removing herbicide-resistant weeds, 2) evaluate how delayed cultivation affects weed emergence, and 3) evaluate cultivation as a method of incorporating residual herbicides immediately after application.

Materials and Methods

Site Description

Field experiments were conducted at two locations in eastern North Dakota and Minnesota in 2017 and three locations in 2018. Each site-year combination was considered an environment. Environments in 2017 were near Wheaton, MN (45°47'11.0"N, 96°21'15.4"W) and Renville, MN (44°47'07.5"N, 95°08'20.2"W). Environments in 2018 were near Hickson, ND (46°42'14.2"N, 96°48'09.3"W), Galchutt, ND (46°21'31.7"N, 96°50'22.7"W), and Nashua, MN (46°02'43.2"N, 96°19'38.5"W). Detailed soil descriptions for each environment can be found in Table 2.1. The dominant weed at the Renville-2017, Hickson-2018, and Nashua-2018 environments was waterhemp, while the dominant weed at the Wheaton-2017 and Galchutt-2018 environments was common lambsquarters. The five environments were separated into two groups: waterhemp and common lambsquarters.

Table 2.1. Soil descriptions for environments in 2017 and 2018.

Environment	Soil series & texture	Soil subgroup	Organic Matter	Soil pH
Wheaton-2017	Doran & Mustinka loam mix	Aquertic Argiudolls & Typic Argiaquolls	5.1%	6.9
Renville-2017	Mayer silty clay loam	Typic Endoaquolls	7.7%	7.9
Hickson-2018	Fargo silty clay	Typic Epiaquerts	6.0%	7.5
Galchutt-2018	Wyndmere loam	Aeric Calciaquolls	5.0%	7.5
Nashua-2018	Croke sandy loam	Oxyaquic Hapludolls	3.5%	7.2

Experimental Procedures

The experiment was a 2x6 factorial split-block randomized complete block design with six replications. Each replication (block) was “grid split” where the horizontal factor was cultivation at two levels and the vertical factor was herbicide at six levels. Untreated plots were nested in the design for comparison. Plots were 3.3 m wide and 9.1 m long. Sugarbeet was planted on May 15, 2017 at Renville, May 8, 2017 at Wheaton, May 7, 2018 at Hickson, May

14, 2018 at Nashua, and May 14, 2018 at Galchutt at a density of 152,000 (+/- 1,000) seeds ha^{-1} in six rows spaced 56 cm apart. S-metolachlor at 534 g ai ha^{-1} was applied preemergence (PRE) within 48 hours after planting in all environments except Hickson-2018.

Herbicides were applied at 4- to 10-leaf sugarbeet with a bicycle wheel-type sprayer with a shielded boom to reduce particle drift at a volume of 159 L ha^{-1}. The center four rows of each six-row plot were sprayed using pressurized CO_2 at 241 kPa through 8002XR nozzles (TeeJet Technologies, Glendale Heights, IL). Half of plots were cultivated immediately 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}. Information and use rates of herbicide can be found in Table 2.2. Dates of planting, herbicide application, and crop stage at herbicide application can be found on Table 2.3.

Table 2.2. Herbicide product information for treatments applied to 8- to 10-leaf sugarbeet in 2017 and 4- to 8-leaf sugarbeet in 2018.

Herbicide [a]	Rate	Trade name	Manufacturer [b]
	kg ai or ae ha^{-1}		
Glyphosate	1.1	Roundup PowerMAX	Monsanto
Glyphosate +	1.1 +	Roundup PowerMAX +	Monsanto +
S-metolachlor	1.34	Dual Magnum	Syngenta
Glyphosate +	1.1 +	Roundup PowerMAX +	Monsanto +
dimethenamid-P	0.95	Outlook	BASF
Glyphosate +	1.1 +	Roundup PowerMAX +	Monsanto
acetochlor	1.37	Warrant	
Glyphosate +	1.1 +	Roundup PowerMAX +	Monsanto +
trifluralin	5.61	Treflan HFP	Gowan
Glyphosate +	1.1 +	Roundup PowerMAX +	Monsanto +
cycloate	2.25	Ro-Neet	Helm Agro

[a] Adjuvants: All 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).

[b] Manufacturer information: Monsanto Company, St. Louis, MO; Syngenta Crop Protection, Greensboro, NC; BASF Corporation, Research Triangle Park, NC; Gowan Company, Yuma, AZ; Helm Agro US, Tampa, FL.

Table 2.3. Planting and application dates and crop stage of environments in 2017 and 2018.

		Application date		
Environment	Planting date	PRE [a]	POST	SGBT stage at POST
Renville, 2017	May 15	May 15	June 26	8-10 leaf
Wheaton, 2017	May 8	May 9	June 27	8-10 leaf
Hickson, 2018	May 7	-	June 20	6-8 leaf
Nashua, 2018	May 14	May 15	June 8	4-6 leaf
Galchutt, 2018	May 14	May 15	June 8	4-6 leaf

[a] Abbreviations: PRE = preemergence; POST = postemergence; SGBT = sugarbeet.

Data Collection and Analysis

Percent visual overall control and new weed emergence control were evaluated 14, 28, and 42 (+/- 3) days after treatment (DAT). Evaluation was a scale of 0% (no control) to 100% (complete control) relative to the untreated check rows between treatments. ‘New weed emergence control’ evaluated weeds that emerged since the last treatment, while ‘overall control’ evaluated old and new growth. 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 DAT at the Renville-2017, Hickson-2018, and Nashua-2018 environments. Waterhemp plants counted were considered glyphosate resistant because only plants that emerged prior to herbicide application were counted (all treatments included glyphosate) and seedlings were evaluated as part of ‘new weed emergence control’. Common lambsquarters density was estimated using a 1-m^2 quadrat 14 and 28 DAT at the Galchutt-2018 environment. Sugarbeet density and primary weed species density were estimated using representative treated rows and a 1-m^2 quadrat in the untreated area, respectively. Precipitation data was collected from nearby weather stations operated by the North Dakota Agricultural Weather Network (NDAWN) and National Weather Service (NWS).

Statistical analysis was conducted using SAS 9.4 (SAS Institute, Cary, NC). Data was subjected to ANOVA using PROC MIXED to test for treatment effects and significant interactions. Data was analyzed as a split-block design with expected means squares as recommended by Carmer et al. (1989). Significantly different treatment means were separated using *t*-tests when data was found to be significantly different at the $P \leq 0.05$. The cultivation and herbicide treatment factors were considered fixed effects, while replicate and environment were considered random effects. All environments were analyzed separately because of differences in primary weed species, precipitation, sugarbeet density, and sugarbeet stage at which the treatments were applied. Only main effects are presented when no significant cultivation by herbicide interaction was detected.

Results and Discussion

Field Growing Conditions

Field planting ranged between May 8 and May 15 across all environments (Table 2.3), which is typical for sugarbeet production in eastern North Dakota and Minnesota. Precipitation in the weeks following planting in 2017 was near the 30-year average (Table 2.4), but 2018 was dry in two of three environments. Stand establishment was a production challenge for sugarbeet producers in 2018 because of this dry period immediately following planting. Sugarbeet density in most environments were near the optimal range of 172 to 197 sugarbeets per 30 m row (Cattanach 1994; Smith et al. 1990; M. Metzger 2018, personal communication), but the sugarbeet density at Nashua-2018 was 35% of the recommended density (Table 2.5). Sugarbeet density at Galchutt-2018 was non-uniform with frequent and random gaps, despite having a density at 85% of the recommended range. Hickson-2018 received eight mm of rain immediately after planting and 28 mm the week following planting that contributed to normal densities (Tables 2.4 and 2.5). Crop density is an important component of sugarbeet weed management

(Dawson 1977) and the poor and non-uniform sugarbeet density at Nashua-2018 and Galchutt-2018 likely reduced the contribution of crop canopy for weed suppression.

Table 2.4. Weekly and monthly precipitation data, interval after planting and 28 days after treatment in 2017 and 2018. [a]

Week of	Renville-2017 8-E [b]	Wheaton-2017 15-W	Hickson-2018 18-NE	Nashua-2018 4-NW	Galchutt-2018 14-E	30-yr avg. [d]
	----------mm----------					
May 8	-	0	8	(0) [c]	(0)	
May 15	48	36	28	1	1	
May 22	0	3	6	16	3	
May 29	0	3	14	21	15	
May total	(48)	(43)	(44)	(24)	(5)	81
June 5	25	5	52	49	42	
June 12	14	70	38	33	80	
June 19	4	30	2	0.0	0	
June 26	29	22	35	10	2	
June total	71	128	123	97	136	83
July 3	19	0	28	18	32	
July 10	5	3	7	-	-	
July 17	4	21	23	-	-	
July 24	(0)	(2)	-	-	-	
July total	(28)	(26)	(73)	(18)	(32)	81
Season total	(147)	(197)	(240)	(139)	(173)	

[a] Nashua, Hickson, and Galchutt climate data collected by the North Dakota Agricultural Weather Network (NDAWN); Renville climate data collected from Olivia, MN airport (NWS); Wheaton climate data collected from Wheaton, MN airport (NWS).

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

[c] Precipitation data in parentheses is after planting and before 28 days after treatment.

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

Table 2.5. Primary weed species present, weed density, and sugarbeet density of environments in 2017 and 2018.

Environment	Primary weed species	Weed density [a]	Sugarbeet density [b]
		# m^{-2}	# per 30 m row
Renville-2017	Waterhemp	104	166
Wheaton-2017	Common lambsquarters	70	194
Hickson-2018	Waterhemp	35	187
Nashua-2018	Waterhemp	28	65
Galchutt-2018	Common lambsquarters	68	158

[a] Estimate of primary weed species per m^2 within the untreated check.

[b] Sugarbeet density is average number of sugarbeet plants per 30 m of row.

Waterhemp Control Affected by Cultivation Immediately Following Herbicide Application

Waterhemp density per plot. Cultivation immediately following herbicide application reduced waterhemp number of plants per plot by 50 to 75% across all environments 14 DAT (Table 2.6). Cultivated plots 28 DAT had 50 to 80% fewer waterhemp per plot compared to non-cultivated plots across all environments. This result was expected because the cultivator with 38-cm wide shovels in 56 cm rows covered approximately 68% of field area. The primary value of cultivation is the physical removal of weeds that glyphosate will not control. Only plants that emerged prior to herbicide application were counted to determine the removal of herbicide resistant weeds. Herbicide treatment did not affect waterhemp counts at any environment season-long because most waterhemp biotypes in eastern North Dakota and Minnesota are glyphosate resistant.

Table 2.6. Main effects of cultivation and herbicide on waterhemp counts at Renville-2017, Hickson-2018, and Nashua-2018, 14 and 28 days after treatment (DAT). [a]

	Waterhemp counts, 14 DAT			Waterhemp counts, 28 DAT		
Main effects	Renville	Hickson	Nashua	Renville	Hickson	Nashua
Cultivation [b]		-------------# per plot-------------			-------------# per plot-------------	
With cultivation	2 a	1 a	2 a	3 a	1 a	2 a
No cultivation	6 b	4 b	4 a	7 b	5 b	4 b
Herbicide [c]						
Glyphosate	6 a	2 a	5 a	6 a	3 a	5 a
Glyphosate + S-metolachlor	3 a	1 a	3 a	5 a	3 a	3 a
Glyphosate + dimethenamid-P	3 a	3 a	1 a	3 a	2 a	2 a
Glyphosate + acetochlor	4 a	2 a	3 a	5 a	2 a	4 a
Glyphosate + trifluralin	5 a	4 a	1 a	7 a	3 a	3 a
Glyphosate + cycloate	3 a	4 a	3 a	4 a	6 a	3 a
ANOVA		---------------*p value*---------------			-----------------*p value*---------------	
Cultivation	0.001	0.010	0.143	0.009	0.002	0.019
Herbicide	0.419	0.683	0.801	0.453	0.511	0.949
Cultivation * herbicide	0.118	0.534	0.950	0.170	0.667	0.985

[a] Means within a main effect and environment column not sharing any letter are significantly different by the t-test at the 5% level of significance.

[b] Cultivation treatments were cultivated immediately after spray treatment.

[c] All herbicide treatments included ethofumesate, high surfactant methylated oil concentrate, and liquid ammonium sulfate solution.

New waterhemp emergence control. Cultivation generally did not affect ‘new waterhemp control’ season-long at any environment (Table 2.7). Cultivation improved ‘new waterhemp control’ by 5% at Hickson-2018, 14 DAT, but had no effect 28 DAT. Cultivation improved ‘new waterhemp control’ by 4% at Renville-2017, 28 DAT, but had no effect 14 DAT. The differences were not considered season-long unless differences were seen at both evaluation dates because chloroacetamide herbicides have a 2 to 3 week effective period (Mueller et al. 1999). Cultivation did not affect ‘new waterhemp control’ at Nashua-2018. This occurrence is likely due to an interaction between sugarbeet stand density and the sugarbeet stage at which the treatments were applied. The treatments at Renville-2017 and Hickson-2018 were applied at the 8- to 10- and 6- to 8-leaf sugarbeet stages, respectively, while the treatments at Nashua-2018 were applied at the 4- to 6-leaf sugarbeet stage (Table 2.3). Sugarbeet density at Nashua-2018 was 65 sugarbeets per 30 m row, while sugarbeet density at Renville-2017 and Hickson-2018 was 166 and 187 sugarbeets per 30 m row, respectively (Table 2.5). The recommended sugarbeet density for optimal yield and weed suppression is 172 to 197 sugarbeets per 30 m row (Cattanach 1994; Smith et al. 1990; M. Metzger 2018, personal communication). In an environment with a full and mature crop stand, cultivation would disrupt weed growth and allow the crop canopy to provide shade to suppress further weed emergence. While the crop canopy at Renville-2017 and Hickson-2018 were fuller and more mature than Nashua-2018, the differences were not sufficient to improve ‘new waterhemp control’ across both evaluation dates.

Residual herbicides with glyphosate generally improved ‘new waterhemp control’ relative to glyphosate alone in two of three environments (Table 2.7). Residual herbicides with glyphosate increased new waterhemp control by 7 to 8% and Nashua-2018, 14 DAT and 11 to 14% at Renville-2017 and Nashua-2018, 28 DAT (Table 2.7). Herbicide treatment had no effect on new waterhemp control at Renville-2017, 14 DAT or Hickson-2018 at any evaluation date. Herbicide treatment probably did not increase new waterhemp control at Hickson-2018 at any evaluation date because the environment did not receive adequate precipitation until ten days after herbicide application (Table 2.4). Chloroacetamide herbicides require 10 to 20 mm of precipitation to become activated into soil solution (Anonymous 2014, 2017). Chloroacetamide herbicides tended to provide greater ‘new waterhemp control’ compared to trifluralin and cycloate, but statistical differences were not consistent. This is likely because chloroacetamide herbicides can be activated by rain alone, whereas trifluralin and cycloate require immediate incorporation to become active.

These results demonstrate the importance of mixing chloroacetamide herbicides with glyphosate to reduce the number of emerging waterhemp seedlings. Chloroacetamide herbicides in sugarbeets are applied in a ‘layered’ system where S-metolachlor is applied PRE and S-metolachlor, dimethenamid-P, or acetochlor are tank mixed with glyphosate twice POST to provide ‘layered’ residual control of small-seeded broadleaves until crop canopy closure (Peters et al. 2017). The use of this ‘layered’ system is important, as no herbicides currently labeled in sugarbeet provide season-long glyphosate resistant waterhemp control.

Sugarbeet producers have inquired if inter-row cultivation can be used to incorporate residual herbicides to improve their activity (T. Peters 2017, personal communication). Chloroacetamide herbicides need 10 to 20 mm of precipitation to become activated into soil solution (Anonymous 2014, 2017). In theory, cultivation could incorporate the herbicide into sub-surface soil moisture and activate the herbicide artificially in a dry season. Hickson-2018 received only 2 mm of precipitation in the week following cultivation, while Renville-2017 and Nashua-2018 received 29 and 30 mm, respectively (Table 2.4). Cultivation did not enhance the activity of chloroacetamide herbicides at Hickson-2018 (Table 2.7) which had a dry period following herbicide application. More data is needed to form a reasonable conclusion, but this data suggests inter-row cultivation does not activate chloroacetamide herbicides and contribute to new waterhemp control in a dry season.

Table 2.7. Main effects of cultivation and herbicide on new waterhemp control at Renville-2017, Hickson-2018, and Nashua-2018, 14 and 28 days after treatment (DAT). [a]

	New waterhemp control, 14 DAT [d]			New waterhemp control, 28 DAT		
Main effects	Renville	Hickson	Nashua	Renville	Hickson	Nashua
Cultivation [b]	------------------%------------------			------------------%------------------		
With cultivation	89 a	100 a	97 a	91 a	96 a	95 a
No cultivation	91 a	95 b	96 a	87 b	96 a	93 a
Herbicide [c]						
Glyphosate	83 a	97 a	91 b	81 c	97 a	83 c
Glyphosate + S-metolachlor	91 a	100 a	98 a	89 ab	99 a	96 ab
Glyphosate + dimethenamid-P	92 a	98 a	99 a	93 ab	100 a	98 a
Glyphosate + acetochlor	88 a	100 a	99 a	94 a	98 a	98 a
Glyphosate + trifluralin	92 a	98 a	95 ab	86 bc	94 a	89 bc
Glyphosate + cycloate	94 a	94 a	99 a	92 ab	91 a	98 a
ANOVA	----------------*p value*----------------			-----------------*p value*-----------------		
Cultivation	0.082	0.009	0.328	0.006	0.867	0.423
Herbicide	0.061	0.150	0.004	0.011	0.066	0.004
Cultivation * herbicide	0.661	0.174	0.704	0.292	0.565	0.670

[a] Means within a main effect and environment column not sharing any letter are significantly different by the t-test at the 5% level of significance.

[b] Cultivation treatments were cultivated immediately after spray treatment.

[c] All herbicide treatments included ethofumesate, high surfactant methylated oil concentrate, and liquid ammonium sulfate solution.

[d] Evaluation on scale of 0% (no control) to 100% (complete control). New control is visual evaluation of growth since last treatment.

Overall waterhemp control. Cultivation improved ‘overall waterhemp control’ 6 to 12% across all environments and evaluation dates (Table 2.8). Data from 14 DAT and 28 DAT is representative of early to mid-season control, while data from 42 DAT is representative of season-long control. Cultivation increased ‘overall waterhemp control’ by 6% at Renville-2018, and 11 to 12% at Hickson-2018 and Nashua-2018, 42 DAT (Table 2.8). This data mirrors the waterhemp counts (Table 2.6) and new waterhemp control (Table 2.7) data since overall control is a visual summation of the previous two dependent variables. Cultivation significantly increased overall waterhemp control because it physically removed 50 to 75% of waterhemp plants 14 DAT (Table 2.6) and generally did not affect new waterhemp control. The primary benefit of cultivation is the physical removal of glyphosate resistant waterhemp with no apparent deleterious effects on future weed emergence.

Herbicide treatment did not affect ‘overall waterhemp control’ season-long at any environment (Table 2.8). Chloroacetamide herbicides with glyphosate tended to improve overall waterhemp control as compared to glyphosate alone, but no statistical difference was detected. Trifluralin and cycloate provided similar overall waterhemp control compared to chloroacetamide herbicides. Differences were probably not detected in this data because glyphosate resistant waterhemp had already emerged in all environments at the time of treatment and soil-applied seedling inhibitor herbicides are ineffective for control of emerged waterhemp. Past research indicated mixing a chloroacetamide herbicide with glyphosate can improve season-long overall waterhemp control (Peters et al. 2017), but only if chloroacetamide herbicides are applied prior to waterhemp emergence.

Table 2.8. Main effects of cultivation and herbicide on overall waterhemp control at Renville-2017, Hickson-2018, and Nashua-2018, 14, 28, and 42 days after treatment (DAT). [a]

	Overall control, 14 DAT [d]			Overall control, 28 DAT			Overall control, 42 DAT		
Main effects	Renville	Hickson	Nashua	Renville	Hickson	Nashua	Renville	Hickson	Nashua
Cultivation [b]	---------------%---------------			---------------%---------------			---------------%---------------		
With cultivation	93 a	97 a	96 a	91 a	93 a	90 a	84 a	91 a	83 a
No cultivation	85 b	91 b	88 b	83 b	85 b	83 a	78 b	79 b	72 b
Herbicide [c]									
Glyphosate	87 a	95 a	88 a	83 a	89 a	81 a	78 a	84 a	71 a
Glyphosate + S-metolachlor	89 a	95 a	93 a	87 a	90 a	89 a	80 a	85 a	90 a
Glyphosate + dimethenamid-P	91 a	95 a	93 a	90 a	94 a	92 a	83 a	90 a	83 a
Glyphosate + acetochlor	89 a	95 a	96 a	88 a	87 a	88 a	82 a	88 a	77 a
Glyphosate + trifluralin	87 a	93 a	93 a	85 a	92 a	87 a	80 a	85 a	78 a
Glyphosate + cycloate	92 a	90 a	90 a	90 a	83 a	83 a	81 a	76 a	67 a
ANOVA	------------*p value*------------			------------*p value*------------			------------*p value*------------		
Cultivation	0.002	0.004	0.006	0.011	0.004	0.058	0.008	0.002	0.041
Herbicide	0.452	0.752	0.676	0.344	0.624	0.778	0.864	0.517	0.243
Cultivation * herbicide	0.157	0.762	0.919	0.245	0.732	0.533	0.087	0.425	0.723

[a] Means within a main effect and environment column not sharing any letter are significantly different by the t-test at the 5% level of significance.
[b] Cultivation treatments were cultivated immediately after spray treatment.
[c] All herbicide treatments included ethofumesate, high surfactant methylated oil concentrate, and liquid ammonium sulfate solution.
[d] Evaluation on scale of 0% (no control) to 100% (complete control). Overall control is visual evaluation of old and new growth.

Common Lambsquarters Control Affected by Cultivation Immediately Following Herbicide Application

New common lambsquarters control and density. Cultivation improved 'new common lambsquarters control' by 8 to 9% at Wheaton-2017, 14 and 28 DAT (Tables 2.9 and 2.10). An interaction of cultivation and herbicide 14 DAT at Wheaton-2017 demonstrates control with chloroacetamide herbicides generally was not improved with cultivation, but new common lambsquarters control with trifluralin and cycloate was improved with cultivation (Table 2.10). This result was expected because trifluralin and cycloate require immediate incorporation to provide effective control, while chloroacetamide herbicides are effective with timely precipitation alone. In contrast, cultivation decreased ‘new common lambsquarters control’ by 10 to 15% at Galchutt-2018, 14 and 28 DAT (Table 2.9). Weed density data mirrors this result as cultivated treatments had nearly 100% more common lambsquarters per m^2 compared to non-cultivated treatments at Galchutt-2018, 28 DAT (Table 2.11).

The difference in effect of cultivation on ‘new common lambsquarters control’ between Wheaton-2017 and Galchutt-2018 was likely due to an interaction between sugarbeet density, calendar date, and the sugarbeet stage at which the treatments were applied. Sugarbeet density at Wheaton-2017 was full and uniform with 194 sugarbeets per 30 m row, while sugarbeet density at Galchutt-2018 was non-uniform and with 158 sugarbeets per 30 m row (Table 2.5). Treatments were applied to 8- to 10-leaf sugarbeet at Wheaton-2017 and 4- to 6-leaf sugarbeet at Galchutt-2018 (Table 2.3). This difference in crop maturity between environments likely affected the role of canopy coverage on new common lambsquarters control. Based on calendar date, Galchutt-2018 was treated 18 days before Wheaton-2017 (Table 2.3). A cultivation/herbicide treatment later in the season would have less emergence following cultivation because common lambsquarters is an early season C3 weed. An early cultivation with little canopy coverage would also have exposed the tilled seeds to light. Buhler (1997) reported common lambsquarters emergence increased nearly 250% when tillage was performed in the light compared to the dark. This implies producers should avoid cultivation until the crop canopy can provide shade to reduce the stimulation of common lambsquarters emergence.

Residual herbicides with glyphosate improved ‘new common lambsquarters control’ compared to glyphosate alone in one of two environments (Tables 2.9 and 2.10). Chloroacetamide herbicides provided greater ‘new common lambsquarters control’ compared to glyphosate alone and glyphosate with trifluralin and cycloate at Wheaton-2017, 14 DAT (Table

2.10), but no difference was detected 28 DAT (Table 2.9). Residual herbicides mixed with glyphosate controlled new emergence significantly better than glyphosate alone at Galchutt-2018, 14 and 28 DAT (Table 2.9). The density per m^2 of common lambsquarters at Galchutt-2018, 28 DAT mirrors these results where residual herbicides with glyphosate resulted in approximately 50% less common lambsquarters per m^2 compared to glyphosate alone (Table 2.11). Wheaton-2017 and Galchutt-2018 likely had different herbicide responses because of the difference in crop stage at time of treatment. Wheaton-2017 treatments were applied to 8- to 10-leaf sugarbeet, while Galchutt-2018 treatments were applied to 4- to 6-leaf sugarbeet (Table 2.3). Crop canopy at Wheaton-2017 likely provided shade and suppressed weed emergence, reducing the effect of herbicide treatment.

Table 2.9. Main effects of cultivation and herbicide on new common lambsquarters control at Wheaton-2017 and Galchutt-2017, 14 and 28 days after treatment (DAT). [a]

	New common lambsquarters control, 14 DAT [d]	New common lambsquarters control, 28 DAT	
Main effects	Galchutt	Wheaton	Galchutt
Cultivation [b]	--%--	-------------%-------------	
With cultivation	80 b	91 a	65 b
No cultivation	90 a	83 b	80 a
Herbicide [c]			
Glyphosate	70 b	87 ab	47 b
Glyphosate + S-metolachlor	89 a	89 ab	80 a
Glyphosate + dimethenamid-P	90 a	90 a	82 a
Glyphosate + acetochlor	87 a	92 a	75 a
Glyphosate + trifluralin	85 a	80 b	70 a
Glyphosate + cycloate	90 a	81 ab	81 a
ANOVA	*-p value-*	-----------*p value*-----------	
Cultivation	0.003	0.007	0.001
Herbicide	< 0.001	0.010	< 0.001
Cultivation * herbicide	0.320	0.223	0.132

[a] Means within a main effect and environment column not sharing any letter are significantly different by the t-test at the 5% level of significance.

[b] Cultivation treatments were cultivated immediately after spray treatment.

[c] All herbicide treatments included ethofumesate, high surfactant methylated oil concentrate, and liquid ammonium sulfate solution.

[d] Evaluation on scale of 0% (no control) to 100% (complete control). New control is visual evaluation of growth since last treatment.

Table 2.10. Interaction of cultivation and herbicide on new common lambsquarters control at Wheaton-2017, 14 days after treatment (DAT). [a]

	New common lambsquarters control, 14 DAT [d]
Cultivation * herbicide interaction	Wheaton
With cultivation	--%--
Glyphosate	92 ab
Glyphosate + S-metolachlor	92 ab
Glyphosate + dimethenamid-P	93 a
Glyphosate + acetochlor	94 a
Glyphosate + trifluralin	92 ab
Glyphosate + cycloate	92 ab
No cultivation	
Glyphosate	83 cd
Glyphosate + S-metolachlor	90 ab
Glyphosate + dimethenamid-P	90 ab
Glyphosate + acetochlor	87 bc
Glyphosate + trifluralin	76 de
Glyphosate + cycloate	69 e
ANOVA	*-p value-*
Cultivation	0.002
Herbicide	0.084
Cultivation * herbicide	0.010

[a] Means not sharing any letter are significantly different by the t-test at the 5% level of significance.

[b] Cultivation treatments were cultivated immediately after spray treatment.

[c] All herbicide treatments included ethofumesate, high surfactant methylated oil concentrate, and liquid ammonium sulfate solution.

[d] Evaluation on scale of 0% (no control) to 100% (complete control). New control is visual evaluation of growth since last treatment..

Table 2.11. Main effects of cultivation and herbicide on common lambsquarters density at Galchutt-2017, 14 and 28 days after treatment (DAT). [a]

	Common lambsquarters density, 14 DAT	Common lambsquarters density, 28 DAT
Main effects	Galchutt	Galchutt
Cultivation [b]	# per m^2	# per m^2
With cultivation	20 a	48 a
No cultivation	18 a	25 b
Herbicide [c]		
Glyphosate	25 a	80 b
Glyphosate + S-metolachlor	12 a	34 a
Glyphosate + dimethenamid-P	14 a	32 a
Glyphosate + acetochlor	13 a	28 a
Glyphosate + trifluralin	27 a	24 a
Glyphosate + cycloate	20 a	20 a
ANOVA	*-p value-*	*-p value-*
Cultivation	0.217	0.018
Herbicide	0.098	< 0.001
Cultivation * herbicide	0.620	0.099

[a] Means within a main effect and evaluation date column not sharing any letter are significantly different by the t-test at the 5% level of significance.

[b] Cultivation treatments were cultivated immediately after spray treatment.

[c] All herbicide treatments included ethofumesate, high surfactant methylated oil concentrate, and liquid ammonium sulfate solution.

Overall common lambsquarters control. Cultivation and residual herbicides did not affect season-long 'overall common lambsquarters control' at any environment or evaluation date (Table 2.12). Cultivation tended to increase overall control 42 DAT at Wheaton-2017, but the differences were not statistically significant ($P = 0.069$). Cultivation tended to decrease overall control 42 DAT at Galchutt-2018, but the differences were not statistically significant ($P = 0.127$). Overall control is a visual summation of new emergence and old growth control, so this data is consistent with new emergence control and weed density data where cultivation reduced new common lambsquarters control and increased weed density 28 DAT at Galchutt-2018 (Table 2.10). Herbicide treatment had no notable effect on season-long overall common lambsquarters control at either environment (Table 2.12). There was a numerical trend at Galchutt-2018 for residual herbicides with glyphosate providing 11 to 27% greater control 42 DAT, but this difference was not statistically significant ($P = 0.085$). This trend was not present at Wheaton-2017 where glyphosate alone gave relatively equal overall control compared to glyphosate mixed with a residual herbicide (Tables 2.12).

Table 2.12. Main effects of cultivation and herbicide on overall common lambsquarters control at Wheaton-2017 and Galchutt-2018, 14, 28, and 42 days after treatment (DAT). [a]

	Overall control, 14 DAT [d]		Overall control, 28 DAT		Overall control, 42 DAT	
Main effects	Wheaton	Galchutt	Wheaton	Galchutt	Wheaton	Galchutt
Cultivation [b]	----------%----------		----------%----------		----------%----------	
With cultivation	98 a	100 a	96 a	83 a	78 a	73 a
No cultivation	96 a	100 a	94 a	87 a	70 a	80 a
Herbicide [c]						
Glyphosate	99 a	100 a	99 a	77 a	73 a	60 a
Glyphosate + S-metolachlor	99 a	99 a	98 a	88 a	77 a	80 a
Glyphosate + dimethenamid-P	97 a	100 a	97 a	88 a	86 a	87 a
Glyphosate + acetochlor	98 a	100 a	96 a	89 a	77 a	81 a
Glyphosate + trifluralin	93 a	100 a	89 a	82 a	68 a	71 a
Glyphosate + cycloate	95 a	100 a	90 a	86 a	66 a	81 a
ANOVA	-------*p value*-------		-------*p value*-------		-------*p value*-------	
Cultivation	0.363	0.363	0.446	0.158	0.069	0.127
Herbicide	0.438	0.438	0.057	0.229	0.162	0.085
Cultivation * herbicide	0.438	0.438	0.467	0.114	0.645	0.902

[a] Means within a main effect and environment column not sharing any letter are significantly different by the t-test at the 5% level of significance.

[b] Cultivation treatments were cultivated immediately after spray treatment.

[c] All herbicide treatments included ethofumesate, high surfactant methylated oil concentrate, and liquid ammonium sulfate solution.

[d] Evaluation on scale of 0% (no control) to 100% (complete control). Overall control is visual evaluation of old and new growth.

Conclusion: Should I cultivate immediately after herbicide application?

Cultivation immediately after herbicide application can increase overall waterhemp control because it physically removes waterhemp that glyphosate will not control. The cultivator removed 50 to 75% of herbicide resistant waterhemp, which translated to approximately 6 to 12% improved season-long control across all waterhemp environments (Tables 2.6 and 2.8). Sugarbeet producers have asked if cultivation can be used to activate chloroacetamide herbicides in a dry year. Hickson-2018 was the only environment with little precipitation (2 mm) in the ten days following the treatment and greater 'new waterhemp control' was not observed with cultivation in that environment (Table 2.7). Further research is needed to strengthen this conclusion, but these data suggest incorporation via this method of cultivation is not a valid method for activating chloroacetamide herbicides in a dry year. Cultivation after herbicide application reduced common lambsquarters control at Galchutt-2018 (Table 2.9) because cultivation was implemented too early or before sugarbeet canopy was sufficiently developed to suppress further common lambsquarters emergence. Cultivation immediately after herbicide application is not necessary to control glyphosate-susceptible common lambsquarters because a repeat glyphosate application is cheaper and more reliable.

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CHAPTER 3. DELAYED CULTIVATION TO SUPPLEMENT CHLOROACETAMIDE HERBICIDES IN SUGARBEET

Introduction

Weeds have been a major production challenge for sugarbeet (*Beta vulgaris)* 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 postemergence 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 took a lesser role in sugarbeet weed management as more herbicides were developed. From the 1970s to 2000s, desmedipham and phenmedipham were the primary herbicides used to control *Amaranthus* and *Chenopodium* species in sugarbeet (Dexter 1977; Dexter 1994; Dale et al. 2006), 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 use of glyphosate in sugarbeet (Bollman and Sprague 2007).

The commercialization of glyphosate-resistant (GR) sugarbeet cultivars in 2008 was a drastic change to sugarbeet weed management as glyphosate alone was cheaper, safer, and more effective than desmedipham, phenmedipham, and inter-row cultivation. Guza et al. (2002) reported greater than 95% redroot pigweed (*Amaranthus retroflexus)* and common lambsquarters (*Chenopodium album)* control could be achieved with two glyphosate applications postemergence in sugarbeet. Dexter and Luecke (2000) reported glyphosate improved sugarbeet safety and weed control compared to the conventional micro-rate program, which contributed to significantly greater root yield. Other research suggested inter-row cultivation for controlling weeds was unnecessary and possibly detrimental to yield (Dexter et al. 2000). Survey data from 2007 indicated 99% of ND and MN 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 (*Amaranthus tuberculatus*) 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 glyphosate-only treatments in sugarbeet gave only 30 to 40% waterhemp control 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 postemergence control options.

Use of chloroacetamide herbicides S-metolachlor, dimethenamid-P, and acetochlor applied early postemergence has increased from 15% in 2014 to 70% in 2017 according to surveyed producers (Carlson et al. 2015; Peters et al. 2018). Chloroacetamide herbicides are activated into soil solution by precipitation and provide residual control of emerging small-seeded broadleaf weeds, including *Amarathus* species. The current recommendation for waterhemp control in sugarbeet is to apply S-metolachlor and/or ethofumesate preemergence followed by split applications of a chloroacetamide herbicide early-postemergence (Peters et al. 2017). Stacking residual chloroacetamide herbicides throughout the season will prevent weed emergence until the sugarbeet crop canopy can provide shade to suppress further weed growth. Chloroacetamide herbicides are not perfect, however, as they require 10 to 20 mm precipitation for activation into soil solution and do not control already emerged weeds (Anonymous 2014, 2017). Herbicide-resistant weed escapes are a concern in a season with limited precipitation that results in poor herbicide activation or a year with excessive precipitation that makes timely herbicide applications impossible. Many sugarbeet producers have used inter-row cultivation as a means to remove glyphosate-resistant weeds that escaped the residual chloroacetamide herbicide layer.

Sugarbeet producers will apply 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 there is inconsistent control with herbicides. Producers have inquired if inter-row cultivation is a viable tool to remove weeds that glyphosate did not control. Producers also have inquired if delayed cultivation will expose untreated soil causing weed seed germination and emergence. Therefore, the objectives of this experiment were to 1) evaluate the effectiveness of cultivation at removing herbicide-resistant weeds and 2) evaluate how delayed cultivation affects weed emergence.

Materials and Methods

Site Description

Field experiments were conducted at two locations in eastern North Dakota and Minnesota in 2017 and two locations in 2018. Each site-year combination is considered an environment. Environments in 2017 were near Wheaton, MN (45°47'11.0"N, 96°21'15.4"W) and Renville, MN (44°47'07.5"N, 95°08'20.2"W). Environments in 2018 were near Galchutt, ND (46°21'31.7"N, 96°50'22.7"W), and Nashua, MN (46°02'43.2"N, 96°19'38.5"W). Excessive precipitation destroyed two of six replications during two evaluations at the Wheaton-2017 environment. Detailed soil descriptions for each environment can be found in Table 3.1. The dominant weed at the Renville-2017 and Nashua-2018 environments was waterhemp and the dominant weed at the Wheaton-2017 and Galchutt-2018 environments was common lambsquarters. The four environments were separated into two groups: waterhemp and common lambsquarters.

Table 3.1. Soil descriptions for environments in 2017 and 2018.

Environment	Soil series & texture	Soil subgroup	Organic Matter	Soil pH
Wheaton-2017	Doran & Mustinka loam mix	Aquertic Argiudolls & Typic Argiaquolls	5.1%	6.9
Renville-2017	Mayer silty clay loam	Typic Endoaquolls	7.7%	7.9
Galchutt-2018	Wyndmere loam	Aeric Calciaquolls	5.0%	7.5
Nashua-2018	Croke sandy loam	Oxyaquic Hapludolls	3.5%	7.2

Experimental Procedures

The experiment was a 2x4 factorial split-block randomized complete 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. Untreated plots were nested in the design for comparison. Plots were 3.3 m wide and 9.1 m long. Sugarbeet was planted on May 15, 2017 at Renville, May 8, 2017 at Wheaton, May 14, 2018 at Nashua, and May 14, 2018 at Galchutt to a density of 152,000 (+/- 1,000) seeds ha^{-1} in six rows spaced 56 cm apart. S-metolachlor at 534 g ai ha^{-1} was applied preemergence (PRE) within 48 hours after planting in all environments.

Herbicides 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}. The center four rows of each six-row plot were sprayed using pressurized CO_2 at 241 kPa through 8002XR nozzles (TeeJet Technologies, Glendale Heights, IL). Half of the plots were cultivated approximately two weeks 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}. Information and use rates of herbicide can be found in Table 3.2. Dates of planting, herbicide application, cultivation, and crop stage at herbicide application can be found on Table 3.3.

Table 3.2. Herbicide product information for treatments applied to 8-10 cm weeds.

Herbicide [a]	Rate	Trade name	Manufacturer [b]
	kg ai or ae ha^{-1}		
Glyphosate	1.1	Roundup PowerMAX	Monsanto
Glyphosate +	1.1 +	Roundup PowerMAX +	Monsanto +
S-metolachlor	1.34	Dual Magnum	Syngenta
Glyphosate +	1.1 +	Roundup PowerMAX +	Monsanto +
dimethenamid-P	0.95	Outlook	BASF
Glyphosate +	1.1 +	Roundup PowerMAX +	Monsanto
acetochlor	1.37	Warrant	

[a] Adjuvants: All treatments included ethofumesate at 140 g ai ha^{-1} (Ethofumesate 4SC, Willowood LLC, Roseburg, OR), high surfactant methylated oil concentrate (HSMOC) at 1.75 L ha^{-1} (Destiny HC, Winfield Solutions LLC, St. Paul, MN), and ammonium sulfate (AMS) liquid solution at 2.5% v/v (N-Pak AMS liquid, Winfield Solutions LLC, St. Paul, MN).
[b] Manufacturer information: Monsanto Company, St. Louis, MO; Syngenta Crop Protection, Greensboro, NC; BASF Corporation, Research Triangle Park, NC.

Table 3.3. Planting, herbicide application, and cultivation dates and crop stage of environments in 2017 and 2018.

		Application date			SGBT stage
Environment	Planting date	PRE [a]	POST	Cultivation date	at cultivation
Renville, MN-2017	May 15	May 15	June 26	July 10	8-10 leaf
Wheaton, MN-2018	May 8	May 9	June 27	July 14	8-10 leaf
Nashua, MN-2018	May 14	May 15	June 12	June 26	6-8 leaf
Galchutt, ND-2018	May 14	May 15	June 21	July 5	6-8 leaf

[a] Abbreviations: PRE = preemergence; POST = postemergence; SGBT = sugarbeet.

Data Collection and Analysis

Percent visual overall control and new weed emergence control were evaluated 14, 28, and 42 (+/- 3) days after the cultivation treatment (DAC). Evaluation was a scale of 0% (no control) to 100% (complete control) relative to the untreated check rows between treatments. ‘New weed emergence control’ evaluated weeds that emerged since last treatment, while ‘overall control’ evaluated old and new growth. 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. Waterhemp plants counted were considered glyphosate resistant because only plants that emerged prior to herbicide application were counted (all treatments included glyphosate) and seedlings were evaluated as part of 'new weed emergence control'. Sugarbeet density and primary weed species density were estimated using representative treated rows and a 1-m^{-2} quadrat in the untreated area, respectively. Precipitation data was collected from nearby weather stations operated by the North Dakota Agricultural Weather Network (NDAWN) and National Weather Service (NWS).

Statistical analysis was conducted using SAS 9.4 (SAS Institute, Cary, NC). Data was subjected to ANOVA using PROC MIXED to test for treatment effects and significant interactions. Data was analyzed as a split-block design with expected means squares as recommended by Carmer et al. (1989). Significantly different treatment means were separated using *t*-tests when data was found to be significantly different at the $P \leq 0.05$. The cultivation and herbicide treatment factors were considered fixed effects, while replicate and environment were considered random effects. All environments were analyzed separately because of differences in primary weed species, precipitation, sugarbeet density, and sugarbeet stage at which the treatments were applied. Only main effects are presented when no significant cultivation by herbicide interaction was detected.

Results and Discussion

Field Growing Conditions

Field planting occurred between May 8 and May 15 across all environments (Table 3.3), which is typical for sugarbeet production in eastern North Dakota and Minnesota. Precipitation in the weeks following planting in 2017 was near the 30-year average (Table 3.4), but 2018 was dry. Stand establishment was a production challenge for sugarbeet producers in 2018 because of this dry period immediately after planting. Sugarbeet density at Renville-2017, Wheaton-2017, and Galchutt-2018 was near the optimal range of 172 to 197 sugarbeets per 30 m row (Cattanach 1994; Smith et al. 1990; M. Metzger 2018, personal communication), but sugarbeet density at Nashua-2018 was 50% of the recommended density (Table 3.5). Crop density is an important component of sugarbeet weed management (Dawson 1977) and the poor sugarbeet density at Nashua-2018 and Galchutt-2018 likely reduced the contribution of crop canopy to weed suppression.

Table 3.4. Weekly and monthly precipitation data, interval after planting and 28 days after cultivation in 2017 and 2018. [a]

Week of	Renville-2017 8-E [b]	Wheaton-2017 15-W	Nashua-2018 4-NW	Galchutt-2018 14-E	30-yr avg. [d]
	--	--	mm	--	
May 8	-	0	(0) [c]	(0)	
May 15	48	36	1	1	
May 22	0	3	16	3	
May 29	0	3	21	15	
May total	48	43	(24)	(5)	81
June 5	25	5	49	42	
June 12	14	70	33	80	
June 19	4	30	0.0	0	
June 26	29	22	10	2	
June total	71	128	97	136	83
July 3	19	0	18	36	
July 10	5	3	12	14	
July 17	4	21	97	59	
July 24	28	2	-	4	
July 31	27	41	-	(0)	
July total	56	25	(138)	(115)	81
Aug 7	(0)	(0)	-	-	
Season total	202	236	258	256	

[a] Nashua and Galchutt climate data collected by the North Dakota Agricultural Weather Network (NDAWN); Renville climate data collected from Olivia, MN airport (NWS); Wheaton climate data collected from Wheaton, MN airport (NWS).

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

[c] Precipitation data in parentheses is after planting and before 28 days after cultivation treatment.

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

Table 3.5. Primary weed species present, weed density, and sugarbeet density of environments in 2017 and 2018.

Environment	Primary weed species	Weed density [a]	Sugarbeet density [b]
		# m^{-2}	# per 30 m row
Renville-2017	Waterhemp	104	180
Wheaton-2017	Common lambsquarters	70	193
Nashua-2018	Waterhemp	24	85
Galchutt-2018	Common lambsquarters	72	162

[a] Estimate of primary weed species per m^2 within the untreated check.

[b] Sugarbeet density is average number of sugarbeet plants per 30 m of row.

Waterhemp Control Affected by Delayed Cultivation

Waterhemp density per plot. Delayed cultivation reduced the amount of waterhemp plants per plot in one of two environments (Table 3.6). At Renville-2017, cultivation removed nearly 65% of the waterhemp plants from the cultivated plots 14 DAC. At Nashua-2018, cultivation numerically reduced waterhemp per plot by one third; however, densities as low as 2 to 3 plants per plot were insufficient to detect a statistical difference ($P = 0.119$) because of the discrete quantitative nature of weed counts. Had densities at Nashua-2018 been greater or data was collected on a larger scale, a 65 to 70% reduction in waterhemp plants per plot would be expected because cultivators with 38-cm wide shovels cover approximately 68% of the plot area in 56 cm rows and remove emerged weeds. The primary value of cultivation is the physical removal of weeds that glyphosate did not control. Once herbicide-resistant waterhemp is established, no labeled herbicide in sugarbeet will control it, making cultivation necessary to prevent further competition and contribution to the weed seed bank.

Herbicide treatment did not affect waterhemp plants per plot at any environment (Table 3.6). Numerical differences are considered coincidental because there is little biological explanation for why waterhemp counts between herbicide treatments should be different. The glyphosate alone treatment numerically had the least amount of waterhemp plants per plot at both environments. This observation suggests antagonism between tank-mixed herbicides; however, past research does not indicate significant antagonism between chloroacetamide herbicides and glyphosate exists (Tharp and Kells 2002).

Table 3.6. Main effects of cultivation and herbicide on waterhemp counts at Renville-2017 and Nashua-2018, 14 and 28 days after cultivation treatment (DAC). [a]

	Waterhemp counts, 14 DAC		Waterhemp counts, 28 DAC	
Main effects	Renville	Nashua	Renville	Nashua
Cultivation [b]	-------# per plot-------		-------# per plot-------	
With cultivation	7 a	2 a	9 a	2 a
No cultivation	19 b	3 a	20 b	3 a
Herbicide [c]				
Glyphosate	8 a	1 a	9 a	1 a
Glyphosate + S-metolachlor	21 a	2 a	23 a	2 a
Glyphosate + dimethenamid-P	9 a	3 a	11 a	4 a
Glyphosate + acetochlor	15 a	3 a	16 a	3 a
ANOVA	----------*p value*----------		----------*p value*----------	
Cultivation	0.013	0.379	0.026	0.119
Herbicide	0.062	0.739	0.069	0.576
Cultivation * herbicide	0.535	0.108	0.676	0.801

[a] Means within a main effect and environment column not sharing any letter are significantly different by the t-test at the 5% level of significance.

[b] Cultivation treatments were cultivated approximately two weeks after spray treatment.

[c] All herbicide treatments included ethofumesate, high surfactant methylated oil concentrate, and liquid ammonium sulfate solution.

New waterhemp emergence control. Cultivation did not affect ‘new waterhemp control’ at Nashua-2018, but improved ‘new waterhemp control’ by 11% at Renville-2017 (Table 3.7). Only data from 14 DAC is reported for ‘new waterhemp control’ because chloroacetamide herbicides only have an effective period of 2 to 3 weeks (Mueller et al. 1999), and 14 DAC is 28 days after spray application. This occurrence is likely attributable to the timing of the cultivation. When cultivation was timed near crop canopy closure, cultivation disrupted the emerging growth of new weeds between the rows and allowed the crop canopy to provide shade, suppressing any further emergence. Oryokot et al. (1997) reported tillage has no effect on pigweed emergence. This is because tillage has no effect on the moisture or temperature in the top 2.5 cm layer of soil due to an equalizing soil-atmosphere relationship, and pigweed is physiologically limited to emergence in the top 2.5 cm of soil. Producers have similar concerns that cultivation will disrupt/destroy the effectiveness of an activated chloroacetamide herbicide. Cultivation timed two weeks after herbicide application likely will have little effect on herbicidal activity because chloroacetamide herbicides have an effective period of 2 to 3 weeks (Mueller et al. 1999).

The reason why cultivation reduced weed emergence at Renville-2017 is likely due to an interaction between precipitation after the cultivation and the sugarbeet density in each environment. Nashua-2018 received over 25 mm of precipitation in the two weeks following cultivation while Renville-2017 received less than 10 mm (Table 3.4). Cultivation at Renville-2017 may have disrupted new weed growth and conditions between cultivation and canopy closure were not conducive for further weed emergence. Conditions were conducive for weed growth at Nashua-2018, regardless of cultivation. In addition, sugarbeet density at Nashua-2018 was 85 sugarbeets per 30 m row, or half an optimal density (Table 3.5); Renville-2017 meanwhile had a full and uniform density of 180 sugarbeets per 30 m row. This difference in density between the two environments would have affected the role of crop canopy on weed suppression, which is a crucial component of weed management in sugarbeets (Dawson 1977).

Chloroacetamide herbicides with glyphosate increased ‘new waterhemp control’ by 5 to 8% compared to glyphosate alone at both environments (Table 3.7). Chloroacetamide herbicides similarly controlled waterhemp emergence relative to each other at both environments. This result was expected since chloroacetamide herbicides in sugarbeet provide residual control of emerging small-seeded broadleaf weeds. These results demonstrate the value of mixing chloroacetamide herbicides with glyphosate to reduce the number of emerging waterhemp seedlings. Chloroacetamide herbicides in sugarbeets are applied in a ‘layered’ system where S-metolachlor is applied PRE and S-metolachlor, dimethenamid-P, or acetochlor are tank mixed with glyphosate twice POST to provide "layered" residual control of small-seeded broadleaves until crop canopy closure (Peters et al. 2017). The use of this 'layered' system is important, as no herbicides currently labeled in sugarbeet provide season-long glyphosate resistant waterhemp control.

Table 3.7. Main effects of cultivation and herbicide on new waterhemp control at Renville-2017 and Nashua-2018, 14 days after cultivation treatment (DAC). [a]

	New waterhemp control, 14 DAC [d]	
Main effects	Renville	Nashua
Cultivation [b]	---------------------%---------------------	
With cultivation	100 a	98 a
No cultivation	89 b	98 a
Herbicide [c]		
Glyphosate	90 b	92 b
Glyphosate + S-metolachlor	95 a	100 a
Glyphosate + dimethenamid-P	97 a	100 a
Glyphosate + acetochlor	95 a	100 a
ANOVA	-------------------*p value*-------------------	
Cultivation	0.007	1.000
Herbicide	0.028	0.022
Cultivation * herbicide	0.282	0.515

[a] Means within a main effect and environment column not sharing any letter are significantly different by the t-test at the 5% level of significance.
[b] Cultivation treatments were cultivated approximately two weeks after spray treatment.
[c] All herbicide treatments included ethofumesate, high surfactant methylated oil concentrate, and liquid ammonium sulfate solution.
[d] Evaluation on scale of 0% (no control) to 100% (complete control). New control is visual evaluation of growth since last treatment.

Overall waterhemp control. Cultivation improved season-long 'overall waterhemp control' at Renville-2017, but did not affect season-long waterhemp control at Nashua-2018 (Table 3.8). Data from 14 DAC and 28 DAC is representative of early to mid-season control, while data from 42 DAC is representative of season-long control. Cultivation significantly increased overall control 15 to 20% season-long at Renville-2017, but did not significantly increase control at Nashua-2017 (Table 3.8). This data mirrors the waterhemp counts (Table 3.6) and new waterhemp control (Table 3.7) data since overall control is a visual summation of the two previous dependent variables. At Renville-2017, cultivation reduced the amount of waterhemp present by nearly 65% and increased control of new waterhemp emergence, while cultivation had no effect on waterhemp counts or emergence at Nashua-2018. Poor sugarbeet density (Table 3.5) and low weed density per treated plot (Table 3.6) at Nashua-2018 is likely responsible for inconsistency between environments.

Herbicide treatment did not affect ‘overall waterhemp control’ at Nashua, but S-metolachlor with glyphosate provided less season-long waterhemp control than other herbicides at Renville-2017 (Table 3.8). S-metolachlor with glyphosate had less overall control at Renville-2017 because of coincidentally greater numbers of herbicide-resistant weeds in plots, as new weed emergence control was not different compared with other chloroacetamide herbicides (Table 3.7). Counted plants were considered glyphosate resistant because only plants emerged prior to herbicide application were counted. Numerically, there were 21 waterhemp plants per plot in the S-metolachlor with glyphosate treatment compared with eight waterhemp per glyphosate alone treatment, but the difference was not statistically significant (Table 3.6). This observation would imply antagonism between glyphosate and S-metolachlor, but past research does not indicate antagonism exists (Tharp and Kells 2002).

Table 3.8. Main effects of cultivation and herbicide on overall waterhemp control at Renville-2017 and Nashua-2018, 14, 28, and 42 days after cultivation treatment (DAC). [a]

	Overall control, 14 DAC [d]		Overall control, 28 DAC		Overall control, 42 DAC	
Main effects	Renville	Nashua	Renville	Nashua	Renville	Nashua
Cultivation [b]	----------%----------		----------%----------		----------%----------	
With cultivation	86 a	91 a	80 a	88 a	76 a	87 a
No cultivation	71 b	89 a	63 b	82 a	57 b	82 a
Herbicide [c]						
Glyphosate	83 a	88 a	77 a	86 a	74 a	84 a
Glyphosate + S-metolachlor	70 b	90 a	61 b	85 a	58 b	86 a
Glyphosate + dimethenamid-P	83 a	88 a	77 a	81 a	73 a	80 a
Glyphosate + acetochlor	80 a	91 a	71 a	88 a	67 a	88 a
ANOVA	--------*p value*--------		--------*p value*--------		---------*p value*---------	
Cultivation	< 0.001	0.252	0.001	0.115	0.001	0.245
Herbicide	0.005	0.893	0.005	0.836	0.002	0.788
Cultivation * herbicide	0.915	0.134	0.744	0.524	0.716	0.144

[a] Means within a main effect and environment column not sharing any letter are significantly different by the t-test at the 5% level of significance.

[b] Cultivation treatments were cultivated approximately two weeks after spray treatment.

[c] All herbicide treatments included ethofumesate, high surfactant methylated oil concentrate, and liquid ammonium sulfate solution.

[d] Evaluation on scale of 0% (no control) to 100% (complete control). Overall control is visual evaluation of old and new growth.

Common Lambsquarters Control Affected by Delayed Cultivation

New common lambsquarters control. Cultivation improved ‘new common lambsquarters control’ at Wheaton-2017, but had no effect at Galchutt-2018 (Table 3.9). Sugarbeet density and stage at which the treatments were applied is likely the reason for this difference. Herbicide was applied to 8- to 10-leaf sugarbeet at Wheaton-2017 and 6- to 8-leaf sugarbeet at Galchutt-2018 (Table 3.3). Wheaton-2017 had a full and uniform density of 193 beets per 30 m row, while the density at Galchutt-2018 was less than optimal at 162 beets per 30 m row (Table 3.5). Sugarbeet density at Galchutt-2018 was also noted to be non-uniform with frequent and random gaps. The smaller and less dense/uniform sugarbeet stand at Galchutt-2018 would have reduced the contribution of canopy closure on weed emergence. At Wheaton-2017, cultivation disrupted weed growth and allowed the thick canopy to suppress further emergence, but the gaps in stand and canopy at Galchutt-2018 at the time of treatment created conditions conducive for further weed growth after the cultivation. This would imply the optimal time to cultivate is mid-July or near canopy closure when a healthy crop canopy can provide shade and suppress further weed emergence.

Chloroacetamide herbicides with glyphosate improved ‘new common lambsquarters control’ compared to glyphosate alone in one of two environments. Chloroacetamide herbicides with glyphosate improved ‘new common lambsquarters control’ as compared with glyphosate alone at Wheaton-2017, but had no effect at Galchutt-2018 (Table 3.9). The result from Wheaton-2017 is consistent with previous research reporting improved residual control of emerging small-seeded broadleaves from chloroacetamide herbicides (Peters et al. 2017). Chloroacetamide herbicides at Galchutt-2018 provided a 9% numerical increase in control compared to glyphosate alone, but the variation was too high to measure treatment differences ($P = 0.160$) (Table 3.9).

Table 3.9. Main effects of cultivation and herbicide on new common lambsquarters control at Wheaton-2017 and Galchutt-2018, 14 days after cultivation treatment (DAC). [a]

	New common lambsquarters control, 14 DAC [d]	
Main effects	Wheaton	Galchutt
Cultivation [b]	------------------%------------------	
With cultivation	92 a	97 a
No cultivation	77 b	94 a
Herbicide [c]		
Glyphosate	76 b	89 a
Glyphosate + S-metolachlor	87 a	98 a
Glyphosate + dimethenamid-P	92 a	98 a
Glyphosate + acetochlor	82 ab	98 a
ANOVA	----------------*p value*----------------	
Cultivation	0.027	0.220
Herbicide	0.032	0.160
Cultivation * herbicide	0.991	0.106

[a] Means within a main effect and environment column not sharing any letter are significantly different by the t-test at the 5% level of significance.

[b] Cultivation treatments were cultivated approximately two weeks after spray treatment.

[c] All herbicide treatments included ethofumesate, high surfactant methylated oil concentrate, and liquid ammonium sulfate solution.

[d] Evaluation on scale of 0% (no control) to 100% (complete control). New control is visual evaluation of growth since last treatment.

Overall common lambsquarters control. Cultivation did not significantly affect season-long 'overall common lambsquarters control' at any environment (Tables 3.10 and 3.11). An increase of 10% control as observed 14 DAC at Wheaton-2017, but the statistical significance disappears at later evaluation dates due to variation ($P = 0.060$ to $P = 0.108$). This data mirrors new emergence control since overall control is a visual summation of old and new growth. Overall common lambsquarters control was numerically 7 to 19% greater with cultivation 42 DAC (Table 3.10), but no statistical difference occurred at either environment ($P = 0.060$).

Chloroacetamide herbicides with glyphosate did not affect 'overall common lambsquarters control' compared to glyphosate alone (Tables 3.10 and 3.11). An interaction between cultivation and herbicide 28 DAC at Galchutt-2018 indicates overall control with glyphosate alone was increased by cultivation (Table 3.11). This interaction demonstrates cultivation was beneficial with glyphosate but was not beneficial when residual activity from chloroacetamide herbicides controlled common lambsquarters without cultivation. Cultivation and tank-mixing a chloroacetamide herbicide with glyphosate are probably not necessary to manage common lambsquarters, as glyphosate provides excellent common lambsquarters control alone (Sivesend et al. 2011). A repeat glyphosate application would be less expensive and more effective than a cultivation.

Table 3.10. Main effects of cultivation and herbicide on overall common lambsquarters control at Wheaton-2017 and Galchutt-2018, 14, 28, and 42 days after cultivation treatment (DAC). [a]

	Overall control, 14 DAC [d]		Overall control, 28 DAC	Overall control, 42 DAC	
Main effects	Wheaton	Galchutt	Wheaton	Wheaton	Galchutt
Cultivation [b]	----------%----------		--%--	----------%----------	
With cultivation	95 a	99 a	96 a	92 a	94 a
No cultivation	85 b	96 a	81 a	73 a	87 a
Herbicide [c]					
Glyphosate	83 a	95 a	92 a	87 a	83 a
Glyphosate + S-metolachlor	91 a	97 a	81 a	78 a	92 a
Glyphosate + dimethenamid-P	95 a	100 a	89 a	85 a	95 a
Glyphosate + acetochlor	91 a	99 a	91 a	80 a	92 a
ANOVA	-------*p value*-------		-*p value*-	-------*p value*-------	
Cultivation	0.046	0.058	0.108	0.060	0.060
Herbicide	0.110	0.106	0.393	0.504	0.055
Cultivation * herbicide	0.927	0.134	0.478	0.389	0.108

[a] Means within a main effect and environment column not sharing any letter are significantly different by the t-test at the 5% level of significance.

[b] Cultivation treatments were cultivated approximately two weeks after spray treatment.

[c] All herbicide treatments included ethofumesate, high surfactant methylated oil concentrate, and liquid ammonium sulfate solution.

[d] Evaluation on scale of 0% (no control) to 100% (complete control). Overall control is visual evaluation of old and new growth.

Table 3.11. Interaction of cultivation and herbicide on overall common lambsquarters control at Galchutt-2018, 28 days after cultivation treatment (DAC). [a]

	Overall control, 28 DAC [d]
Cultivation * herbicide interaction	Galchutt
With cultivation	--%--
Glyphosate	88 b
Glyphosate + S-metolachlor	92 ab
Glyphosate + dimethenamid-P	100 a
Glyphosate + acetochlor	98 a
No cultivation	
Glyphosate	72 c
Glyphosate + S-metolachlor	93 ab
Glyphosate + dimethenamid-P	93 ab
Glyphosate + acetochlor	98 a
ANOVA	*-p value-*
Cultivation	0.067
Herbicide	0.013
Cultivation * herbicide	0.042

[a] Means not sharing any letter are significantly different by the t-test at the 5% level of significance.

[b] Cultivation treatments were cultivated approximately two weeks after spray treatment.

[c] All herbicide treatments included ethofumesate, high surfactant methylated oil concentrate, and liquid ammonium sulfate solution.

[d] Evaluation on scale of 0% (no control) to 100% (complete control). Overall control is visual evaluation of old and new growth.

Conclusion: Should I follow herbicide application with a delayed cultivation pass?

Inter-row cultivation two weeks after herbicide application improved overall waterhemp control because it physically removed weeds that glyphosate could not control. The cultivator removed 65% of herbicide-resistant waterhemp, which translated to 20% greater season-long overall control at Renville-2017 (Tables 3.6 and 3.8). At Nashua-2018, no benefit from cultivation was observed because of low waterhemp densities and thin/non-uniform sugarbeet densities. Many producers have asked if cultivation is a viable option to control herbicide-resistant waterhemp escapes without disrupting an activated herbicide barrier. This data suggests cultivation will effectively remove two thirds of weed escapes with no apparent deleterious effects. Cultivation timed two weeks after residual herbicide application or near canopy closure will disrupt weed growth and allow the crop canopy to suppress further emergence. Delayed cultivation is not necessary to control glyphosate-susceptible common lambsquarters because a repeat glyphosate application is cheaper and more reliable.

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CHAPTER 4. INTER-ROW CULTIVATION TIMING EFFECT ON SUGARBEET YIELD AND QUALITY

Introduction

Weed management in sugarbeet (*Beta vulgaris*) has become increasingly more difficult in the past decade. This is largely due to the increased prevalence of herbicide-resistant weeds in the northern Great Plains, but can also be attributed to the reduced number of labeled sugarbeet herbicide options. Mechanical weed control methods such as inter-row cultivation were commonly used in sugarbeet fields until the release of glyphosate resistant (GR) sugarbeet cultivars in 2008 made the use of inter-row cultivation unnecessary. Survey data from 2007 indicated 99% of ND and MN 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). The recent migration of GR waterhemp (*Amaranthus tuberculatus*) into northern sugarbeet growing regions has compelled producers to use inter-row cultivation to achieve acceptable weed control.

Inter-row cultivation mid-season has benefits and drawbacks. The greatest benefit is that inter-row cultivation is a non-selective method of removing weeds between crop rows that herbicides did not/cannot control. Other benefits include drying/loosening of the soil and incorporation of fertilizer and residual herbicide. Numerous studies have evaluated the effect of inter-row cultivation on sugarbeet yield and quality. Results of these studies generally demonstrate 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 and Luecke (2000) reported cultivation had a negative effect on sugarbeet yield and quality in certain environments. They reported a trend for greater yield with two cultivations compared to no cultivation in certain environments, but they also reported a trend of less yield and quality in three out of ten environments with five cultivations. Dexter (1983) reported 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 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 cultivation later in the season is likely due to two factors, physical damage to the sugarbeet plant tissue and increased infection of *Rhizoctonia solani* that causes *Rhizoctonia* crown and root rot. Giles et al. (1990) excavated roots in mid-July and observed less root development in the top seven centimeters of soil in treatments that received a large number (4 to 7) 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 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 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 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 (Windels and Lamey 1998, Schneider et al. 1982).

Sugarbeet producers frequently used inter-row cultivation to control herbicide-resistant weeds in 2018 (Peters et al. 2018). Many producers are concerned that inter-row cultivation will reduce sugarbeet yield and quality because of the results of the early work by Dexter and Giles. Most producers consider one to two cultivation passes mid-season a “rescue” strategy rather than contributing to an integrated weed management strategy. Inter-row cultivation has also been associated with *Rhizoctonia* crown and root rot because of the early work done by Schneider. The objectives of this experiment were to 1) evaluate the effect of inter-row cultivation timing and number of passes on sugarbeet yield and quality and 2) evaluate if inter-row cultivation timing and number of passes increases severity of *Rhizoctonia solani* on sugarbeet.

Materials and Methods

Site Description

Field experiments were conducted in three environments in grower fields near Glyndon, MN (46°51'52.7"N, 96°31'15.5"W), Hickson, ND (46°42'18.9"N, 96°48'08.1"W), and Amenia, ND (47°00'10.4"N, 97°06'21.9"W) in 2018. Previous crop grown in fields were soybean, sugarbeet, and wheat at the Glyndon, Hickson, and Amenia fields, respectively. The soil at the Glyndon environment was a Wyndmere fine sandy loam (Coarse-loamy, mixed, superactive, frigid Aeric Calciaquolls). The soil at the Hickson field was a Fargo silty clay (Fine, smectitic, frigid Typic Epiaquerts). The soil at the Amenia field was a mix of Bearden (Fine-silty, mixed, superactive, frigid Aeric Calciaquolls) and Lindaas (Fine, smectitic, frigid Typic Argiaquolls) silty clay loams. All environments were chisel plowed in the fall and prepared for spring sugarbeet planting with a field cultivator. Field site information can be found in Table 4.1.

Table 4.1. Soil descriptions for cultivation safety environments in 2018.

Environment	Soil series & texture	Soil subgroup	Organic matter	Soil pH
Amenia, ND	Bearden & Lindass silty clay loam mix	Aeric Calciaquolls & Typic Argiaquolls	3.9%	8.0
Hickson, ND	Fargo silty clay	Typic Epiaquerts	6.0%	7.5
Glyndon, MN	Wyndmere fine sandy loam	Aeric Calciaquolls	2.6%	8.2

Experimental Procedures

The experiment was a randomized complete block with four replicates. Plots were 3.3 m wide and 9.1 m long. Treatments were applied every two weeks through the growing season starting June 21 and ending August 16. Treatments were a combination of the cultivation date and number up to three passes and an untreated control (Table 4.2). Cultivation date and frequency were reflective of current practices by growers (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}.

Table 4.2. Date of cultivation treatments in sugarbeet of environments in 2018.

Treatment #	Cultivation passes	Cultivation dates [a]
1	Control	Control
2	Single	June 21
3	Single	July 5
4	Single	July 19
5	Single	August 2
6	Single	August 16
7	Double	June 21 + July 19
8	Double	July 5 + Aug 2
9	Double	July 19 + Aug 16
10	Triple	June 21 + July 19 + Aug 16

[a] Treatments were cultivated within three days (+/-) of the listed date.

The sugarbeet cultivar ‘Crystal 355RR’ (American Crystal Sugar Company, Moorhead, MN) was planted 3 cm deep to a density of 152,000 (+/- 1,000) seeds ha^{-1} in six rows spaced 56 cm apart. Planting dates were May 3, 2018 at Glyndon, May 7, 2018 at Hickson, and May 14, 2018 at Amenia. Sugarbeet seeds were treated with penthiopyrad (Kabina ST, Sumitomo Corporation, New York, NY). Nitrogen, phosphorus, and potassium fertilizer was applied based on spring soil tests and incorporated prior to planting. Weeds and disease were controlled so 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}. No more than three glyphosate applications were made at each location and herbicide resistant waterhemp was removed by hand-weeding. Root disease pressure from *Rhizoctonia 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), and difenoconazole/propiconazole (Inspire XT, Syngenta Crop Protection, Greensboro, NC).

Data Collection and Analysis

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. Harvest dates were September 17, 2018 at Glyndon, September 11, 2018 at Hickson, and September 18, 2018 at Amenia. At harvest, sugarbeet was defoliated with a four-row topper and harvested with a two-row sugarbeet harvester. The sugarbeet roots were weighed and American Crystal Sugar Company, East Grand Forks, ND analyzed a ten-kilogram sample from each plot for percent sucrose and sugar loss to molasses (SLM). 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 the equations below.

$$Root\ yield\ (kg/ha) = \frac{harvested\ plot\ weight\ (kg)}{hectare\ area\ of\ harvested\ plot}$$

$$Purity\ (\%) = \frac{\%\ sucrose\ content - \%\ sugar\ loss\ to\ molasses}{\%\ sucrose\ content} x\ 100$$

$$Recoverable\ sucrose\ (kg/ha) = (\frac{[(\%\ purity\ /\ 100)\ x\ \%\ sucrose\ content]}{100})\ x\ root\ yield$$

Data was subjected to ANOVA using the MIXED procedure in SAS 9.4 (SAS Institute, Cary, NC) to test for treatment effects between means at $P \leq 0.05$. Cultivation treatment was considered a fixed effect, while environment and replicate were considered random effects. Environments were combined for analysis when mean square error values between environments were within a factor of ten. Single-cultivation and double-cultivation treatments were subject to regression analysis ($P \leq 0.05$) to detect relationships between cultivation timing and sugarbeet stand, yield, and quality.

Results and Discussion

Field Growing Conditions

Field planting ranged between May 3 and May 14 across all environments (Table 4.3), which is typical for sugarbeet production in eastern North Dakota and Minnesota. Season-long precipitation at Amenia was slightly below the 30-year average, while Hickson and Glyndon received slightly above the 30-year average (Table 4.4), but Amenia still delivered the greatest root yield across all environments. Sugarbeet density averaged 182 sugarbeets per 30 m row at Amenia prior to the first cultivation (Table 4.3) and the previous crop grown was wheat, which is recommended for sugarbeet growers as wheat is considered a non-host for *Rhizoctonia solani* (Windels and Brantner 2008). Sugarbeet density averaged 187 sugarbeets per 30 m row at Hickson prior to the first cultivation (Table 4.3), but stand mortality from *Rhizoctonia* root rot likely occurred because the previous crop was sugarbeet which is not recommended due to the buildup of disease inoculum (Windels and Brantner 2008). Hickson received excessive hail on August 26 that destroyed 90% of the crop canopy, which likely reduced root yield and sucrose content at harvest.

Glyndon received only 14 mm of precipitation in the month following planting (Table 4.4), which led to an erratic and non-uniform crop stand. Sugarbeet density prior to cultivation at Glyndon was 150 sugarbeets per 30 m row (Table 4.3), but crop stage ranged from cotyledon to 6-leaf sugarbeet. Glyndon soil texture was a fine sandy loam with low organic matter (Table 4.1) which likely contributed to moisture stress throughout the growing season. Sugarbeets at Glyndon were also noted to exhibit foliar potassium deficiency throughout the season, which was possibly due to inadequate fertilization rate, poor crop uptake, or both.

Table 4.3. Dates of planting and harvest, previous crop grown, and sugarbeet density of cultivation safety environments in 2018.

Environment	Planting date	Harvest date	Previous crop	Sugarbeet density prior to first treatment
				# per 30 m row
Amenia, ND	May 14	September 18	Wheat	182
Hickson, ND	May 7	September 11	Sugarbeet	187
Glyndon, MN	May 3	September 17	Soybean	150

Table 4.4. Monthly precipitation data between planting and harvest of cultivation safety environments in 2018. [a]

Month	Amenia 1-W [b]	Hickson 21-N	Glyndon 10-SW	30-yr avg. [d]
	----------------------------------	-------mm-------	----------------------------------	
May total	(41) [c]	(44)	(14)	71
June total	79	123	148	99
July total	65	81	117	71
August total	79	101	92	95
September total	(30)	(15)	(14)	65
Season total	294	364	385	

[a] Climate data from all sites collected by the North Dakota Agricultural Weather Network.

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

[c] Precipitation data in parentheses is after planting and before harvest.

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

Sugarbeet Density Affected by Inter-row Cultivation

Inter-row cultivation did not affect sugarbeet density at any environment in 2018 (Table 4.5). Environments were analyzed separately for stand mortality because mean square error values between environments were not within a factor of ten. Stand mortality at Amenia was relatively low, ranging from 11% to 21%, but no patterns were observed. The stand mortality at Hickson was relatively high, ranging from 30 to 40% (Table 4.5), but stand mortality was consistent between treatments. The relatively high stand mortality at Hickson is probably due to sugarbeet being the previous crop grown on the field site. Planting sugarbeet into sugarbeet residue highly increases chance of infection from *Rhizoctonia solani* (Windels and Brantner 2008). Sugarbeet stand mortality was not observed at Glyndon (Table 4.5). Some sugarbeet roots at Glyndon were small and 6 to 8 leaves at harvest, indicating they had emerged mid-season. Sugarbeet were counted a few hours prior to the first cultivation on June 21, but sugarbeet continued to emerge randomly into the summer at Glyndon, making the stand mortality measurement negative in some random treatments.

Harvested sugarbeet roots were visually inspected for root and crown rot from *R. solani*, but no significant infection due to 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 (Table 4.5). Inter-row cultivation has historically been associated with root and crown rot since cultivation may physically deposit soil onto a beet crown, moving soil-borne pathogens nearer their host. Schneider et al. (1982) reported 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 reducing cultivation ground speed reduces chance 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 was possibly not fast enough to cause significant root rot infection.

Table 4.5. Sugarbeet stand mortality affected by cultivation timing in 2018.

	Stand mortality [a]		
Cultivation timing	Amenia	Hickson	Glyndon
	------------------------%------------------------		
Control	15	32	-14
June 21	20	37	-1
July 5	15	37	4
July 19	20	41	-10
August 2	11	32	-1
August 16	13	30	10
June 21 + July 19	13	31	-7
July 5 + Aug 2	19	36	4
July 19 + Aug 16	21	39	7
June 21 + July 19 + Aug 16	16	37	7
ANOVA	---------------------*p value*---------------------		
Treatment	0.082	0.435	0.848

[a] Percent stand mortality is calculated by multiplying the ratio of harvest stand and pre-treatment stand by 100.

Sugarbeet Root Yield and Quality Affected by Inter-row Cultivation

Root yield. Inter-row cultivation did not affect root yield at any environment (Table 4.6). Root yields were 84 to 90 Mg ha^{-1} at Amenia, 37 to 52 Mg ha^{-1} at Hickson, and 22 to 33 Mg ha^{-1} at Glyndon. No statistical differences between treatments were measured across environments (P = 0.944). 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 two to three implemented in these experiments.

Table 4.6. Sugarbeet root yield affected cultivation timing in 2018.

	Root yield[a]			
Cultivation timing	Amenia	Hickson	Glyndon	All environments
	---------------------------Mg ha^{-1}---------------------------			
Control	83.9	47.4	31.8	54.4
June 21	87.3	45.6	29.4	54.1
July 5	88.9	43.9	33.4	55.4
July 19	89.8	36.8	31.7	52.8
August 2	86.2	52.2	32.5	57.0
August 16	85.2	50.7	28.2	54.7
June 21 + July 19	90.5	50.7	22.1	54.5
July 5 + Aug 2	89.9	49.2	26.8	55.3
July 19 + Aug 16	86.1	41.9	29.7	52.6
June 21 + July 19 + Aug 16	85.8	45.3	26.9	52.7
ANOVA	---------------------------*p value*---------------------------			
Treatment	0.419	0.492	0.466	0.944

[a] Root yield reported in megagrams (Mg) ha^{-1}. One Mg = 1000 kg = one metric ton.

Sucrose content. Inter-row cultivation did not affect sucrose content at any environment (Table 4.7). Sucrose percentages ranged from 15.7 to 16.3% in Amenia, 14.1 to 14.9% in Hickson, and 13.6 to 14.2% in Glyndon, with no significant differences between treatments. Combined analysis tended to demonstrate treatment differences between cultivation number and dates (P = 0.062), but no patterns were observed. Regression analysis to determine if sucrose content was affected by cultivation timing was not significant (data not shown).

Cultivator shanks traveling between sugarbeet rows during cultivation were observed to cause foliar damage, especially at later cultivation dates. Sugarbeet plants compensate for the foliar damage by producing new leaves, potentially lowering sucrose content, but this data demonstrates no reduction in sucrose content. 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.

Table 4.7. Sugarbeet sucrose content affected by cultivation timing in 2018.

	Sucrose content			
Cultivation timing	Amenia	Hickson	Glyndon	All environments
	-------------------------------%-------------------------------			
Control	16.3	14.9	13.8	15.0
June 21	16.2	14.6	13.8	14.8
July 5	16.2	14.7	14.0	14.9
July 19	16.1	14.8	13.7	14.9
August 2	15.9	14.3	13.9	14.7
August 16	15.7	14.1	13.6	14.5
June 21 + July 19	16.0	14.3	13.4	14.5
July 5 + Aug 2	15.8	14.3	13.6	14.6
July 19 + Aug 16	15.8	14.6	14.2	14.8
June 21 + July 19 + Aug 16	16.2	14.2	13.9	14.8
ANOVA	----------------------------*p value*----------------------------			
Treatment	0.872	0.857	0.128	0.062

Recoverable sucrose per hectare. Inter-row cultivation did not affect recoverable sucrose ha^{-1} at any environment (Table 4.8). Recoverable sucrose ha^{-1} (RSH) is a calculation derived from root yield and sucrose content. RSH ranged from 11.9 to 13.1 Mg ha^{-1} at Amenia, 5.0 to 6.8 Mg ha^{-1} at Hickson, and 2.7 to 4.4 Mg ha^{-1} at Glyndon (Table 4.8). No treatment differences were measured in the combined analysis (P = 0.947). This result was expected since treatment means for root yield and sucrose content were not significantly different (Tables 4.6 and 4.7).

Table 4.8. Sugarbeet recoverable sucrose ha^{-1} (RSH) affected cultivation timing in 2018.

	RSH			
Cultivation timing	Amenia	Hickson	Glyndon	All environments
	----------------------------	kg ha^{-1}	----------------------------	
Control	12,387	6,496	4,037	7640
June 21	13,002	6,108	3,733	7591
July 5	12,979	5,981	4,355	7772
July 19	13,055	5,024	3,989	7356
August 2	12,288	6,762	4,147	7733
August 16	11,896	6,534	3,525	7318
June 21 + July 19	13,094	6,649	2,714	7486
July 5 + Aug 2	12,707	6,409	3,406	7507
July 19 + Aug 16	12,267	5,570	3,924	7254
June 21 + July 19 + Aug 16	12,652	5,841	3,496	7330
ANOVA	----------------------------	*p value*	----------------------------	
Treatment	0.422	0.499	0.481	0.947

Conclusion: Will I reduce sugarbeet yield if I control weeds with cultivation?

Inter-row cultivation did not affect sugarbeet density, root yield, or quality at any environment in this experiment. This data suggests up to three cultivations performed as late as August 16 will not negatively affect sugarbeet yield. Most producers in 2018 only used cultivation to remove weeds that glyphosate did/will 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 were also 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 the past work done by Dexter and Giles. While the cultivation methods and procedures used in our experiment are similar to what Dexter and Giles implemented in their experiments, our timing of cultivation was different. Dexter and Giles conducted their cultivations on weekly intervals with the same start date, while our cultivations were two weeks apart with staggered starting dates and timings as late as August 16. Furthermore, certain aspects of sugarbeet production that could affect disease pressure are different from the 1980s and 1990s such as diploid genetics, seed treatments, and soil-applied applications of azoxystrobin. Our results show cultivation 4 to 5 cm deep at 6.4 km h^{-1} with soil-applied applications of azoxystrobin did not affect sugarbeet yield in 2018, 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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SUMMARY

Weed management in sugarbeet has been challenging for the majority of its time as an agricultural crop. The migration of herbicide-resistant weeds into the upper Midwest, in addition to the non-renewed label of desmedipham and phenmedipham, has made management especially difficult in the past decade. Inter-row cultivation can be an important supplement to a sugarbeet weed management strategy if used correctly.

Two cultivation efficacy experiments were conducted to 1) evaluate the effect of cultivation immediately after herbicide application on control of waterhemp and common lambsquarters (Chapter 2) and 2) evaluate the effect of cultivation two weeks after herbicide application on control of waterhemp and common lambsquarters (Chapter 3). Across both experiments, cultivation removed 50-75% of waterhemp plants and generally did not affect waterhemp emergence which translated into 6 to 19% improved overall season-long control. In regards to common lambsquarters, cultivation had little to no benefit to overall control and increased weed emergence when cultivation was timed too early. At Galchutt-2018, a cultivation at the 4- to 6-leaf sugarbeet stage resulted in 100% more common lambsquarters per m^2, 28 days after treatment.

Sugarbeet producers have two inquiries in regards to the application of cultivation: 1) “Can inter-row cultivation immediately after herbicide application be used to incorporate residual herbicides?” and 2) “Will inter-row cultivation two weeks after herbicide application destroy/disrupt an established herbicide barrier and result in further weed emergence?”. Precipitation was ideal in one of five environments to determine if inter-row cultivation can be used to incorporate residual herbicides and increase control of weed emergence, but no benefit was observed. The methods of a single 38-cm sweep shovel in 56 cm rows likely did not provide adequate mixing action; therefore, further experiments with different cultivator configurations are needed to further evaluate this question. A cultivation two weeks after cultivation did not result in greater weed emergence in our environments because the cultivation was timed near canopy closure when the crop canopy could provide natural shade and suppress further weed emergence. Furthermore, chloroacetamide herbicides have an effective period of 2 to 3 weeks, so a delayed cultivation likely would not disrupt what little herbicidal activity is left.

An experiment was conducted to evaluate the effect of inter-row cultivation timing on sugarbeet root yield and quality (Chapter 4). Past research by Drs. Alan Dexter and Joe Giles demonstrated cultivation could cause yield loss in certain environments. Our results showed three cultivation passes as late as August 16 did not affect sugarbeet root yield and quality across three environments. Experimental procedures in our trials were slightly different from Dexter and Giles in that our cultivations were spaced two weeks apart and we utilized soil-applied applications of azoxystrobin. Further research is needed in different environmental conditions to determine how and when cultivation can affect sugarbeet root yield and quality with modern production practices, cultivars, and fungicide applications.

Our recommendation to sugarbeet producers in 2019 and beyond is to use cultivation as a means to control herbicide-resistant weeds after the last herbicide application, or near crop canopy closure. Utilize the current herbicide recommendation of applying S-metolachlor and/or ethofumesate preemergence, following by tank-mixes of a chloroacetamide herbicide and glyphosate twice postemergence. The use of chemical weed control (herbicide), mechanical weed control (cultivation), and cultural weed control (proper timing) will be part of an integrated weed management system that will provide season-long weed control and maximize crop yield.